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

Dr Sarah Whitmee PhD[1], Professor Rosemary Green PhD[1], Dr Kristine Belesova PhD[1,25], Dr Syreen Hassan PhD[1], Dr Soledad Cuevas PhD[1], Dr Peninah Murage PhD[1], Dr Roberto Picetti PhD[1], Mr Romain Clercq-Roques MSc[1], Professor Kris Murray PhD[2], Ms Jane Falconer MA[3], Ms Blanca Anton MSc[1], Ms Tamzin Reynolds MSc[1], Dr Hugh Sharma Waddington, PhD[4,5], Dr Robert Hughes MPH[1], Dr Joseph Spadaro PhD[6], Ms Aimée Aguilar Jaber MSc[7], Dr Yamina Saheb[8], Dr Diarmid Campbell-Lendrum PhD[9], Ms Maria Cortés-Puch MSc[10], Professor Kristie Ebi PhD[11], Dr Rachel Huxley PhD[12], Professor Mariana Mazzucato PhD[13], Dr Tolu Oni PhD[14], Dr Nicole de Paula PhD[15,16], Professor Gong Peng PhD[17], Mr Aromar Revi MSc[18], Professor Johan Rockström PhD[19], Dr Leena Srivastava PhD[20], Professor Lorraine Whitmarsh PhD[21], Dr Robert Zougmoré PhD[22], Ms Joy Phumaphi MSc[23], Rt Hon Helen Clark MA[24], Professor Andy Haines F Med Sci[1]

[1] Centre on Climate Change and Planetary Health, London School of Hygiene & Tropical Medicine, Keppel Street, London WC1E 7HT.
[2] MRC Unit The Gambia at LSHTM, Atlantic Boulevard, Fajara PO Box 273, Banjul, The Gambia.
[3] London School of Hygiene & Tropical Medicine, Keppel Street, London WC1E 7HT.
[4] Environmental Health Group, Department of Disease Control, London School of Hygiene & Tropical Medicine, Keppel Street, London WC1E 7HT.
[5] London International Development Centre, 20 Bloomsbury Square, London WC1A 2NS.
[6] Spadaro Environmental Research Consultants (SERC), Philadelphia, PA, USA.
[7] OECD, 2, rue André Pascal, 75016 Paris, France.
[8] Sciences Po, 27, Rue Saint Guillaume - 75337 Paris Cedex 07, France.
[9] Climate Change and Health Programme, WHO, 20 Avenue Appia, 1211 Geneva 27, Switzerland.
[10] Sustainable Development Solutions Network, 475 Riverside Drive, Suite 530, New York, NY, USA.
[11] Center for Health and the Global Environment, University of Washington, Hans Rosling Center, 3890 15th Avenue NE, Box 351620, Seattle, Washington 98195, USA.
[12] C40 Cities Climate Leadership Group, 120 Park Avenue, Floor 23, New York, NY 10017, USA.
[13] Institute for Innovation and Public Purpose, University College London, Gower Street, London WC1E 6BT, UK.
[14] Global Diet and Activity Research Group, MRC Epidemiology Unit, University of Cambridge School of Clinical Medicine, Box 285 Institute of Metabolic Science, Cambridge Biomedical Campus, Cambridge CB2 0QQ, UK.
[15] Food and Agriculture Organization of the United Nations
[16] Women Leaders for Planetary Health
[17] University of Hong Kong, Pokfulam Road, Hong Kong.
[18] Indian Institute for Human Settlements, Tharangavana, D/5 12th Cross, Rajamahal Vilas Extension, Bengaluru 560 080, India.
[19] Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, 14412, Potsdam, Germany.
[20] Ashoka Centre for a People-centric Energy Transition, New Delhi, India
[21] Department of Psychology, University of Bath, Bath, UK.
[22] AICCRA, International Crops Research for the Semi-Arid Tropics, Bamako, Mali.
[23] African Leaders Malaria Alliance (ALMA).
[24] Helen Clark Foundation, Auckland, New Zealand.
[25] Department of Primary Care and Public Health, Imperial College London, London, UK

Corresponding author: Dr Sarah Whitmee PhD, Centre on Climate Change and Planetary Health, London School of Hygiene & Tropical Medicine, Keppel Street, London WC1E 7HT, UK. Tel: 0207 9272511. Email: sarah.whitmee@lshtm.ac.uk

Executive summary

Deep, rapid cuts in greenhouse gas (GHG) emissions are needed to limit future global temperature increases to 1.5 degrees Celsius (°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 GHG emissions can also deliver near-term health co-benefits, for example, from reduced air pollution, consumption of healthy diets and increased physical activity. Better evidence of 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 GHG emissions by 2050. The Lancet Pathfinder Commission was established to collate and assess the evidence on the near-term health effects of GHG 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 6,902 records, of which 317 full texts were screened. From the full text screening, 26 reviews were found that presented quantitative estimates of both changes in GHG emissions and health outcomes. A total of 200 mitigation actions were identified across all sectors, and the majority of these actions presented modelled estimates of the effects of climate mitigation actions on GHG emissions and health across different sectors and scales: 178 of the 200 identified actions (89%) present modelled results. Mitigation actions were converted to CO_2 equivalents (CO_2eq) to allow the inclusion of other GHGs alongside CO_2. Health co-benefits were quantified in terms of health co-impact intensity (YLL/100,000 population/year) and climate benefits were quantified as carbon mitigation intensity (kilotonnes (kt) CO_2eq/100,000/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 1,279 years of life lost (YLL), per 100,000 population, per year) followed by dietary changes (median estimated reduction of 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, a median reduction of 17 YLL, per 100,000 population, per year, with some evidence for larger benefits in India, which is the only Low Middle-Income Country (LMIC) setting for which relevant evidence was found (median reduction of 182 YLL per 100,000 population per year). Actions to decarbonise electricity generation generally had the greatest carbon mitigation intensity of actions in a single sector (a median estimated reduction of 171 kt CO_2eq, per 100,000 population, per year). Multi-sectoral actions may achieve very high mitigation intensity, but their impacts were highly variable, depending on the country context.

A search of peer-reviewed, and grey literature was also undertaken to further identify examples of implemented actions which 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, socio-economic 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 employed machine learning to classify peer-reviewed research papers on climate and health. In addition, pre-existing databases from C40 Cities and CDP were screened, alongside studies submitted in response to a call for evidence 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 (i.e. nature-based solutions).

A few 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 at scale in the US and the provision of healthcare services to communities in Indonesia to incentivise the preservation and restoration of forests. There is an urgent need for further prospective studies of climate actions in diverse settings and contexts, to evaluate the impact of implemented policies on GHG 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 and Middle-Income countries could help to inform and promote a just and equitable transition to net zero. Better 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 the need for new approaches to scaling up ambitious action, particularly focusing on the systemic drivers of GHG 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 Agreement through Nationally Determined Contributions and Long-Term Low Emissions and Development Strategies (LT-LEDS) can maximise health gains and minimise trade-offs, while reducing inequality, promoting efficient use of resources and meeting climate targets.

Modelled evidence from the umbrella review shows that some actions may deliver large benefits for health with only small benefits for climate mitigation and vice versa, while 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 are 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 resources use could help and engage decision makers and the public in the utility of such an approach. The recommendations of the Commission include the formation of a coalition of actors - including cities, sub-national 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 GHG 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 Nationally Determined Contributions 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.

Key messages

- **Unrealised opportunities:** An abundance of modelled evidence attests to the health co-benefits of climate mitigation action across many sectors of society. Increased ambition and evaluation of implemented actions at scale are urgently needed to accelerate progress and capitalise on the health co-benefits that can be achieved from a transition to a net zero emission future.

- **Multiple pathways connect mitigation action and health in differing contexts.** 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.

- **The inclusion of health and equity into the delivery of all climate policies can support a just and healthy transition to a net zero economy**. The full integration of co-benefits into the delivery of the Paris Agreement through Nationally Determined Contributions and Long-Term Low Emissions and Development Strategies (LT-LEDS) can optimise health gains while reducing inequality and meeting climate targets.

- **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 GHG effects of implemented mitigation actions including through processes such as the Global Stocktake (GST). 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 emissions requires systems approaches that integrate adaptation and mitigation and address underlying structures driving inequity and rising GHG emissions. Examples of implemented and evaluated transformative action are urgently needed to inspire and inform change.

- **A coalition of organisations**, sub-national, and national initiatives is proposed, to accelerate progress towards net zero GHG emissions and improve health, with a commitment to monitor and evaluate effects on health and GHG emissions as well as to share experiences about successes and failures.

Introduction

Urgent cuts in greenhouse gas (GHG) emissions are needed to limit future global temperature increases to 1.5 degrees Celsius (°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 the 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 and speed of the emission reductions needed to achieve the Paris 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 GHG 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 may 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 focussed on supply side solutions that improve efficiency or provide technical solutions to current demands (e.g. greater provision of solar and wind energy) and carbon dioxide removal, but recent analyses have emphasised the need for demand-side strategies in addition, 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 amongst the most well-evidenced co-benefits of mitigation actions, uncertainties exist about their magnitude 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 GHG 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 i) map the pathways linking mitigation actions with health and assess the magnitude of potential health co-benefits and GHG mitigation impacts through synthesis of evidence (umbrella review)[17] ii) investigate and analyse evaluated examples of implemented GHG mitigation actions and, where possible, to understand the reasons for success or failure of such actions.[18] This report presents the findings on the health co-benefits of GHG 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 less need for air conditioning, is included, while stand-alone adaptation activities, even those with links to health (such as early-warning 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 GHG mitigation actions that are the focus of this report. Some exemplary implemented actions to reduce GHG emissions were identified within the healthcare 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 Healthcare.[19]

Issues of global justice are core to achieving a just and equitable transition and to delivering health co-benefits to those most in need.[20] The Commission report acknowledges the importance of understanding the distribution of benefits and disbenefits from the policies identified and reports on distributional impacts where described. 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[21] entitled *"Climate change and health equity."* Their scope of 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 GHG emissions, varying by country and level of development. Partner organisations comprise the C40 Cities network, CDP, Organization of Economic Cooperation and Development (OECD), UN Sustainable Development Solutions Network (SDSN), and the Alliance for Health Policy and Systems Research.

Panel 1. Links with the Lancet Countdown on Health and Climate Change.
The Pathfinder Commission builds on the work of several previous Lancet series and Commissions,[7,8,22–24] including The Lancet Countdown on Health and Climate Change.[25] Lancet Countdown is an international academic collaboration that brings together over 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 over 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 healthcare 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 Pathfinder 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.

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 $PM_{2.5}$ including black carbon, NO_2 and tropospheric ozone) from phasing out fossil fuels by replacing them with clean renewable energy and addressing other sources of GHG 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 to achieve the Paris Agreement climate goals in just nine countries showed that, compared with the current pathways scenario, by 2040 the sustainable pathways scenario resulted in an estimated annual reduction of about 1·2 million air pollution-related premature deaths, 5·9 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 emphasizes health benefits in all climate policies would result in substantial additional estimated reductions of premature deaths.[26] 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.[27,28] An illustrated summary of potential pathways and linkages between climate mitigation and health is given in Figure 1.

Air pollution: On a global scale, the estimates of annual fossil fuel-related ambient air pollution deaths range from the Global Burden of Disease (GBD) estimate of just over a million,[29] based on a limited number of specific health outcomes, to other estimates of 3·6 million[30] and up to 8.7 million annual premature deaths,[31] 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 NCDs including ischaemic heart disease, stroke, diabetes, chronic obstructive pulmonary disease, lung cancer, and acute respiratory infections. This implies that major health benefits will result from replacing fossil fuels with clean renewable energy sources. These health co-benefits are currently predominantly experienced in Asia because of the high levels of fossil fuel related air pollution and due to their increasingly ageing populations facing high levels of exposure. Benefits are, however, appreciable in other regions because even low levels of air pollution are harmful.[30,32,33] Ambient air pollution is increasing across Africa. In the absence of deliberate intervention, it will increase morbidity and mortality, diminish economic productivity, impair human capital formation, and undercut development. Because most African countries are still early in development, 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.[34] Major additional benefits would result from reduced household air pollution, largely in low-income countries.[35]

Short-lived climate pollutants like tropospheric ozone (O3) and black carbon (BC, a component of $PM_{2.5}$) 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 CH_4 (an ozone precursor) and BC emissions which, if implemented, would reduce the projected global mean temperature increase by ~0·5°C by 2050. If properly utilised these measures were also projected to prevent 0·7 to 4·7 million annual premature deaths from ambient air pollution and increase crop yields by 30 to 135 megatonnes (million tonnes) annually from ozone reductions in 2030 and beyond.[36] The Global Methane Assessment shows that methane (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 per cent reduction would prevent an estimated 260,000 premature deaths from tropospheric ozone, 775,000 asthma-related hospital visits, 73 billion hours of lost labour from extreme heat, and 25 million tonnes of crop losses annually.[37]

A worsening cycle of climate-fire feedback may also increase emissions and negatively impact health. 1.76 billion tons of CO_2 was released from burning boreal forests in North America and Eurasia in 2021, this was the equivalent of double the CO_2 emissions produced by global aviation in 2021 and 150% higher than annual mean CO_2 emissions from boreal forests between 2000 and 2020.[38] The global mortality burden associated with wildfire smoke was estimated between 260,000 and 600,000 in 2012,[39] but this could be an underestimate due to increased fire occurrences in heavily populated parts of the world.[40]

Healthy sustainable diets: Systematic reviews have shown the health and GHG benefits of predominantly plant-based diets for adult populations.[41] The EAT-Lancet Commission estimated that about 10-11 million premature deaths from NCDs could be prevented annually worldwide by 2040 if the 'planetary health diet' (characterised by high consumption of plant-based foods and low intake of red meat and dairy products) was widely consumed.[23] Ensuring that such dietary choices are affordable, particularly in low- and middle-income countries, is a major challenge.[42]

Active travel: Physical inactivity is a major risk factor for non-communicable diseases (NCDs) and has been estimated to be responsible for about 5 million premature deaths worldwide annually.[43] Population attributable risks were more than double in high-income 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.[44] 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.[45,46] Additional health benefits could arise from reduced road traffic accidents if integrated policies were implemented.[47]

Other health co-benefits: Mitigation actions such as nature-based solutions, including forest protection, agroforestry and land restoration[48] are likely to offer significant opportunities to sequester and store carbon but quantitative estimates of health benefits currently limited.[8] Likewise 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 normalised difference vegetation index (NDVI) that estimated that over 40,000 annual premature deaths could be prevented by meeting the WHO recommendation of access to green space, amounting to about 2·3% of natural cause mortality, but GHG emission reductions were not estimated.[49] Actions that are primarily designed to improve equity, education and human rights can also have additional GHG mitigation benefits,[50] 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 (see WebAppendix A1). 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 IPCC,[15,51] Drawdown,[50] OECD,[52] and WHO.[53] The framework also draws on specific resources for classification of behavioural solutions, [54] ocean-based solutions,[55] the health and education sectors,[56,57] and urban nature-based solutions.[58] It was designed to respond iteratively to findings generated by the research programme, and therefore the final framework classifies evidence based on the major pathways identified where there was substantial evidence of health co-benefits from mitigation actions. Full methods and typologies are given in the WebAppendix A1 and Figure A1.

We undertook an umbrella review (a review of systematic reviews) of studies in the academic or policy literature that had quantified both changes in GHG 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 solutions 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 prior evidence across sectors and to compare the magnitude of modelled and measured effects of mitigation actions on GHG emissions and health outcomes. The umbrella review of existing systematic reviews 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 (see published protocol for search strategy)[17] identifying 6,902 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 GHG emissions and health-related exposures or outcomes. Of the 26 reviews included from the search, 11 had conducted a formal meta-analysis and these were all in the AFOLU sector. The remaining 15 reviews had produced only a narrative synthesis of the included papers (Figure 2).

Due to the lack 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) where the primary studies met our inclusion criteria of reporting quantitative measures of both reductions in GHG emissions and health exposures, risk factors or outcomes. Some reviews did not contain any primary studies relevant to our analysis (e.g. 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. A separate search of peer-reviewed and grey literature was undertaken to identify further examples of implemented actions which had measured and reported both emission reductions and health impacts,[18] (see WebAppendix A2 for methods). These examples provide evidence on the realities of implementing mitigation actions in different geographical locations, socio-economic settings and at a variety of spatial scales. The search included review of relevant articles from the Pathfinder umbrella review and from a systematic mapping exercise, which employed machine learning to classify peer-reviewed research papers on climate and health.[59] In addition, pre-existing databases from C40 Cities and CDP were screened alongside studies submitted in response to a call for evidence 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 whilst simultaneously addressing societal challenges (i.e. nature-based solutions).[60]

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. We therefore undertook a harmonisation process to increase comparability between studies (Table 1). Studied actions were scaled up to 100,000 of the national population. Where primary studies included in reviews had undertaken their own estimates of scale-up (for example city-level scale-up of a localised intervention or national-level scale-up of a city-level intervention) these were used. Where 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 based on the number of farms of the same type in the country (see WebAppendix A3), whereas city-level studies were scaled up based on the urban population of the country (i.e. 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 (kt) of GHGs 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 GHGs and health outcomes (or exposures/risk factors) and according to temporal and spatial scales and units of measurement.

These measures represent **carbon mitigation intensity** (kt CO_2eq/100,000/year) and **health co-impact intensity** (YLL/100,000 population/year), which have been used throughout as measures of GHG reduction and health outcomes, can be used to compare results of highly heterogeneous studies. An example calculation of scaling up raw data to give these carbon mitigation and health co-impact intensities can be found in the WebAppendix Panel A1. Several assumptions were made in the process of data harmonisation (Table 1); our comparisons should therefore 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 may have the greatest GHG impacts and health co-benefits. All GHG reduction measures are standardised to metric units and given in tonnes (t), kilotonnes (kt - 1,000 tonnes) and megatonnes (Mt - 1 million tonnes). Implemented case studies are reported in their original units.

	Spatial	**Temporal**	**Measurement**
Range of scales	Local, farm-level, city-level, national, regional, global	1 week – 50 years	GHGs: relative vs absolute changes (i.e. % change vs change in tonnes) Health outcomes: relative or absolute deaths (i.e. % change vs change in number of deaths), DALYs, YLL
Scale used for harmonisation	National	1 year	GHGs: Kt CO_2eq per 100,000 population per year Health outcomes: 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 % converted to absolute changes from a baseline scenario by obtaining baseline sector-specific estimates from national GHG inventories if not available from primary study Deaths and DALYs converted to YLL using GBD estimates for the same country and year, disease risk or cause of death.[61]

Table 1. Data harmonisation process for umbrella review estimates.

CO_2 equivalent (CO_2eq) emissions in this report are aggregated using global warming potentials (GWPs) over a 100-year time horizon.[5] For CO_2, CH4, and N2O, these were 1, 28, and 265, respectively, as per the IPCC AR5 recommendations. Some health exposures (e.g. diets) were presented per day but all measured health impacts were based on at least a minimum period of 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, NO, NOx, NO_3, PM_{10}, and $PM_{2.5}$. For heath exposures, the AirQ+ tool developed for WHO Europe was used.[62] The tool allowed long term health impacts of $PM_{2.5}$, PM_{10}, and NO_2 to be evaluated using a life table approach, requiring the area under study and all-cause mortality in adults over 30 to be entered into the tool (estimated by the GBD[61]). 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.[62] This 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 neighbouring countries in Europe. 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 156 actions (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 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, i.e. the number of years of life gained (reduction of years life lost) per tonne of greenhouse gas emissions avoided (see WebAppendix A3.1). However, we did not use these ratios in our results, as they would have given the greatest weighting to actions where there were large health benefits but small mitigation benefits. For example, the provision of clean cookstoves 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. By contrast, actions in 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

Fourteen systematic reviews were included in our umbrella review following a process of screening all primary studies, and 58 of a potential 810 primary studies met the inclusion criteria (7%). These 58 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 since many studies included multiple actions. Data from the umbrella review were found to be based primarily on modelled evidence: 177 of the 200 identified actions (89%) 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 which exemplify actions to reduce GHG emissions at the national, city/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 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, with 103 out of 200 mitigation actions (52% of the total actions), almost all of which focused on dietary changes (Figure 4). The next largest sector was transport with 43 actions (22%), followed by the 'multi-sectoral' interventions (interventions acting across multiple sectors which are often composed of multiple actions whose impacts cannot be distinguished from one another) with 31 (16%). Fewer than 10 actions were reported from each of the sectors of buildings, electricity generation, and industry. Most of the actions were conducted at the national level (110 actions, 55%), but there were also large numbers of actions at the city level (56 actions, 28%), the impacts of which were scaled up to national level as part of our harmonisation process.

Actions primarily came from high-income settings (129 actions, 65%), with a further 30 from upper middle-income settings (15%). All studies from low-income settings were excluded at the second stage of the review because they did not meet the inclusion criteria, while India was the only country from a lower-middle income setting that was included, accounting for 17 actions (19%) (see WebAppendix A4 for a summary of excluded studies). The most common countries included the UK (26 actions – primarily diet interventions) and China (22 actions – mostly multi-sectoral interventions), which accounted for almost all of those from upper-middle income settings. Other countries with at least 10 actions included Finland, France, India, the Netherlands, and the USA, and there were 22 global actions considered (Figure 3 and Figure A2 in WebAppendix).

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 where specific health outcomes such as cardiovascular disease, cancer, diabetes and trauma were estimated. Many actions provided multiple pathways to health (e.g., shifting from cars to active transport may affect health via changes in air pollution, physical activity and traffic injuries, leading to changes in multiple causes of death or morbidity), hence Figure 4 contains more quantified estimates (n=420), than there are unique actions. Estimates were harmonised to the national scale and YLL/100,000/year (Table 1).

The transport sector had the largest number of actions with quantified estimates of the relationship between mitigation action and health (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, and 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 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 (Table A4.3 in WebAppendix).

Measures of greenhouse gases

The most frequently measured greenhouse gas was CO_2 (measured for 101 actions), followed by CH_4 (18), and N_2O (11) with only 9 and 3 actions measuring black carbon and black smoke, respectively (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, while N_2O and CO_2eq were primarily measured in AFOLU, and CH_4 mostly for multi-sectoral 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.[63] Black carbon was measured for a group of multi-sectoral air quality policy actions and a transportation action retrofitting a local railyard, while 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 to CO_2 was not possible. The average residence time of BC in the atmosphere is only about 5 days, with significant regional differences preventing direct comparison with GHGs.[64] Black carbon and black smoke were therefore not included from this point on - the main body of analysis, although they have significant impacts on health. Estimates of GHGs were harmonised to the national scale and CO_2eq/100,000/year (see Table 1).

The challenge of measuring and reporting on GHGs

The carbon dioxide equivalent of a gas is derived by multiplying the tonnes of the gas by its associated Global Warming Potential, usually over 100 years. Therefore, "Carbon Dioxide Equivalent" 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 impacted by a given action and means combining GHGs with quite different residence times in the atmosphere. Actions involving energy and electricity were primarily measured in terms of CO_2 (76%). It is therefore likely that, without any measures of CH_4 which, per unit of mass, has a heating effect 86 times stronger than CO_2 over 20 years (over a 100-year period CH_4 is 28 times stronger), their environmental impacts are underestimated. CO_2eq emissions in this report are, if not stated otherwise, aggregated using global warming potentials (GWPs) over a 100-year time horizon.[65] Although CH_4 and N_2O are major greenhouse gases, the focus in the implementation studies was on estimating reductions in carbon dioxide only, with only one reporting change in CH_4. This contrasts with the umbrella review, where estimates of other greenhouse gases were found. Future studies should aim to capture information about all GHGs (including short lived climate pollutants such as black carbon) affected by a given mitigation action, together with changes in cooling aerosols (e.g. sulphates) that may offset some of the climate benefits.

Mitigation and health co-impacts

The greatest average mitigation intensities were seen for electricity generation, followed by multi-sectoral actions (Figure 5 and 6). All these actions with a high impact on GHGs impacted health via reduced exposure to air pollution (Figure 4). The remaining sectors had an average mitigation intensity around one quarter, or less, of electricity generation.[61] Actions to improve cookstoves had the highest median health co-impact intensity with a reduction of 1,279 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 GHG benefits from improved cookstoves are relatively small compared with 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 impacts on both GHGs and health compared with dietary change per 100,000 population. The overall impact of any action will be dictated by the total potential scale of uptake (for example the scope for implementation of clean cookstoves is much smaller than the scope for replacement of fossil fuels with 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 larger health co-impact intensities of transportation actions in India where baseline levels of air pollution are higher (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 role 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 GHG emissions[15] and therefore actions to mitigate these emissions will be vital 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 [66], 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[29] (and see energy case study). Gas combustion produces negligible quantities of sulphur dioxide, mercury, and particulates and is therefore less polluting than coal but is responsible for substantial GHG emissions, both from gas leaks that emit CH_4 (thus contributing to tropospheric ozone) and from carbon dioxide when burnt. In addition, gas combustion contributes substantially to nitrogen dioxide levels, with implications for health, including increasing incident cases of asthma in children and adolescents from household and ambient NO_2.[67,68]

In 2022, the stock of renewable energy capacity increased by an unprecedented 9.6% and amounting to almost 295 gigawatts (GW) of energy from renewables. Renewables accounted for 40% of installed power capacity globally by the end of 2022, with solar accounting for two thirds of the increase in renewables.[69] Many energy challenges however 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 1,000 GW of renewable capacity additions every year until 2050, with solar power contributing over 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 IEA.[70] Based on current market trends, coal consumption is forecast to plateau at that level through 2025, driven by growing demand in emerging Asian economies. As a result, coal will continue to be easily the largest single source of carbon dioxide emissions from the global energy system. Thus, much greater ambition is needed to bring emissions reductions on track to reach net zero emissions by 2050 or earlier.

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, while urban policy and energy efficiency actions tended to have much smaller effects (Figures 6 and 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 is likely to reflect 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.[71] One study considering the same low carbon electricity generation action in 3 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 smallest health benefits, showing reductions of (17 YLL/100,000/year), followed by China (80 YLL/100,000/year), then India (182 YLL /100,000/year).[72]

Variation in estimates is also dependent on the Exposure Response Function (ERF) used, the health outcomes included, the counterfactual used for the comparison and other factors.[71] 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.[71] Some studies and implemented actions may underestimate the health co-benefits due to methodological limitations.[33] 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,[62,73] but may be absent in older studies.

Within the umbrella review, actions impacting health via ambient air pollution used a wide range of exposure response functions to estimate health impacts. This heterogeneity was often compounded by opaque methods which did not detail the exact functions used, making quantitative inferences regarding the impact different ERFs had on effect sizes difficult. Some studies, however, did specify their ERFs, allowing us to further understand the observed health co-benefits. We present some examples in the WebAppendix A5.

Recent evidence of the adverse effects of low levels of air pollution has resulted in more stringent WHO air pollution guidelines[74] and implies that health benefits of reducing air pollution are greater than those estimated in many studies. Additionally, there were relatively few studies from areas with high air pollution levels.

Developing and delivering sustainable energy may disproportionately impact Indigenous communities, ethnic minorities, and low-income communities.[75] 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.[76] Pastoralists are, however, often not adequately informed of their rights or consulted about the energy projects. Green energy projects can therefore interfere with livestock migration routes, access to pasture, and disrupt the pastoral land-use system. As a result, local communities may be forced migrate to different areas, often with less favourable conditions, making it harder to maintain their traditional farming systems and creating food and financial insecurity.[77] 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 US during the period between 2005-2016,[78–80] including decommissioning of coal-fired power plants, as well as an increase in solar and wind power replacing both coal and natural gas in the generation of electricity. The percentage of renewable energy that replaced fossil fuel generation varied widely between regions in the US over the period in question. This was partly due to varying levels of stringency between states in meeting certain policies, such as the renewable portfolio standards (RPS) which require electric companies to meet a growing portion of their load with eligible forms of renewable electricity.

In total, 147 Mt of CO_2 emissions were avoided from wind and solar power generation over the study period, and improvements in air quality resulted in between 3000 and c.13,000 avoided premature deaths. In addition, meeting RPS compliance obligations in 2013 also resulted in a reduction in power-sector water withdrawals and consumption equivalent to about 38,000 litres of withdrawal and 1,200 litres of consumption saved per MWh of generation of renewable electricity. The economic benefits of renewable energy power generation were estimated at between 30 and 100+ billion US dollars.[80,81]

In a separate complementary action in the U.S., 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 22,583 (16,896-43,428) fewer deaths from air pollution related conditions and, as a beneficial effect of reduced aerosol and ozone levels, crop yields increased in yield by an estimated 329 million (169-490 million) bushels of corn over this period. However natural gas should be seen as a transition fuel from coal to renewable energy in view of the accompanying CO_2 and CH_4 emissions, as well as other negative consequences of fracking.[82]

In 2021, in the US, about 61% of electricity generation was from fossil fuels, 19% from nuclear energy, and 20% from renewable energy sources.[83] There is major scope therefore to scale up these actions with additional benefits for health and GHG emissions. For example, it was estimated that nearly 52,000 lives could be saved annually by transitioning from coal to PV-powered electrical generation, which requires 755 GW of U.S. PV installations.[84] Rigorous procedures to ensure accountability and compliance can help to promote the achievement of policies and regulation standards designed to reduce GHG emissions. In addition, current utility rate structures hinder the deployment of renewable energy and a change in the system to distributed generation would be required. Standard procedures to connect renewable energy systems to the electrical grid are lacking and policies to address limited 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.[61] Our review found limited 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 found 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 relatively small (Figure 7). These were also city-level actions, therefore largely accruing 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, over 40,000 premature deaths per year in Europe were attributable to biomass smoke.[85] 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.[86]

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 likely contributed to a cooling of between 0.0°C and 0.8°C since the baseline period of 1850-1900.[87,88]

Buildings and infrastructure

The housing sector is responsible for substantial GHG emissions. For example, about 20% of GHG 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 amongst high-income households.[89] A combination of decarbonisation of the energy system and deep retrofits of existing housing stock will be needed to reduce GHG 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 sufficiently to increase 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 GHG 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 and detailed in 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. A previous systematic review has shown however that improved combustion stoves (ICS) or venting (e.g. through flue or chimney) were less effective than cooking with clean fuels including ethanol, liquefied petroleum gas (LPG) and electricity at lowering $PM_{2.5}$ levels. In practice, stove stacking (whereby polluting sources of energy continue to be used alongside clean fuels) and high background levels of ambient air pollution, have prevented most clean fuel interventions from reaching the WHO interim target $PM_{2.5}$ level 1 of 35 μg m^{-3}. More integrated approaches addressing ambient and household air pollution in tandem are needed.[90] The climate benefits of cleaner household energy in low-income settings are due partly to reduced black carbon emissions[91] and, in some cases, reduced deforestation. In countries such as India, LPG is used to replace solid fuels in households and although it is a fossil fuel there is evidence that there are modest net climate benefits.[35] To achieve total rural electrification and universal access to clean-combusting cooking fuels and stoves by 2030 an additional investment of US$ (2005) 65–86 billion 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.[92] 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 and exposure to violence during fuel collection may be reduced.[20]

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 above 600 (i.e. 600 years of life gained) per 100,000 people per year (Figures 6 and 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. Other actions involving improving energy use in buildings included home retrofitting and behaviour change and showed smaller mitigation intensities compared with other actions involving energy, but again these could still be substantial at scale (Figures 6 and 7 and 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 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, healthcare utilisation, self-reported health and quality of life in the state of Victoria in Australia. The program 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 $2,809 AUD per household. Households were divided into intervention (upgraded before winter) and control (upgraded after winter). Indoor temperature was measured every 30 minutes using a data logger installed in the main living area. A regression model was developed to determine whether households with an upgrade experience higher average home temperatures when compared to households without an upgrade. The surveys included questions on self-reported health conditions, including cardiovascular disease, asthma, chronic obstructive pulmonary disease (COPD) and breathlessness, thermal comfort and quality of life.

The outcomes from the control and intervention groups over 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 GJ and electricity use by 81.9 kWh over the 3-month winter period, which can be converted to a reduction of 0.128 t CO_2eq per upgrade for gas and 0.078 t CO_2eq for electricity. Average savings in energy were $85 AUD in the intervention group over the winter period. After winter, the intervention group had significantly higher mental health scores than controls (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 (mean = 5.4) absent from usual activities than the control group (mean = 7.3). Total healthcare costs were lower for the intervention (mean = $3,394 AUD) than control (mean = $4,172 AUD) group and the intervention households were significantly warmer than the control group, by 0.33°C (95% CI 0.05, 0.60; p=0.022).[93]

Sustainability Victoria aims to increase the Victorian Healthy Homes Program and upgrade 20,000 homes over the next four years at a projected cost of about $70 AUD million and an emissions reduction of 5,778 t CO_2eq. The figure takes into consideration the increased use of renewable energy in Victoria over this period. Insulating homes in conjunction with current renewable energy trends, however, will not provide sufficient change to reach net zero in Victoria. The high dependence on gas burning for residential energy use needs to be addressed to accelerate the shift to renewable energies. The carbon savings of retrofitting insulation in homes are also likely to be much less in other states (e.g. South Australia), which has almost entirely removed coal from its electricity generation.

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 likely because the basket of actions included in each national policy included some policies with large co-benefits (e.g. changes to transport) and others with negligible benefits for health (e.g. manufacturing efficiency standards) (Figures 6 and 8).

The impacts of multi-sectoral actions were highly variable depending on the country context; the largest GHG 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 CO_2eq/100,000/year), India (-332 CO_2eq/100,000/year), and the EU (-261 CO_2eq/100,000/year). As seen in electricity generation with actions impacting health via air pollution, this study found the greatest reductions in YLL in India (-66 YLL/100,000/year), followed by China (-29 YLL/100,000/year) and the EU (-7 YLL/100,000/year). The next largest GHG impacts for multi-sectoral actions were seen in national mitigation policies in Russia and the USA, with benefits in Latin America being smaller on average (Figures 6 and 8). 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 (e.g., free bus passes and cycle maps), improved infrastructure (e.g. cycle lanes) and sanctions (e.g., taxation, congestion charges, restrictions[94] and see Transport Case Studies). These measures can improve air quality, reduce injury and accident rates, as well as benefiting health through increased physical activity, 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 have limited impacts. The replacement of fossil fuel powered private cars with electric cars powered by electricity from renewables will reduce GHG emissions and air pollution from NO_2 and probably also from PM2.5, but it does not achieve health benefits from increased physical activity, nor will it reduce road danger for pedestrians and cyclists. In the UK fine particles from 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.[95] 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.[96]

There is also a potential for spillover effects as a result of the increasing demand for cobalt for use in batteries for electric vehicles (EV). Hazardous artisanal cobalt mining, where informal miners use bespoke and unsafe methods to extract cobalt, sometimes involving child labour, is common in the DRC, with around 150,000-200,000 artisanal miners, and many more dependent on their income. For this reason, the DRC government has set up the Enterprise Générale du Cobalt (ECG) in 2009 to regulate artisanal mining, giving the miners opportunities to work legally, prevent tension and conflict around the mining sites and reduce accidents,[97] 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 where the intervention involved reduction in private car use and increased public transport /active travel. The provision of cycle infrastructure alone had small average mitigation intensity (Figures 6 and 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 (for example where increased cycling did not result in substantially reduced driving and therefore air pollution levels remained similar) and some of these included trade-offs for health through increased injuries from walking or cycling.

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 identified that residents believed the local public transportation system to be unsafe, so to improve sustainable transport within the city they developed a campaign to increase 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. While changes in public transport use and thus GHG reductions are yet to be quantified, they have so far succeeded in reducing gender-based violence by 34.5% since 2017.[98]

Transport case study: Tokyo Vehicle Emission Reduction Program

The Tokyo Metropolitan Government (TMG) has introduced several measures to tackle environmental issues caused by rapid industrialisation and the mass adoption of automobiles since the post- World War II economic boom. In the 1970's, 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 automobiles, 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 five-year Vehicle Emission Reduction Plan and an annual performance report, outlining their fuel consumption as well as efforts to reduce greenhouse gas emissions and air pollution. Businesses with 200 vehicles or more are legally required to have their vehicle fleet consisting of 30%-low-emission and fuel-efficient vehicles, and 20% of their passenger car fleet must be Battery Electric Vehicles (BEV), Plug-in Hybrid Electric Vehicles (PHEV), Fuel Cell Vehicles (FCV), or hybrid cars.

As part of the Vehicle Emission Reduction Program, each year, the TMG also selects 120 businesses based on their plans and reports and provides them with advice and guidance on emission reduction actions. Around 1,600 businesses submitted their plans and reports in 2019. CO_2 reductions were calculated based on the fuel consumption of each vehicle used by each business, and NOx and PM_{10} reductions were calculated based on vehicle type and mileage of each vehicle, from each business. Between 2016 and 2019, total emissions decreased by 240,000 t of CO_2, 931 t of NOx and 36 t 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. Moving to low-or zero-emission vehicles would, however, 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 TMG; what are the characteristics of the businesses that have failed to implement changes and the barriers that hinder implementation; which changes businesses were feasible to implement and the reasons underlying a lack of implementation for those not enacted.

Transport case study: Active travel – New Plymouth, New Zealand
The Model Communities Programme is a central and local government-funded initiative focusing on promotion of cycling and walking, as well as infrastructure investment, to improve urban active travel networks in New Plymouth and Hastings. As part of the programme, New Plymouth added 12 km of off-road facilities, 20 km of cycle lanes, installed cycle parking, widened path entries, created several shared spaces with reduced speed limits for vehicles (30 km/h), and ran media campaigns, events, and cycle-skills training and Hastings added 30 km of arterial paths (roads which provide direct routes for long-distance travel throughout the city), 50 km of on-and off-road walking and cycling facilities and undertook a 'Share the Road' campaign. 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 a reduction of 1,150 tons of CO_2 emissions between 2011 and 2013 and an estimated 34 DALYs and two deaths were avoided over the same period.[99]

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/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 lack of public transport meant that cycling and walking replaced shorter rather than longer car trips, and therefore had only a limited impact on reducing emissions from the transport sector.

Car ownership in New Zealand is about 86%, 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.[100] The total population of New Zealand is approximately five million, of whom 87% live in urban areas. Assuming the primary target population of such interventions would be those between 15 to 65 years of age (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 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 a total of 20 Kt 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 GHG emissions, a system change is needed that includes short-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 nitrous oxide emissions. The EAT-Lancet Commission identified four levers for sustainable land use and food systems: (i) changes in diet, often towards less red meat consumption, increased plant-based foods and reduced calorie intake; (ii) productive and sustainable agriculture; (iii) improved land use design, particularly to protect and restore nature; and (iv) rapid reductions in food loss and waste. The Commission has estimated that around 11 million premature deaths annually by 2040 (or over 20% of deaths worldwide) could be averted by following a sustainable and healthy diet.[23]

More sustainable diets, are typically high in plant-based food and low in animal-sourced and processed foods,[101] and have been shown to have great benefits to human health, increase average life expectancy, and decrease risk of lung or stomach cancer.[102] 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 while there is some evidence linking the two the uncertainties are large and there is heterogeneity between studies.[103] This may imply that, while the environmental benefits of low red meat consumption are compelling, the health benefits of dietary change may largely result from increased consumption of fruits, vegetables and whole grains. Dietary shifts could also cut GHG emissions from AFOLU by above half and reduce forest loss by 20% between 2030-2050 compared with current trends.[104] However, if not properly implemented, sustainable diets can lead to a reduction in intakes of certain micronutrients (primarily vitamin B-12, Calcium, and Zinc).[105–107]

Actions to promote productive and sustainable agriculture include changes in farming practices (e.g., conservation agriculture, optimising fertiliser use and nutrient cycling),[108–110] and employing technical solutions to reduce emissions in existing approaches (e.g., using nitrification inhibitors).[111,112] These actions can substantially reduce GHG 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 incomplete knowledge of exposure pathways. Improved land use includes agroforestry (see section on nature-based solutions page 31) 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.[113] The Food, Agriculture, Biodiversity, Land Use & Energy (FABLE) Consortium is developing a set of sustainable land use pathways for the United States to 2050 that optimize trade-offs between production (including food and biofuels), conservation, and GHG targets by 2050.[114] 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 sea grass beds can increase carbon sequestration and benefit local flood protection, livelihoods, and food security but we found no published evaluations of effects on health.[55]

Reduction of food waste could contribute to GHG emission reductions, particularly in high-income countries where much waste occurs at the retail and household level compared to low-income countries where food loss between harvest and sale predominates. Approximately 88 Mt of food are wasted every year in the European Union, representing 15–16% of the environmental impact of its entire food value chain and causing annual emissions of 186 Mt CO_2eq. The Ukraine-Russia war 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 GHG 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 one third in the EU.[115]

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 (i.e. 300 years of life gained) per 100,000 people per year (Figures 6 and 10). Dietary change was also linked with large mitigation intensities (comparable in size to the multi-sectoral policies on average), with particularly large GHG reductions seen for vegan and vegetarian / pescetarian diets, and other actions like substituting plant-based for animal-based foods also showing consistently positive health outcomes (Figures 6 and 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 were smallest in India where average diets already have low GHG emissions due to low meat consumption.

Shifts in agricultural practices had much smaller mitigation intensities compared to dietary interventions (with organic farming increasing rather than reducing emissions slightly) and had negligible health co-impact intensities apart from one study in Brazil which modelled health impacts from dietary changes resulting from reduced meat production. It is, however, likely 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 may not fully represent the evidence in this area. Likewise, 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 a lack of) environmental benefits when assessments are based only on GHG 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.”[116] 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 (and see Circular Economy section).[117] Within a bioeconomy, however, care must be taken to carefully balance food production against the use of natural resources for animal feed and increased use 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 crucial to achieve progress towards a bioeconomy.[118] 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

While 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 pathway to health showed that the diet pathway tended to show the largest health co-impact intensities, while 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 and 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 with larger societal transformations towards active travel, injury rates would be reduced.

Nature-based solutions (NBS)

NBS actions work to enhance natural or modified ecosystems to deliver biodiversity benefits whilst simultaneously addressing societal challenges.[60] NBS benefits to human health (see Figure 12) are achieved largely through enhanced ecosystem services with the pathways linked to regulation of ecosystem processes such as natural hazard mitigation, air quality, climate and disease regulation, the provision of natural resources including food, water and timber, as well as cultural and recreational services to improve mental health and cognition.[119]

Natural climate solutions (NCS) are a subset of NBS that can be employed to limit heating by reducing atmospheric greenhouse-gas concentrations by reducing GHG emissions or increasing carbon sinks or both.[120,121] They comprise three broad approaches:

1. protecting ecosystems, for example 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 well designed and implemented NBS have potential to deliver cost effective annual emission reductions and removals of 5 to 11.7 Gt CO_2eq by 2030, rising to between 10 to 18 Gt CO_2eq by 2050,[122] these estimates are usually cost constrained at $100 USD per tonne of CO_2eq to account for cost of global production of food and wood, respect of land tenure rights and sufficient biodiversity conservation.[120] 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,[122] by offering many win-win strategies for addressing climate change adaptation, safeguarding human health and stemming biodiversity loss.[123] 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.[122,124]

There is a lack of quantitative evidence encompassing the full range of pathways by which actions that have the potential to achieve significant mitigation and health benefits. No systematic reviews of 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 (see WebAppendix A6), of which, 6 studies 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 to the estimated scale of mitigation from the protection and restoration of intact ecosystems, improved agroforestry and land-management for food production.[123,125]

Urban trees

Several studies documented how the sustainable management of urban trees can improve air quality and deliver GHG mitigation estimated either as carbon sequestration, carbon storage and 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 (and see WebAppendix A6). The effectiveness of pollutant uptake, mitigation and energy savings varied by species; consideration of species is needed to optimise benefits including to enhance biodiversity whilst minimising potential trade-offs such as ozone production, increased allergies and altered dispersion of pollutants.[126] While the evidence base for the mental health benefits of access to greenspace is large,[127] no studies linking the provision of greenspace with mental health co-benefits and GHG emission reductions were identified.

Air quality: Urban trees in California are estimated to sequester or help avoid 8.5 Mt of CO_2 per year, of which 1.3 Mt were from avoided emissions from building energy savings due to the cooling effect from trees (see Energy Savings below).[128] This total mitigation impact is equivalent to the removal of 1.8M cars from Californian roads.[128] Alongside this a net air pollutant uptake 3,537 t/year is estimated as the difference between uptake of PM_{10}, NO_2, SO2 and O3 and the emission of biogenic volatile organic compound (BVOCs) which can act as a precursor to local ground-level ozone pollution as trees can both remove and contribute to tropospheric ozone formation.[129] The value of air quality improvements (value that society places on clean air) is estimated at $56.2M USD,[128] although this is likely under-estimates the true benefit of cleaner air; a previous study estimated the air quality benefits attributed to Californian trees as $446M USD, which is the cost of avoided mortality and care of acute respiratory diseases.[130] There are an estimated 5.5 billion urban trees in the United States, with 343 million urban trees in California making it among the top 5 states, alongside Florida, Georgia, North Carolina and Texas. Analyses showed that California has the greatest pollution removal values by urban forests ($639 million USD per year) and a high estimated carbon sequestration by urban forests (2.9 million tons of carbon per year) compared to other states in the United States.[131]

Energy savings: Urban trees alter building energy use and associated emissions from power plants by shading buildings, cooling air temperatures, and altering wind speeds around buildings.[131]. This results to electricity savings from cooling, natural gas savings from reduced heating needs and avoided emissions of air pollutants from power plants and space-heating equipment.[128] Regional variation in the extent of energy savings was apparent, for instance street trees in Lisbon had an estimated energy savings of $6.16/tree/year,[132] the equivalent was an average of $13/tree/year across 5 US cities,[133] and in Toronto energy savings were valued at $36/tree.[134] 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. While urban trees can provide a range of benefits to the environment, human health and well-being,[128] studies also suggest that access to these benefits is often unequal, and certain groups can benefit more than others.[135] For example, urban trees can increase property values,[128] and if distributed unevenly, may 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 parts due to greening initiatives.[136] Green climate gentrification has been documented in North American cities and cities in Spain, Belgium, and South Korea.[136] 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.[137]

Protecting and restoring ecosystems.

The protection and restoration of community forests can also deliver human health and wellbeing benefits such as food and nutritional security and livelihood benefits. These are implemented solutions by rural subsistence farmers in low- 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 low and middle-income countries to reduce overall GHG emissions. For example, an investigation of the impact of a **climate compatible development (CCD)** project in Malawi found a 50 year mitigation potential of 4.5 million tonnes carbon sequestration, which was attributed to implementation of ecosystem-based actions such as conservation agriculture, forestry activities such as woodlot regeneration, alongside other actions such as improved cookstoves and access to loans.[138] Human-wellbeing benefits were linked to increased income, enhanced crop-yields, better nutrition and better 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 (CDM; a UN run carbon-offset scheme), aimed at increasing carbon sequestration, reducing poverty and improving ecosystem restoration. The project utilised Farmer Managed Natural Regeneration (FMNR), which regenerates native tree across agricultural landscapes and community forests[139] and was estimated to sequester 165,000 tons of CO2 and generate $726,000 over the first ten 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.[140]

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.[141] 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/hectare.[142] Project activities included promotion of alternative energy (e.g. 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 increase in social capital, enhanced coping during adversity and reduced inequities through enhanced benefit sharing that target livelihood improvements for the most deprived (including of food supplements e.g. 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.[142]

Consistent participation of local communities of both men and women throughout REDD+ processes is vital. REDD+ projects have historically been dogged by reports of inequity across all 3 key dimensions: 1) contextual equity—the conditions embedded in the social and political context that put some people or groups at a disadvantage (e.g. Indigenous communities or poorer members of traditional communities); 2) procedural equity—the level of representation, participation and equal say in decision making processes; 3) distributive equity—the distribution of costs and benefits of policies and actions among stakeholders.[143] A review of rights abuses from REDD+ has highlighted multiple allegations about possible welfare impacts on forest-dependent, especially Indigenous Peoples .[141] This can be due to the implementation process of the action or from the pre-existing local context (e.g., 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.[144]

Healthcare 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. Health in Harmony (HiH), 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, 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. HiH, 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 based on the amount of logging in each community. Conservation programmes, educational programmes, and alternative livelihood trainings were also offered.[145]

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 healthcare based on participation. The intervention provided healthcare 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, chronic obstructive pulmonary disease (COPD), and diabetes in all communities. Neglected tropical diseases (NTDs) diagnoses 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.[145,146]

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 between 2008-2018, an approximately 70% reduction in annual forest loss compared to the equivalent period between 2001 and 2007. This reduction in forest loss was estimated to have prevented 590,000 tonnes of above ground carbon loss (90% CI, 270,000–1,130,000 tonnes). This may be an underestimate as the project has also promoted the regeneration of secondary forest and the impact of prevented losses of below ground carbon have not yet been quantified.[145]

A major factor in the success of this intervention was that it provided multiple cross-sectoral solutions simultaneously in response to the problems identified in the community (i.e. they required access to healthcare, 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 e.g. clinic visits, attending meetings, education activities, livelihoods training), showed a significant decrease in forest loss, while medium engagement communities showed no change and least engaged villages showed an increase.

Lack of access to health care has been shown to be the main driver for ecosystem degradation in other parts of Indonesia (Bukit Baka Bukit Raya National Park), in Madagascar, the Philippines, and Brazil. Other organisations that have used the same or similar techniques (i.e., radical listening to understand community priorities) in other parts of Indonesia, Malaysia, Mozambique, and Rwanda have also found healthcare access to be one of the main drivers.[147] 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 GHG 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. Passive ventilation, cool roofs and increasing green space in cities by contrast can reduce energy demands and reduce extreme heat exposure. Although mitigation and adaptation actions must increasingly be integrated there are few documented examples of integrated actions to guide policy and practice.[59] In our review we found piecemeal evidence of implemented green infrastructure with quantified assessment of mitigation, adaptation and health co-benefits (see WebAppendix Table A6.2). Overall adaptation actions have rarely been evaluated to assess their health effects particularly in LMICs.[148] Climate funders, policymakers 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.

Carbon pricing

Carbon pricing can include carbon taxes, emissions trading schemes (ETS) and carbon credits, as well as fuel taxation and the withdrawal of subsidies. Such mechanisms and policies can be cost-effective in reducing GHG emissions and can potentially have important impacts on health through pathways such as improved air quality, encouraging active travel, the redistribution of wealth and raising funds for health care.[149] 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. There is, however, the potential for carbon pricing mechanisms to lead to negative health and wellbeing outcomes, especially if socioeconomic inequalities are exacerbated.[150]

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 for example depending on whether public financing of fossil fuels (such as that from state-owned enterprises) are included. A recent IMF 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 estimated subsidies or 6.8% of global 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 "efficient prices" required to account for the resulting damages.[151] This makes a compelling case for implementing carbon prices at a level that reflects both emission reduction targets and the co-benefits of decarbonisation. But the barriers to implementation include powerful opposition from some fossil fuel companies, concerns about job losses, and the effects of unabated energy prices.[152]

Carbon pricing, which in 2022 covered 23% of global emissions, often at low levels,[153] has been found to be insufficient on its own to drive deep decarbonisation and the systemic transformation it requires.[154] In coordination with other policies, however, carbon pricing isa key component of transformative and ambitious mitigation strategies. Health co-benefits 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,[155] showing different ways in which health co-benefits assessments can inform carbon pricing design and implementation.

Evidence on the magnitude of health co-benefits and their monetized value can provide more accurate estimates of policy costs, optimal or efficient price levels, [32,156] or the price levels at which the economic costs of the taxes are fully offset by co-benefits, implying net zero costs. For example, implementation of Renewable Portfolio Standards (RPS) in the 'Rust Belt' region of the USA could generate health co-benefits valued at $94 per ton CO_2 reduced ($2-477/t CO_2) in 2030.[157] The central estimate is 34% larger than total policy costs. Compared with an RPS approach carbon pricing yields greater health co-benefits per ton of CO_2 worth $211/t CO_2. In the US, monetized human health benefits from improved air quality can offset 26–1,050% of the cost of US carbon policies depending on context and assumptions. Flexible policies that minimize costs, such as through cap-and-trade standards, have been found to have larger net co-benefits than policies that target specific sectors.[158] 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.[159]

The use of revenues from carbon pricing is another possible pathway for health promotion and equity. Use of revenues for income compensation can address potential food insecurity trade-offs in low-income countries.[160] Other suggestions include subsidising healthy foods,[160] funding universal health coverage, public transportation or insulation for low-income households.[161] Revenue-neutral intervention designs that subsidize low-emission food groups can result in negative health impacts in high-income countries, e.g. because of increased consumption of sugar and soft drinks, showing that climate and health co-benefits do not always move in the same direction.[162]

Other specific features of ETS 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 found to be associated with lower co-benefits, especially in areas which become net purchasers of allowances.[163] 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.[160,164] 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.[160] 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 higher population density, agricultural mitigation would lead to substantial food calorie loss with little contribution to global GHG mitigation, depending on crop substitution assumptions.[164] 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 improved agricultural land management.[165]

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.[162,166] Likewise, 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 focusses on potential food insecurity impacts.[160,162] Some studies also suggest that carbon cap and trade programs (used interchangeably with ETS here) can lead to localized increases in emissions as a product of permits trading.[167] An improved understanding of these and other potential trade-offs is indispensable for the adequate design of compensatory and redistributive policies which 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 healthcare

Policies that reassign revenues from fossil fuel subsidies can accelerate the shift to renewable energy generation while increasing investments in healthcare, education, infrastructure, or other social services that benefit vulnerable populations. Reassigning funds to healthcare in the form of providing free medicines or diagnostic tests can provide tangible benefits in the form of economic returns.[168] Indonesia is among several countries that allocated large sums of fossil fuel subsidies to finance healthcare and other social services.[169] It is regarded as a success, although the country was faced with backtracks in recentyears.[170] Recent fuel subsidy reforms demonstrate how, through public information campaigns, a timely implementation and roll-out of social programs compensation schemes, violent protests and oppositions can be circumvented. The example from Indonesia shows that reassigning revenues from fossil fuel subsidies to healthcare 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.[170]

Circular economy approaches

A significant gap is evident on the health and GHG effects of circular economy (CE) and bioeconomy strategies.[117,171] They are both potentially important contributors to GHG mitigation because consumption-based emissions embodied in traded goods and services increased from 4.3 Gt CO_2 in 1990 (20% of global emissions) to 7.8 Gt CO_2 in 2008 (26%).[172] The 2022 Circularity Gap report has estimated that the current world economy only cycles 8.6% of the resources it uses leaving a 'Circularity Gap' of over 90%.[173] According to their estimates global circularity declined from 9.1% in 2018 to 8.6% in 2020 and in 2019, 100 billion tonnes 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, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended.[174] The CE offers potential benefits to businesses and society including through reduced demand for primary materials, less waste and lower GHG 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 CE approaches to climate change mitigation, in the run up to COP26 only one-third of all nations had any mention of the circular economy in their Nationally Determined Contributions under the Paris Agreement, and less than 40% of these pledges included any plans for training to support implementation.[173]

A systematic review has assessed the contribution that CE and related approaches could make to climate change mitigation.[175] 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 GHG 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 lowest gains are projected in agriculture.[176] Some large GHG savings were observed for specific actions, for example between 60%–90% from the recycling of iron and concrete.

There has been little systematic assessment of the health effects which could be both beneficial (e.g., reduced air pollution from less waste burning and more efficient use of resources; more affordable food from reduced food waste; savings to health systems from more efficient resource use freeing funds for health care) or harmful (e.g., increased exposure to toxic chemicals from poorly regulated recycling of electronic waste). A report from WHO Euro discussed the potential pathways by which CE 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.[171]

However, the CE 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,[177] but resources can only be i) dissipated which increases losses in quantity and quality or ii) converted which requires new materials and energy.[178] There are limitations in conserving materials through successive re-use cycles which result in leakage from the system.[179] There are for example, 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 kilograms of e-waste per person, the second highest amount in the world, much of which is exported, mainly to Ghana and Nigeria.[180,181] 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 may be particularly hazardous to neonates. Breast milk samples from women residing near the Agbogbloshie Market contained elevated concentrations of polychlorinated biphenyls and brominated flame retardants.[182] 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

A lack of demand-based policies is an impediment to reaching 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.[183,184] For example, global emissions in the housing sector[15] and total emissions from transport in European countries,[185] both show that efficiency gains (per unit of habitable surface and per kilometre travelled) have been significant, but these have been more than offset by growing emissions linked to a growing demand (i.e. growth in floor per capita and passenger-km travelled per capita). 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 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.[185] Transport demand in Europe (measured in terms of passenger kilometres), 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 airplanes.

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] Within the most recent IPCC WG 3 report on mitigation[15] highlights the need for “systemic infrastructure changes that enable behavioural modifications and reductions in demand that can in turn reduce energy demand.” 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]

Actions on demand reduction, however, 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 (IAMs) which combine concepts from climate science and economics into a single modelling framework.[186] Despite being criticised in the literature these scenarios are the only long-term scenarios submitted by the scientific community to the 2022 IPCC report on climate mitigation.[187,188] Such scenarios tend to be heavily focused on efficiency gains. For example, IPCC AR6 WGIII Chapter 7 reviews the mitigation policies within the AFOLU sector, including in IAMs, of these only "reduce 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 to efficiency gains (128 studies on demand reduction compared to 62 studies on efficiency, with 7 unclassified). However, many of these studies show no mechanism for 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 are limited 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.[189] Modellers should therefore consider the emerging multi-disciplinary literature on policy packages, that 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.[190,191]

A systems approach to achieving demand reduction and delivering 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 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 GHG 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.[189] This will be a major focus for the second phase of the Pathfinder Initiative.

Transformative change case study - The Irish transport sector

Understanding what policies can bring systemic change (i.e. change the system structure) to trigger large behavioural change can achieve both the climate goals of the Paris Agreement and the improvement of health equity. A first step is to map the dynamics characterising the current systems that lead to unsustainable results (e.g. poor health, high emissions, unequal access to services and opportunities). In 2022, OECD mapped the Irish transport sector using their Systems Innovation for Net Zero approach.[192] 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 mapped, the next step is to identify transformative policies by analysing:

a. the intent of a given policy (i.e. whether it aims to anticipate and "cope" with car-dependent systems, or whether its aims to transform the system and encourage a shift away from car dependency and see Figure 14); and

b. 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 (see WebAppendix A8 for more detail).

The result of the policy assessment applied to Ireland's transport system indicated 3 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, while efforts to improve infrastructure for public and active transport modes while reducing travel costs have a transformative intent and a medium transformative potential.
3. Incentives for private electric vehicles, do not weaken or help shift away from, and rather reinforce, the system dynamics underlying induced car demand and urban sprawl. As such they have an anticipatory intent (see Figure 14 and see WebAppendix A8), and a low potential to transform the system.

It 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 (e.g. 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 where the use of other modes is not possible.

Discussion

The Pathfinder umbrella review confirmed the large potential benefits for GHG 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 impact (compared to those reliant on an assumption of large-scale behaviour change without explaining how this would be achieved) had much smaller estimated impacts on both emissions and health. 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 demonstrate 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 a lack of either quantified health or GHG mitigation outcomes, suggesting that a large body of research on health and climate change mitigation effects of potentially relevant actions has been synthesised in disciplinary silos and 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 is the evidence base 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 lack of evidence of effects of actions in low and middle-income countries and on inequities, a dearth of research on circular economy approaches and a relative lack of evidence 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. 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 NCDs 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 may be longer time lags in realising the full benefit to health (e.g., reductions in lung cancer incidence from air pollution). More generally the lack of consistent approaches to estimating health co-benefits reinforces the need to follow guidance on the design and reporting of health co-benefits assessments.[193] 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 policymakers and implementers.

Synergies and trade-offs of climate mitigation actions can depend on the means of implementation, timing, stringency as well as the political and developmental context.[15] In order to capitalise synergies and minimise trade-offs, it is vital 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.[194]

There were major gaps in assessing NBS impacts on health and GHG 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, the reverse is probably true. The gaps in evidence could be attributed to methodological challenges; assessing the health impacts of changes in ecosystems requires in-depth assessments in both the biophysical structure of the given ecosystem, shifts in ecosystems functions and services and associated changes in human wellbeing.[195] 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.[196] Equally, studies on agroforestry could quantify the impact on dietary diversity which is a proxy for nutrient adequacy of individual and household dietary intake.[197] 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.[198]

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 and 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.[199]

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 Agreement targets and capitalise on the potential. Collectively human activities were responsible for the emissions of about 56 billion tonnes of CO_2eq each year during the decade 2010–2019, about 9 GtCO2-eq yr–1 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 limited overshoot requires ambitious GHG reduction of 34–60% by 2030 and 73–98% by 2050 relative to 2019 levels.[15]

The implemented actions documented in our case studies make relatively 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 may 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,[200] allow implementing actors to identify and respond to trade-offs and 'course-correct' 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.[201] A recent study has shown the potential air pollution co-benefits of dietary change from reductions in particulate matter and tropospheric ozone 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 USD 1.3 trillion (with a range of USD 0.5-3.0 trillion).[202] Further evaluations of interventions to achieve sustained dietary changes in diverse populations should therefore be a priority.

In the transport sector some small-scale (i.e., single city) interventions were found where 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. A recent paper estimates a global reduction of 686 million metric tons of carbon annually if a Dutch cycling pattern was followed worldwide, with daily cycling distance of 2.6 kilometres.[203] This is about 20% of the GHG emissions from the global passenger car fleet in 2015 and could also prevent about 0.62 million deaths. Realising such benefits would however 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 (see transport case study: active travel) 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 elderly for whom the benefits of physical activity are large. There is moderate evidence that use of e-bicycles may improve cardiorespiratory fitness in the physically inactive.[204]

Case study 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.[79–81] More rapid action can be facilitated by using multiple reinforcing approaches, for example 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.[30] Actions to promote clean renewable energy do not require major changes in behaviour and may therefore be easier to implement than other climate actions once price differences and energy intermittency issues are addressed.

Between 71–76% of global energy-related carbon emissions originate from activities in cities.[205] 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, over 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.[206] 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[206] 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% [25,207] Carbon intensity, however, cannot be used as an overall measure of GHG emissions because total emissions can increase despite reducing carbon intensity if economic activity is increasing rapidly. In China, 41% of cities experienced rising $PM_{2.5}$ concentrations despite decreasing their carbon intensity,[207] and national GHG emissions in China rose by more than 3.4% to 14.3 $GtCO_2e$ in 2021.[208] Despite the range of climate mitigation actions being undertaken in cities there are few examples of actions that evaluate changes in both GHG and health-related indicators, suggesting missed opportunities for capitalising on health co-benefits.[24] 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, water and sanitation, public transport and active travel, accessible health services and education, with adequate green space are essential to achieve climate resilient net zero development.[209]

Few studies were identified that provided evidence of implemented real-world actions that measure both GHG mitigation and health effects. In addition, most identified evaluations reported solely on direct impacts and offer limited 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, and contextual barriers and enablers of these actions.

The diversity of timescales and metrics employed across a range of co-benefits studies reinforces the need to follow guidance to improve the quality and usability of research.[193] Adaptation of current guidelines for the evaluation of complex interventions, natural experiments, and process evaluations to encompass measures of GHG emissions would provide helpful benchmarks for rigorous evaluation of health and climate effects of mitigation actions.[210–212] 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 pandemic would bring vital evidence more quickly to the attention of the research, practitioner and policy communities[213,214]

An approach that puts planetary health at the centre of policymaking, from design to implementation and evaluation will be needed to accelerate transformation towards a net zero economy. This 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 re-frame 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 re-framing include the World Report on Social Determinants of Health Equity (World Report),[168] Sustainable Development Goals (SDGs),[169] doughnut economics[170] and the OECD wellbeing framework,[48] as well as the Earth for All report.[171] 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.[215,216] The Earth for All analysis proposes 5 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.

There are opportunities to embed health into the Paris Climate Agreement, for example by integrating health into the Nationally Determined Contributions (NDCs)that each signatory nation submits. A recent WHO analysis of the contribution of health to the NDCs has shown that only about 30% mention health and 10% provide a quantitative estimate of the health co-benefits of national mitigation actions.[217] There are also unrealised opportunities to embed health into long term low GHG emission development strategies 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.[218]

Building the evidence base for action

An interactive Pathfinder Climate and Health Evidence Bank has been developed, accessible through an online dashboard www.climatehealthevidence.org, 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 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 during the next phase of Pathfinder. Currently available tools and resources for estimating climate change mitigation impacts on GHG 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 will require reducing the material demand for products and services responsible for large GHG 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.[219]

Engagement from all sectors in the societal and behavioural changes required to reach net zero is essential to climate change mitigation.[220] While most publics globally are concerned about climate change, there remain barriers to behaviour change and to support for transformative policies.[192] 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[221]

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 well-being 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).[192]

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,[222] while others find they are no more effective than environmental messages,[223] 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 reduced red/processed meat consumption, although the *combination* of these framings produced more durable behavioural effects,[224,225] at least for more sustainability-conscious consumers.[226] For low-carbon travel, research similarly shows health benefit messaging to promote active travel is more persuasive than other arguments (e.g., convenience, environment) for walking, particularly when advocated by an expert source.[227] Health arguments are less persuasive to young people,[227] who are more influenced by cost and environmental factors in choosing active modes.[228]

Recommendations

Through this work we have identified actions across three broad headings and for a variety of stakeholders to accelerate progress towards healthy, net zero GHG emission societies 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 sub-national 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** (see Panel 5).

- **Climate funders and policy actors** should support the co-design of actions should be co-designed and implemented 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 Agreement** should support the integration of health into climate policies including by ensuring that future NDCs (Nationally Determined Contributions) and LT-LEDS (long-term low greenhouse gas emission development strategies) include 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 GST, 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 (e.g. CH_4 and black carbon) as well as of carbon dioxide 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 will enable co-benefits and trade-offs to be captured, tracked and reported, 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 healthcare sector.

Better evidence for decision making:

- **To enable faster and easier learning** across studies and contexts. **Researchers and research funders** should support:
    (a) **real-world, at scale, intervention evaluations** and the data collection systems required for these including **on mental health outcomes**;
    (b) **the development and use of well validated decision support tools to accelerate the integration of health into climate mitigation policies;**
    (c) **harmonisation of both modelling and evaluative research methods across health co-impact pathways**;
    (d) **efforts to strengthen research capacity where it is most needed**, especially in LMICs and for Indigenous communities;
    (e) **living syntheses of research evidence** which can both help to communicate important emerging evidence and highlight critical evidence gaps or questions.

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:
    - (a) Integration and learnings from existing research on health policy and social change to understand how social tipping points in mitigation and health can be achieved;
    - (b) Research on the commercial determinants of health and the underlying societal drivers that must be addressed to promote demand reduction;
    - (c) The role of nature-based solutions and natural climate solutions in delivering equitable mitigation and adaptation benefits, while promoting human health and wellbeing;
    - (d) The data needs and capacity support opportunities within currently low-emitting countries to enable a just and equitable transition to a low emission future;
    - (e) The health co-benefits and GHG reductions from actions to mitigate short-lived climate pollutants (e.g. CH_4 and black carbon)

Next Steps

Developing a 'Coalition on Climate Action for Health'

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 foundation of a Coalition of willing signatories of those taking action to mitigate greenhouse gases including but not limited to cities, nations, non-governmental organizations, 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 GHG emissions and health exposures and outcomes over time to prospectively measure progress towards climate and health goals.

The 'Coalition' will comprise:

- Research Partners – academic collaborators to support further synthesis and application of evidence to local contexts,

- Enabling Partners – networks of organizations 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.

- Implementing Partners – organisations that are already implementing or planning GHG mitigation actions that are likely to have significant health co-benefits including those identified through the umbrella review and case studies.

Implementing partners will a) Use tailored tools, guidelines and briefs to identify relevant metrics, data and indicators for at least one climate mitigation intervention which has health co-benefits. b). Measure and monitor progress on mitigation actions including GHG emission reductions, health relevant exposures (e.g., air pollution) and policy relevant outcomes, with a particular focus on equity.

Strengthening capacity on monitoring and evaluation

Supporting implementation of high-ambition climate change mitigation initiatives by strengthening 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 7 principles for (research) capacity development[229] and will include:

- 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.

- Establishment of a community of practice across the Coalition, using a combination of online and 'in-person' learning exchanges.

- Determining critical factors for scaling successful GHG mitigation initiatives. This 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, accessible through an online dashboard www.climatehealthevidence.org, sharing 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 GHG 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 GHG 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, policymakers and implementers in a timely fashion. Evaluation of the effects of GHG mitigation actions on health, equity and GHG emissions must be undertaken in real time, using standardised approaches informed by guidelines so that outcomes are comparable across sectors and locations. This will be essential to combat disinformation and '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 GHG emissions within planetary boundaries must be developed and implemented at scale through equitable collaboration and shared learning.

References

1 United Nations / Framework Convention on Climate Change. Adoption of the Paris Agreement. 21st Conference of the Parties. Paris, 2015 https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

2 United Nations Environment Programme. Emissions Gap Report 2022: The Closing Window — Climate crisis calls for rapid transformation of societies. Nairobi, 2022 https://www.unep.org/resources/emissions-gap-report-2022 (accessed Nov 7, 2022).

3 World Health Organisation. Fact sheet: Climate change and health. 2021. https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health (accessed Nov 9, 2022).

4 Boehm S, Jeffery L, Levin K, *et al.* State of Climate Action 2022. 2022 DOI:10.46830/wrirpt.22.00028.

5 IPCC Core Writing Team. Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In: Lee H, Romero J, eds. . Geneva, Switzerland, 2023.

6 Wilkinson P, Smith KR, Davies M, *et al.* Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *The Lancet* 2009; **374**: 1917–29.

7 Haines A, McMichael AJ, Smith KR, *et al.* Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *The Lancet* 2009; **374**: 2104–14.

8 Whitmee S, Haines A, Beyrer C, *et al.* Safeguarding human health in the Anthropocene epoch: Report of the Rockefeller Foundation-Lancet Commission on planetary health. *The Lancet* 2015; **386**: 1973–2028.

9 Steffen W, Richardson K, Rockström J, *et al.* Planetary boundaries: Guiding human development on a changing planet. *Science (1979)* 2015; **347**: 1259855.

10 Dasandi N, Graham H, Hudson D, Jankin S, vanHeerde-Hudson J, Watts N. Positive, global, and health or environment framing bolsters public support for climate policies. *Communications Earth & Environment 2022 3:1* 2022; **3**: 1–9.

11 Creutzig F, Niamir L, Bai X, *et al.* Demand-side solutions to climate change mitigation consistent with high levels of well-being. *Nat Clim Chang* 2022; **12**: 36–46.

12 Stoddard I, Anderson K, Capstick S, *et al.* Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve? *Annu Rev Environ Resour* 2021; **46**: 653–89.

13 Jennings N, Fecht D, De Matteis S. Mapping the co-benefits of climate change action to issues of public concern in the UK: a narrative review. *Lancet Planet Health* 2020; **4**: e424–33.

14 Mundaca L, Ürge-Vorsatz D, Wilson C. Demand-side approaches for limiting global warming to 1.5 °C. *Energy Effic* 2019; **12**: 343–62.

15 IPCC. Climate Change 2022 - Mitigation of Climate Change. Cambridge, UK and New York, NY, USA.: Cambridge University Press, 2023 DOI:10.1017/9781009157926.

16 Haines A, Clark H, Phumaphi J, Whitmee S, Green R. The Lancet Pathfinder Commission: pathways to a healthy, zero-carbon future — a call for evidence. *The Lancet* 2021; **397**: 779.

17 Belesova K, Green R, Clercq-Roques R, *et al.* Quantifying the effectiveness and health co-benefits of climate change mitigation actions across sectors: a protocol for an umbrella review. *Wellcome Open Res* 2022; **7**: 98.

18 Hassan S, Cuevas Garcia-Dorado S, Belesova K, *et al.* A protocol for analysing the effects on health and greenhouse gas emissions of implemented climate change mitigation actions. *Wellcome Open Res* 2021; **6**: 111.

19 Lancet Commission on Sustainability in Healthcare (LCSH) < Yale Center on Climate Change and Health. https://ysph.yale.edu/yale-center-on-climate-change-and-health/healthcare-sustainability-and-public-health/lancet-commission-on-sustainable-health-care/ (accessed April 27, 2023).

20 Jameel Y, Patrone CM, Patterson KP, West PC. Climate–poverty connections: Opportunities for synergistic solutions at the intersection of planetary and human well-being. 2022 DOI:10.55789/y2c0k2p2.
21 World Report on Social Determinants of Health Equity. https://www.who.int/initiatives/action-on-the-social-determinants-of-health-for-advancing-equity/world-report-on-social-determinants-of-health-equity (accessed April 28, 2023).
22 Haines A. Energy and health Series. *Lancet* 2007; **370**: 922.
23 Willett W, Rockström J, Loken B, *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* 2019; **393**: 447–92.
24 Lowe M, Adlakha D, Sallis JF, *et al.* City planning policies to support health and sustainability: an international comparison of policy indicators for 25 cities. *Lancet Glob Health* 2022; **10**: e882–94.
25 Romanello M, Napoli C Di, Drummond P, *et al.* The 2022 report of the Lancet Countdown on health and climate change: health at the mercy of fossil fuels. *The Lancet* 2022; **400**: 1619–54.
26 Hamilton I, Kennard H, McGushin A, *et al.* The public health implications of the Paris Agreement: a modelling study. *Lancet Planet Health* 2021; **5**: e74–83.
27 Willets E, Campbell-Lendrum D. WHO Review of IPCC Evidence 2022: climate change, health, and well-being. 2022. https://cdn.who.int/media/docs/default-source/climate-change/who-review-of-ipcc-evidence-2022-adv-version.pdf?sfvrsn=cce71a2c_3&download=true (accessed Nov 7, 2022).
28 Mitchell D, Heaviside C, Schaller N, *et al.* Extreme heat-related mortality avoided under Paris Agreement goals. *Nature Climate Change 2018 8:7* 2018; **8**: 551–3.
29 McDuffie EE, Martin R V., Spadaro J V., *et al.* Source sector and fuel contributions to ambient PM2.5 and attributable mortality across multiple spatial scales. *Nat Commun* 2021; **12**: 1–12.
30 Lelieveld J, Klingmüller K, Pozzer A, Burnett RT, Haines A, Ramanathan V. Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proc Natl Acad Sci U S A* 2019; **116**: 7192–7.
31 Vohra K, Vodonos A, Schwartz J, Marais EA, Sulprizio MP, Mickley LJ. Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. *Environ Res* 2021; **195**: 110754.
32 Markandya A, Sampedro J, Smith SJ, *et al.* Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. *Lancet Planet Health* 2018; **2**: e126–33.
33 Hales S, Atkinson J, Metcalfe J, Kuschel G, Woodward A. Long term exposure to air pollution, mortality and morbidity in New Zealand: Cohort study. *Science of The Total Environment* 2021; **801**: 149660.
34 Fisher S, Bellinger DC, Cropper ML, *et al.* Air pollution and development in Africa: impacts on health, the economy, and human capital. *Lancet Planet Health* 2021; **5**: e681–8.
35 Floess E, Grieshop A, Puzzolo E, *et al.* Scaling up gas and electric cooking in low- and middle-income countries: climate threat or mitigation strategy with co-benefits? *Environmental Research Letters* 2023; **18**: 034010.
36 Shindell D, Kuylenstierna JCI, Vignati E, *et al.* Simultaneously mitigating near-term climate change and improving human health and food security. *Science (1979)* 2012; **335**: 183–9.
37 United Nations Environment Programme and Climate and Clean Air Coalition. Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. 2021.
38 Zheng B, Ciais P, Chevallier F, *et al.* Record-high CO2 emissions from boreal fires in 2021. *Science (1979)* 2023; **379**: 912–7.
39 Johnston FH, Henderson SB, Chen Y, *et al.* Estimated global mortality attributable to smoke from landscape fires. *Environ Health Perspect* 2012; **120**: 695–701.
40 Ebi KL, Vanos J, Baldwin JW, *et al.* Extreme Weather and Climate Change: Population Health and Health System Implications. *Annu Rev Public Health* 2021; **42**: 293–315.

41 Aleksandrowicz L, Green R, Joy EJM, Smith P, Haines A. The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: A systematic review. *PLoS One* 2016; **11**: 1–16.
42 Springmann M, Clark MA, Rayner M, Scarborough P, Webb P. The global and regional costs of healthy and sustainable dietary patterns: a modelling study. *Lancet Planet Health* 2021; **5**: e797–807.
43 Lee IM, Shiroma EJ, Lobelo F, *et al.* Effect of physical inactivity on major non-communicable diseases worldwide: An analysis of burden of disease and life expectancy. *The Lancet* 2012; **380**: 219–29.
44 Katzmarzyk PT, Friedenreich C, Shiroma EJ, Lee IM. Physical inactivity and non-communicable disease burden in low-income, middle-income and high-income countries. *Br J Sports Med* 2022; **56**: 101–6.
45 Rissel C, Curac N, Greenaway M, Bauman A. Physical Activity Associated with Public Transport Use—A Review and Modelling of Potential Benefits. *Int J Environ Res Public Health* 2012; **9**: 2454.
46 Patterson R, Webb E, Millett C, Laverty AA. Physical activity accrued as part of public transport use in England. *J Public Health (Bangkok)* 2019; **41**: 222–30.
47 World Health Organization; Global status report on road safety 2018. Geneva, 2018.
48 Rosenstock TS, Dawson IK, Aynekulu E, *et al.* A Planetary Health Perspective on Agroforestry in Sub-Saharan Africa. *One Earth* 2019; **1**: 330–44.
49 Barboza EP, Cirach M, Khomenko S, *et al.* Green space and mortality in European cities: a health impact assessment study. *Lancet Planet Health* 2021; **5**: e718–30.
50 Drawdown. Drawdown solutions. 2020. https://drawdown.org/solutions/table-of-solutions.
51 IPCC. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press. In: Edenhofer O, Pichs-Madruga R, Sokona Y, *et al.*, eds. Ipcc Wgiii Ar5. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press, 2014: 35.
52 OECD. Accelerating Climate Action. OECD Publishing, Paris: OECD, 2019 DOI:10.1787/2f4c8c9a-en.
53 WHO Commission on Social Determinants of Health & World Health Organization. Closing the gap in a generation: Health equity through action on the social determinants of health: Commission on Social Determinants of Health final report. 2008.
54 Faber J, Schroten A, Bles M, *et al.* Behavioural Climate Change Mitigation Options and Their Appropriate Inclusion in Quantitative Longer Term Policy Scenarios. *CE Delft* 2012; : 1–87.
55 Hoegh-Guldberg O, Caldeira K, Chopin T, *et al.* The Ocean as a Solution to Climate Change: Five Opportunities for Action. Washington, DC: World Resources Institute., 2019.
56 UNESCO. Climate Change Education and Awareness. 2020 https://en.unesco.org/themes/addressing-climate-change/climate-change-education-and-awareness.
57 Guillebaud J. Voluntary family planning to minimise and mitigate climate change. *BMJ* 2016; **353**. DOI:10.1136/BMJ.I2102.
58 Evans S, Winch R, Hartley S, Lane J. Nature-based solutions to the climate emergency. The benefits to business and society. 2020.
59 Berrang-Ford L, Sietsma AJ, Callaghan M, *et al.* Systematic mapping of global research on climate and health: a machine learning review. *Lancet Planet Health* 2021; **5**: e514–25.
60 Cohen-Shacham E, Walters G, Janzen C, Maginnis S. Nature-based solutions to address global societal challenges. IUCN International Union for Conservation of Nature, 2016 DOI:10.2305/IUCN.CH.2016.13.en.
61 Institute for Health Metrics and Evaluation (IHME). GBD Compare Data Visualization. Seattle, WA: IHME, University of Washington. 2020.

62 World Health Organization. Regional Office for Europe; Achieving health benefits from carbon reductions: manual for CaRBonH calculation tool. iv. 2018; : 0–21.
63 Short-Lived Climate Pollutants (SLCPs) | Climate & Clean Air Coalition. https://www.ccacoalition.org/en/content/short-lived-climate-pollutants-slcps (accessed Nov 7, 2022).
64 Lund MT, Samset BH, Skeie RB, *et al.* Short Black Carbon lifetime inferred from a global set of aircraft observations. *NPJ Clim Atmos Sci* 2018; **1**: 31.
65 IPCC. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change IPCC. In: Pachauri RK, Meyer LA, eds. Climate Change 2014: Synthesis Report. Geneva, 2014: 151 pp.
66 Markandya A, Wilkinson P. Electricity generation and health. *The Lancet* 2007; **370**: 979–90.
67 Lin W, Brunekreef B, Gehring U. Meta-analysis of the effects of indoor nitrogen dioxide and gas cooking on asthma and wheeze in children. *Int J Epidemiol* 2013; **42**: 1724–37.
68 Chowdhury S, Haines A, Klingmüller K, *et al.* Global and national assessment of the incidence of asthma in children and adolescents from major sources of ambient NO2. *Environmental Research Letters* 2021; **16**: 035020.
69 IRENA. Renewable capacity statistics. Abu Dhabi., 2023.
70 IEA. Coal 2022. Paris, 2022.
71 Pozzer A, Anenberg SC, Dey S, Haines A, Lelieveld J, Chowdhury S. Mortality Attributable to Ambient Air Pollution: A Review of Global Estimates. *Geohealth* 2023; **7**. DOI:10.1029/2022GH000711.
72 Markandya A, Armstrong BG, Hales S, *et al.* Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation. *Lancet* 2009; **374**: 2006–15.
73 Li M, Zhang D, Li C-T, Selin NE, Karplus VJ. Co-benefits of China's climate policy for air quality and human health in China and transboundary regions in 2030. *Environmental Research Letters* 2019; **14**: 084006.
74 WHO. WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva, 2021.
75 Levenda AM, Behrsin I, Disano F. Renewable energy for whom? A global systematic review of the environmental justice implications of renewable energy technologies. *Energy Res Soc Sci* 2021; **71**: 101837.
76 Anderson T, Paul H. Agrofuels and the myth of marginal lands. 2008.
77 Waters-Bayer A, Wario HT. Pastoralism and large-scale REnewable energy and green hydrogen projects. Germany: Heinrich-Böll-Stiftung, Brot für die Welt, 2022 Retrieved from https://policycommons.net/artifacts/2434285/pastoralism-and-large-scale-renewable-energy-and-green-hydrogen-projects/3455877/ on 25 Apr 2023. (accessed April 28, 2023).
78 Barbose G, Wiser R, Heeter J, *et al.* A retrospective analysis of benefits and impacts of U.S. renewable portfolio standards. *Energy Policy* 2016; **96**: 645–60.
79 Burney JA. The downstream air pollution impacts of the transition from coal to natural gas in the United States. *Nat Sustain* 2020; **3**: 152–60.
80 Millstein D, Wiser R, Bolinger M, Barbose G. The climate and air-quality benefits of wind and solar power in the United States. *Nature Energy 2017 2:9* 2017; **2**: 1–10.
81 Barbose G, Wiser R, Heeter J, *et al.* A retrospective analysis of benefits and impacts of U.S. renewable portfolio standards. *Energy Policy* 2016; **96**: 645–60.
82 Landrigan PJ, Frumkin H, Lundberg BE. The False Promise of Natural Gas. *New England Journal of Medicine* 2020; **382**: 104–7.
83 Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA). https://www.eia.gov/tools/faqs/faq.php?id=427&t=3 (accessed Nov 8, 2022).
84 Pearce JM, Prehoda EW. Potential lives saved by replacing coal with solar photovoltaic electricity production in the U.S. *Renewable and Sustainable Energy Reviews* 2017; **80**: 710–5.

85 Sigsgaard T, Forsberg B, Annesi-Maesano I, *et al.* Health Impacts of Anthropogenic Biomass Burning in the Developed World. *European Respiratory Journal* 2015; **46**: 1577–88.
86 Camia A, Giuntoli J, Jonsson R, *et al.* The use of woody biomass for energy production in the EU. Luxembourg: Publications Office of the European Union, 2020 DOI:doi:10.2760/831621.
87 Shindell D, Smith CJ. Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature* 2019; **573**: 408–11.
88 Pörtner H-O, Roberts DC, Tignor M, *et al.* Summary for Policymakers. In: Climate Change 2022 – Impacts, Adaptation and Vulnerability. Cambridge, UK and New York, NY, USA,: Cambridge University Press, 2023: 3–34.
89 Goldstein B, Gounaridis D, Newell JP. The carbon footprint of household energy use in the United States. *Proc Natl Acad Sci U S A* 2020; **117**: 19122–30.
90 Pope D, Johnson M, Fleeman N, *et al.* Are cleaner cooking solutions clean enough? A systematic review and meta-analysis of particulate and carbon monoxide concentrations and exposures. *Environmental Research Letters* 2021; **16**: 083002.
91 Anenberg SC, Schwartz J, Shindell D, *et al.* Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls. *Environ Health Perspect* 2012; **120**: 831–9.
92 Pachauri S, Van Ruijven BJ, Nagai Y, *et al.* Pathways to achieve universal household access to modern energy by 2030. *Environmental Research Letters* 2013; **8**: 024015.
93 Sustainability Victoria and University of Technology Sydney. The Victorian Healthy Homes Program. Research findings. Melbourne, 2022.
94 Hulkkonen M, Mielonen T, Prisle NL. The atmospheric impacts of initiatives advancing shifts towards low-emission mobility: A scoping review. *Science of the Total Environment* 2020; **713**: 136133.
95 Air Quality Expert Group. Non-Exhaust Emissions from Road Traffic. 2019.
96 Garcia E, Johnston J, McConnell R, Palinkas L, Eckel SP. California's early transition to electric vehicles: Observed health and air quality co-benefits. *Science of The Total Environment* 2023; **867**: 161761.
97 Sovacool BK. When Subterranean Slavery Supports Sustainability Transitions? Power, Patriarchy, and Child Labor in Artisanal Congolese Cobalt Mining. *he Extractive Industries and Society* 2021; **8**: 271–93.
98 Field J, Girot C, Ghojeh M, Huxley R, Kirbyshire A. Climate, Health and Equity. Global Ideas for US Solutions. London, UK, 2020.
99 Chapman R, Keall M, Howden-Chapman P, *et al.* A cost benefit analysis of an active travel intervention with health and carbon emission reduction benefits. *Int J Environ Res Public Health* 2018; **15**: 1–10.
100 Callister P, Callahan HO. How to decarbonise New Zealand's transport sector. 2021.
101 Jarmul S, Dangour AD, Green R, Liew Z, Haines A, Scheelbeek PFFD. Climate change mitigation through dietary change: a systematic review of empirical and modelling studies on the environmental footprints and health effects of 'sustainable diets'. *Environmental Research Letters* 2020; **15**: 123014.
102 Milner J, Green R, Dangour AD, *et al.* Health effects of adopting low greenhouse gas emission diets in the UK. *BMJ Open* 2015; **5**.
103 Lescinsky H, Afshin A, Ashbaugh C, *et al.* Health effects associated with consumption of unprocessed red meat: a Burden of Proof study. *Nature Medicine 2022 28:10* 2022; **28**: 2075–82.
104 Roe S, Streck C, Obersteiner M, *et al.* Contribution of the land sector to a 1.5 °C world. *Nature Climate Change 2019 9:11* 2019; **9**: 817–28.
105 Eshel G, Shepon A, Noor E, Milo R. Environmentally Optimal, Nutritionally Aware Beef Replacement Plant-Based Diets. *Environ Sci Technol* 2016; **50**: 8164–8.

106 Chen C, Chaudhary A, Mathys A. Dietary Change Scenarios and Implications for Environmental, Nutrition, Human Health and Economic Dimensions of Food Sustainability. *Nutrients* 2019; **11**.
107 Millward JD, Garnett T. Plenary Lecture 3 Food and the planet: nutritional dilemmas of greenhouse gas emission reductions through reduced intakes of meat and dairy foods. *Proceedings of the nutrition society* 2010; **69**: 103–18.
108 Xia L, Lam SK, Yan X, Chen D. How Does Recycling of Livestock Manure in Agroecosystems Affect Crop Productivity, Reactive Nitrogen Losses, and Soil Carbon Balance? *Environ Sci Technol* 2017; **51**: 7450–7.
109 Xia L, Lam SK, Wolf B, Kiese R, Chen D, Butterbach-Bahl K. Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. *Glob Chang Biol* 2018; **24**: 5919–32.
110 Xia L, Lam SK, Chen D, Wang J, Tang Q, Yan X. Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta-analysis. *Glob Chang Biol* 2017; **23**: 1917–25.
111 Wu D, Zhang Y, Dong G, *et al.* The importance of ammonia volatilization in estimating the efficacy of nitrification inhibitors to reduce N2O emissions: A global meta-analysis. *Environmental Pollution* 2021; **271**: 116365.
112 Wang Y, Li X, Yang J, *et al.* Mitigating Greenhouse Gas and Ammonia Emissions from Beef Cattle Feedlot Production: A System Meta-Analysis. *Environ Sci Technol* 2018; **52**: 11232–42.
113 Stefano A De, Jacobson MG. Soil carbon sequestration in agroforestry systems: a meta-analysis. *Agroforestry Systems 2017 92:2* 2017; **92**: 285–99.
114 FABLE. Pathways to Sustainable Land-Use and Food Systems: 2020 Report of the FABLE Consortium. 2020.
115 Sun Z, Scherer L, Zhang Q, Behrens P. Adoption of plant-based diets across Europe can improve food resilience against the Russia–Ukraine conflict. *Nature Food 2022 3:11* 2022; **3**: 905–10.
116 Pacheco-Torgal F. Introduction to biobased materials and biotechnologies for eco-efficient construction. *Bio-based Materials and Biotechnologies for Eco-efficient Construction* 2020; : 1–16.
117 Haines A. Health in the bioeconomy. *Lancet Planet Health* 2021; **5**: e4–5.
118 Muscat A, de Olde EM, de Boer IJM, Ripoll-Bosch R. The battle for biomass: A systematic review of food-feed-fuel competition. *Glob Food Sec* 2020; **25**: 100330.
119 World Resources Institute. Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Synthesis. 2005.
120 Girardin CAJ, Jenkins S, Seddon N, *et al.* Nature-based solutions can help cool the planet — if we act now. *Nature* 2021; **593**: 191–4.
121 Griscom BW, Adams J, Ellis PW, *et al.* Natural climate solutions. *Proceedings of the National Academy of Sciences* 2017; **114**: 11645–50.
122 UNEP and IUCN. Nature-based solutions for climate change mitigation. 2021.
123 Smith P, Arneth A, Barnes DKA, *et al.* How do we best synergize climate mitigation actions to co-benefit biodiversity? *Glob Chang Biol* 2022; **28**: 2555–77.
124 Seddon N, Chausson A, Berry P, Girardin CAJ, Smith A, Turner B. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences* 2020; **375**: 20190120.
125 Teo HC, Zeng Y, Sarira TV, *et al.* Global urban reforestation can be an important natural climate solution. *Environmental Research Letters* 2021; **16**: 034059.
126 Salmond JA, Tadaki M, Vardoulakis S, *et al.* Health and climate related ecosystem services provided by street trees in the urban environment. *Environmental Health* 2016; **15**: S36.

127 Collins RM, Spake R, Brown KA, Ogutu BO, Smith D, Eigenbrod F. A systematic map of research exploring the effect of greenspace on mental health. *Landsc Urban Plan* 2020; **201**: 103823.
128 McPherson EG, Xiao Q, van Doorn NS, *et al.* The structure, function and value of urban forests in California communities. *Urban For Urban Green* 2017; **28**: 43–53.
129 Fitzky AC, Sandén H, Karl T, *et al.* The Interplay Between Ozone and Urban Vegetation—BVOC Emissions, Ozone Deposition, and Tree Ecophysiology. *Frontiers in Forests and Global Change* 2019; **2**. DOI:10.3389/ffgc.2019.00050.
130 Nowak DJ, Hirabayashi S, Bodine A, Greenfield E. Tree and forest effects on air quality and human health in the United States. *Environmental Pollution* 2014; **193**: 119–29.
131 Nowak DJ, Greenfield EJ. US urban forest statistics, values, and projections. *J For* 2018; **116**: 164–77.
132 Soares AL, Rego FC, McPherson EG, Simpson JR, Peper PJ, Xiao Q. Benefits and costs of street trees in Lisbon, Portugal. *Urban For Urban Green* 2011; **10**: 69–78.
133 Mcpherson G, Simpson JR, Peper PJ, Maco SE, Xiao Q. Municipal Forest Benefits and costs in five U.S. cities. *J For* 2005; **103**: 411–6.
134 Millward AA, Sabir S. Benefits of a forested urban park: What is the value of Allan Gardens to the city of Toronto, Canada? *Landsc Urban Plan* 2011; **100**: 177–88.
135 Greene CS, Robinson PJ, Millward AA. Canopy of advantage: Who benefits most from city trees? *J Environ Manage* 2018; **208**: 24–35.
136 Jelks NO, Jennings V, Rigolon A. Green Gentrification and Health: A Scoping Review. *Int J Environ Res Public Health* 2021; **18**.
137 Wolf KL, Lam ST, McKeen JK, Richardson GRA, Bosch M van den, Bardekjian AC. Urban Trees and Human Health: A Scoping Review. *Int J Environ Res Public Health* 2020; **17**: 1–30.
138 Wood BT, Quinn CH, Stringer LC, Dougill AJ. Investigating Climate Compatible Development Outcomes and their Implications for Distributive Justice: Evidence from Malawi. *Environ Manage* 2017; **60**: 436–53.
139 Brown DR, Dettmann P, Rinaudo T, Tefera H, Tofu A. Poverty alleviation and environmental restoration using the clean development mechanism: A case study from Humbo, Ethiopia. *Environ Manage* 2011; **48**: 322–33.
140 Buckingham K, Hanson C. The Restoration Diagnostic. Case Example: Humbo, Ethiopia. 2015.
141 Sarmiento Barletti JP, Larson AM. Rights abuse allegations in the context of REDD+ readiness and implementation: A preliminary review and proposal for moving forward. Center for International Forestry Research (CIFOR), 2017 DOI:10.17528/cifor/006630.
142 Pandey SS, Cockfield G, Maraseni TN. Assessing the roles of community forestry in climate change mitigation and adaptation: A case study from Nepal. *For Ecol Manage* 2016; **360**: 400–7.
143 McDermott M, Mahanty S, Schreckenberg K. Examining equity: A multidimensional framework for assessing equity in payments for ecosystem services. *Environ Sci Policy* 2013; **33**: 416–27.
144 UNFCCC. Safeguards - REDD+. https://redd.unfccc.int/fact-sheets/safeguards.html. 2018. https://redd.unfccc.int/fact-sheets/safeguards.html (accessed July 23, 2023).
145 Jones IJ, MacDonald AJ, Hopkins SR, *et al.* Improving rural health care reduces illegal logging and conserves carbon in a tropical forest. *Proc Natl Acad Sci U S A* 2020; **117**: 28515–24.
146 Webb K, Jennings J, Minovi D. A community-based approach integrating conservation, livelihoods, and health care in Indonesian Borneo. *Lancet Planet Health* 2018; **2**: S26.
147 Webb K. Personal Communication. 2022.
148 Scheelbeek PFD, Dangour AD, Jarmul S, *et al.* The effects on public health of climate change adaptation responses: a systematic review of evidence from low- and middle-income countries. *Environmental Research Letters* 2021; **16**: 073001.
149 Cuevas S, Haines A. Health benefits of a carbon tax. The Lancet. 2016; **387**: 7–9.

150 Parry IAN, Veung C, Heine D. How Much Carbon Pricing is in Countries' Own Interests? The Critical Role of Co-Benefits. IMF Working Paper. 2014; **WP/14/174**. DOI:10.1142/S2010007815500190.
151 Parry I, Black S, Vernon N. Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies. IMF Working Paper. 2021; **WP/21/236**.
152 Timperley J. Why fossil fuel subsidies are so hard to kill. *Nature* 2021; **598**: 403–5.
153 The World Bank Carbon Pricing Dashboard. Up-to-date overview of carbon pricing initiatives. 2022. https://carbonpricingdashboard.worldbank.org/ (accessed Aug 9, 2022).
154 Tvinnereim E, Mehling M. Carbon pricing and deep decarbonisation. *Energy Policy* 2018; **121**: 185–9.
155 Cuevas S, Nachtigall D, Aguilar Jaber A, *et al.* Carbon pricing, health co-benefits and trade-offs: protocol for a systematic framework synthesis. *Wellcome Open Research (accepted)* 2022.
156 Kim SE, Xie Y, Dai H, *et al.* Air quality co-benefits from climate mitigation for human health in South Korea. *Environ Int* 2020; **136**: 105507.
157 Dimanchev EG, Paltsev S, Yuan M, *et al.* Health co-benefits of sub-national renewable energy policy in the US. *Environmental Research Letters* 2019; **14**. DOI:10.1088/1748-9326/ab31d9.
158 Thompson TM, Rausch S, Saari RK, Selin NE. Air quality co-benefits of subnational carbon policies. *J Air Waste Manage Assoc* 2016; **66**: 988–1002.
159 Sampedro J, Smith SJ, Arto I, *et al.* Health co-benefits and mitigation costs as per the Paris Agreement under different technological pathways for energy supply. *Environ Int* 2020; **136**: 105513.
160 Springmann M, Mason-D'Croz D, Robinson S, *et al.* Mitigation potential and global health impacts from emissions pricing of food commodities. *Nat Clim Chang* 2017; **7**: 69–74.
161 Yates R. Recycling fuel subsidies as health subsidies. *Bull World Health Organ* 2014; **92**: 547-547A.
162 Briggs ADM, Kehlbacher A, Tiffin R, Scarborough P. Simulating the impact on health of internalising the cost of carbon in food prices combined with a tax on sugar-sweetened beverages. *BMC Public Health* 2016; **16**: 107.
163 Zhang H, Zhang B. The unintended impact of carbon trading of China's power sector. *Energy Policy* 2020; **147**: 111876.
164 Frank S, Havlík P, Soussana JF, *et al.* Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters* 2017; **12**: 105004.
165 Lal R. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degrad Dev* 2006; **17**: 197–209.
166 Thompson TM, Rausch S, Saari RK, Selin NE. A systems approach to evaluating the air quality co-benefits of US carbon policies. *Nat Clim Chang* 2014; **4**: 917–23.
167 Ščasný M, Massetti E, Melichar J, Carrara S. Quantifying the Ancillary Benefits of the Representative Concentration Pathways on Air Quality in Europe. *Environ Resour Econ (Dordr)* 2015; **62**: 383–415.
168 Yates R. Recycling fuel subsidies as health subsidies. *Bull World Health Organ* 2014; **92**: 9–10.
169 Gupta V, Dhillon R, Yates R. Financing universal health coverage by cutting fossil fuel subsidies. *Lancet Glob Health* 2015; **3**: 306–7.
170 Lindebjerg ES, Peng W, Yeboah S. Do policies for phasing out fossil fuel subsidies deliver what they promise? Social gains and repercussions in Iran, Indonesia and Ghana. 2015.
171 World Health Organization. Regional Office for Europe. Circular economy and health: opportunities and risks. 2018 https://apps.who.int/iris/handle/10665/342218.
172 Peters GP, Minx JC, Weber CL, Edenhofer O. Growth in emission transfers via international trade from 1990 to 2008. *Proc Natl Acad Sci U S A* 2011; **108**: 8903–8.
173 Circle Economy. The Circularity Gap Report 2022. 2022 https://www.circularity-gap.world/2022#Download-the-report.

174 European Parliament. Circular economy: definition, importance and benefits. 26-04-2022. 2022. https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits (accessed Aug 9, 2022).
175 Cantzler J, Creutzig F, Ayargarnchanakul E, Javaid A, Wong L, Haas W. Saving resources and the climate? A systematic review of the circular economy and its mitigation potential. *Environmental Research Letters* 2020. DOI:10.1088/1748-9326/abbeb7.
176 Material Economics; The Circular Economy. A Powerful Force for Climate Mitigation. 2018.
177 Casson C, Welch D. Sustainable Consumption and Production, Volume II. Cham: Springer International Publishing, 2021 DOI:10.1007/978-3-030-55285-5.
178 Cullen JM. Circular Economy: Theoretical Benchmark or Perpetual Motion Machine? *J Ind Ecol* 2017; **21**: 483–6.
179 Korhonen J, Nuur C, Feldmann A, Birkie SE. Circular economy as an essentially contested concept. *J Clean Prod* 2018; **175**: 544–52.
180 Forti V, Baldé CP, Kuehr R, Bel G. The Global E-waste Monitor 2020. 2020 http://ewastemonitor.info/.
181 House of Commons Environmental Audit Committee; Electronic Waste and the Circular Economy. First Report of Session 2019–21. 2020 https://committees.parliament.uk/publications/3675/documents/35777/default/.
182 Daum K, Stoler J, Grant R. Toward a More Sustainable Trajectory for E-Waste Policy: A Review of a Decade of E-Waste Research in Accra, Ghana. *Int J Environ Res Public Health* 2017; **14**: 135.
183 GIZ. Transformative project design. 2022. www.giz.de.
184 OECD Working Party on Climate, Investment and Development. Transport Strategies for Net-Zero Systems by Design. OECD, 2021 DOI:10.1787/0a20f779-en.
185 Bousquet A, Bigo A, Lapillonne B, Sudries L. Transport emissions trends in the EU Analyst Brief – September 2022. 2022.
186 Stern N. Economics: Current climate models are grossly misleading. *Nature 2016 530:7591* 2016; **530**: 407–9.
187 Stern N, Stiglitz J, Karlsson K, Taylor C. A Social Cost of Carbon Consistent with a Net-Zero Climate Goal. Issue Brief. 2022.
188 Asefi-Najafabady S, Villegas-Ortiz L, Morgan J. The failure of Integrated Assessment Models as a response to 'climate emergency' and ecological breakdown: the Emperor has no clothes. *Globalizations* 2021; **18**: 1178–88.
189 Moore B, Verfuerth C, Minas AM, *et al.* Transformations for climate change mitigation: A systematic review of terminology, concepts, and characteristics. *WIREs Climate Change* 2021; **12**. DOI:10.1002/wcc.738.
190 Kern F, Rogge KS, Howlett M. Policy mixes for sustainability transitions: New approaches and insights through bridging innovation and policy studies. *Res Policy* 2019; **48**: 103832.
191 Nemet GF, Jakob M, Steckel JC, Edenhofer O. Addressing policy credibility problems for low-carbon investment. *Global Environmental Change* 2017; **42**: 47–57.
192 OECD. Redesigning Ireland's Transport for Net Zero. Paris: OECD, 2022 DOI:10.1787/b798a4c1-en.
193 Hess JJ, Ranadive N, Boyer C, *et al.* Guidelines for modeling and reporting health effects of climate change mitigation actions. *Environ Health Perspect* 2020; **128**: 1–10.
194 Cohen B, Cowie A, Babiker M, Leip AA, Smith P. Co-Benefits and Trade-Offs of Climate Change Mitigation Actions and the Sustainable Development Goals. *Sustain Prod Consum* 2021; **26**: 805–13.
195 Murage P, A Asenga, A Tarimo, T Njung'e, T van der Zaan, F Chiwanga. Natural regeneration of drylands and associated pathways to human health outcomes: perspectives from rural

households. *PREPRINT (Version 3) available at Research Square* 2022; published online Dec 28. DOI:https://doi.org/10.21203/rs.3.rs-2003043/v3.

196 Murage P, Kovats S, Sarran C, Taylor J, McInnes R, Hajat S. What individual and neighbourhood-level factors increase the risk of heat-related mortality? A case-crossover study of over 185,000 deaths in London using high-resolution climate datasets. *Environ Int* 2020; **134**: 105292.

197 Kennedy, G., Terri, Ballard and MarrieClaude D. Guidelines for measuring household and individual dietary diversity. 2010 www.foodsec.org.

198 Fa JE, Watson JEM, Leiper I, *et al.* Importance of Indigenous Peoples' lands for the conservation of Intact Forest Landscapes. *Front Ecol Environ* 2020; **18**: 135–40.

199 Hepburn C, Stiglitz JE, Stern NN, Stiglitz JE. Carbon pricing special issue in the European economic review. *Eur Econ Rev* 2020; **127**. DOI:10.1016/j.euroecorev.2020.103440.

200 World Health Organization. A framework for the quantification and economic valuation of health outcomes originating from health and non-health climate change mitigation and adaptation action. Geneva, 2023.

201 Eustachio Colombo P, Elinder LS, Patterson E, Parlesak A, Lindroos AK, Andermo S. Barriers and facilitators to successful implementation of sustainable school meals: a qualitative study of the OPTIMAT™-intervention. *International Journal of Behavioral Nutrition and Physical Activity* 2021; **18**: 1–11.

202 Springmann M, Van Dingenen R, Vandyck T, Latka C, Witzke P, Leip A. The global and regional air quality impacts of dietary change. *In press* 2023.

203 Chen W, Carstensen TA, Wang R, *et al.* Historical patterns and sustainability implications of worldwide bicycle ownership and use. *Communications Earth & Environment 2022 3:1* 2022; **3**: 1–9.

204 Bourne JE, Sauchelli S, Perry R, *et al.* Health benefits of electrically-assisted cycling: A systematic review 11 Medical and Health Sciences 1117 Public Health and Health Services. *International Journal of Behavioral Nutrition and Physical Activity* 2018; **15**: 1–15.

205 Seto KC, Dhakal S, Bigio A, *et al.* Human Settlements, Infrastructure and Spatial Planning. In: Edenhofer O, Pichs-Madruga R, Sokona Y, *et al.*, eds. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2014.

206 CDP. Over 100 global cities get majority of electricity from renewables. *cdp.net* 2018; published online Feb. https://www.cdp.net/en/articles/cities/over-100-global-cities-get-majority-of-electricity-from-renewables.

207 UNEP. Synergizing action on the environment and climate: good practise in China and around the globe. 2019.

208 China | Climate Action Tracker. https://climateactiontracker.org/countries/china/ (accessed April 28, 2023).

209 United Nations Human Settlements Programme (UN-Habitat). Envisaging the Future of Cities. World Cities Report 2022. 2022.

210 Skivington K, Matthews L, Simpson SA, *et al.* A new framework for developing and evaluating complex interventions: update of Medical Research Council guidance. *BMJ* 2021; **374**: n2061.

211 Craig P, Dieppe P, Macintyre S, Mitchie S, Nazareth I, Petticrew M. Developing and evaluating complex interventions: The new Medical Research Council guidance. *Bmj* 2008; **337**: 979–83.

212 Moore GF, Audrey S, Barker M, *et al.* Process evaluation of complex interventions: Medical Research Council guidance. *BMJ* 2015; **350**: h1258–h1258.

213 Siemieniuk RAC, Bartoszko JJ, Ge L, *et al.* Drug treatments for covid-19: living systematic review and network meta-analysis. *BMJ* 2020; **370**: 28.

214 Elliott J, Lawrence R, Minx JC, *et al.* Decision makers need constantly updated evidence synthesis. *Nature 2021 600:7889* 2021; **600**: 383–5.

215 Bardi U. Limits and Beyond: 50 years on from The Limits to Growth, what did we learn and what's next? Club of Rome. 2022 https://www.clubofrome.org/publication/limits-and-beyond/ (accessed Aug 9, 2022).
216 Meadows DH, Meadows DL, Randers J, Behrens W. The Limits to growth; a report for the Club of Rome's project on the predicament of mankind. Club of Rome. New York: Universe Books, 1972.
217 World Health Organization. 2023 WHO review of health in Nationally Determined Contributions and long-term strategies: health at the heart of the Paris Agreement. Geneva, 2023.
218 UNFCCC. Global Stocktake. 2023. https://unfccc.int/topics/global-stocktake (accessed Sept 2, 2023).
219 Sachs JD, Schmidt-Traub G, Mazzucato M, Messner D, Nakicenovic N, Rockström J. Six Transformations to achieve the Sustainable Development Goals. *Nat Sustain* 2019; **2**: 805–14.
220 Whitmarsh L, Poortinga W, Capstick S. Behaviour change to address climate change. *Curr Opin Psychol* 2021; **42**: 76–81.
221 Garnett EE, Balmford A, Sandbrook C, Pilling MA, Marteau TM. Impact of increasing vegetarian availability on meal selection and sales in cafeterias. *Proc Natl Acad Sci U S A* 2019; **116**: 20923–9.
222 Cordts A, Nitzko S, Spiller A. Consumer Response to Negative Information on Meat Consumption in Germany. *International Food and Agribusiness Management Review* 2014; **17**.
223 Carfora V, Catellani P, Caso D, Conner M. How to reduce red and processed meat consumption by daily text messages targeting environment or health benefits. *J Environ Psychol* 2019; **65**: 101319.
224 Shreedhar G, Galizzi MM. Personal or planetary health? Direct, spillover and carryover effects of non-monetary benefits of vegetarian behaviour. *J Environ Psychol* 2021; **78**: 101710.
225 Amiot CE, El Hajj Boutros G, Sukhanova K, Karelis AD. Testing a novel multicomponent intervention to reduce meat consumption in young men. *PLoS One* 2018; **13**: e0204590.
226 Verain MCD, Sijtsema SJ, Dagevos H, Antonides G. Attribute Segmentation and Communication Effects on Healthy and Sustainable Consumer Diet Intentions. *Sustainability 2017, Vol 9, Page 743* 2017; **9**: 743.
227 Pangbourne K, Bennett S, Baker A. Persuasion profiles to promote pedestrianism: Effective targeting of active travel messages. *Travel Behav Soc* 2020; **20**: 300–12.
228 Simons D, Clarys P, De Bourdeaudhuij I, de Geus B, Vandelanotte C, Deforche B. Why do young adults choose different transport modes? A focus group study. *Transp Policy (Oxf)* 2014; **36**: 151–9.
229 Seven principles for strengthening research capacity in low- and middle-income countries: simple ideas in a complex world. ESSENCE Good practice document series. WHO REFERENCE NUMBER: TDR/ESSENCE/2.14, 2014.
230 Chancel L. Climate change & the global inequality of carbon emissions, 1990-2020. 2021 www.wid.world.
231 Büchs M, Cass N, Mullen C, Lucas K, Ivanova D. Emissions savings from equitable energy demand reduction. *Nature Energy 2023 8:7* 2023; **8**: 758–69.
232 Scovronick N, Anthoff D, Dennig F, *et al.* The importance of health co-benefits under different climate policy cooperation frameworks. *Environmental Research Letters* 2021; **16**: 055027.
233 Mustard C, Haines A, Belesova K, Cousens S. Achieving good health with a low environmental footprint – A comparison of national indicators. *Wellcome Open Res* 2022; **7**: 299.
234 Watts N, Amann M, Arnell N, *et al.* The 2020 Report of The Lancet Countdown on Health and Climate Change: Responding to Converging Crises. *The Lancet* 2021; **397**: 129–70.
235 Bang G, Rosendahl KE, Böhringer C. Balancing cost and justice concerns in the energy transition: comparing coal phase-out policies in Germany and the UK. *Climate Policy* 2022.

236 Stanley MC, Strongman JE, Perks RB, *et al.* Managing Coal Mine Closure: Achieving a Just Transition for All. Washington: World Bank Group, 2018.
237 Wang X, Lo K. Political economy of just transition: Disparate impact of coal mine closure on state-owned and private coal workers in Inner Mongolia, China. *Energy Res Soc Sci* 2022; **90**.
238 Braunger I, Walk P. Power in transitions: Gendered power asymmetries in the United Kingdom and the United States coal transitions. *Energy Res Soc Sci* 2022; **87**: 102474.
239 Mebratu D, Mbandi A. Open Burning of Waste in Africa: Challenges and opportunities. 2022.
240 Chirgwin H, Cairncross S, Zehra D, Sharma Waddington H. Interventions promoting uptake of water, sanitation and hygiene (WASH) technologies in low- and middle-income countries: An evidence and gap map of effectiveness studies. *Campbell Systematic Reviews* 2021; **17**: e1194.
241 Cairncross S, Hunt C, Boisson S, *et al.* Water, sanitation and hygiene for the prevention of diarrhoea. *Int J Epidemiol* 2010; **39**: i193–205.
242 Wolf J, Hunter PR, Freeman MC, *et al.* Impact of drinking water, sanitation and handwashing with soap on childhood diarrhoeal disease: updated meta-analysis and meta-regression. *Tropical Medicine & International Health* 2018; **23**: 508–25.
243 Venkataramanan V, Crocker J, Karon A, Bartram J. Community-Led Total Sanitation: A Mixed-Methods Systematic Review of Evidence and Its Quality. *Environ Health Perspect* 2018; **126**: 026001.
244 Sharma Waddington H, ME, BS, CS. Impact on childhood mortality of interventions to improve drinking water, sanitation, and hygiene (WASH) to households: Systematic review and meta-analysis. *PLoS Med* 2023.
245 Macura B, Del Duca L, Soto A, *et al.* PROTOCOL: What is the impact of complex WASH interventions on gender and social equality outcomes in low- and middle-income countries? A mixed-method systematic review protocol. *Campbell Systematic Reviews* 2021; **17**: e1164.
246 Torondel B, Sinha S, Mohanty JR, *et al.* Association between unhygienic menstrual management practices and prevalence of lower reproductive tract infections: a hospital-based cross-sectional study in Odisha, India. *BMC Infect Dis* 2018; **18**. DOI:10.1186/S12879-018-3384-2.
247 Jasper C, Le TT, Bartram J. Water and sanitation in schools: a systematic review of the health and educational outcomes. *Int J Environ Res Public Health* 2012; **9**: 2772–87.
248 Kulak M, Shah N, Sawant N, Unger N, King H. Technology choices in scaling up sanitation can significantly affect greenhouse gas emissions and the fertiliser gap in India. *Journal of Water Sanitation and Hygiene for Development* 2017; **7**: 466–76.
249 Van Eekert MHA, Gibson WT, Torondel B, *et al.* Anaerobic digestion is the dominant pathway for pit latrine decomposition and is limited by intrinsic factors. *Water Science and Technology* 2019; **79**: 2242–50.
250 Barreto ML, Genser B, Strina A, *et al.* Effect of city-wide sanitation programme on reduction in rate of childhood diarrhoea in northeast Brazil: assessment by two cohort studies. *Lancet* 2007; **370**: 1622.
251 McNicol G, Jeliazovski J, François JJ, Kramer S, Ryals R. Climate change mitigation potential in sanitation via off-site composting of human waste. *Nature Climate Change 2020 10:6* 2020; **10**: 545–9.
252 Ryals R, McNicol G, Porder S, Kramer S. Greenhouse gas fluxes from human waste management pathways in Haiti. *J Clean Prod* 2019; **226**: 106–13.
253 Russel KC, Hughes K, Roach M, *et al.* Taking Container-Based Sanitation to Scale: Opportunities and Challenges. *Front Environ Sci* 2019; **7**: 1–7.
254 Grolle K, Ensink J, Gibson W, Torondel B, Zeeman G. Efficiency of additives and internal physical chemical factors for pit latrine lifetime extension. *Waterlines* 2018; **37**: 207–28.

255 Schmidt W, Haider I, Hussain M, *et al.* The effect of improving solid waste collection on waste disposal behaviour and exposure to environmental risk factors in urban low-income communities in Pakistan. *Tropical Medicine & International Health* 2022; **27**: 606–18.
256 Pardo G, Moral R, Aguilera E, del Prado A. Gaseous emissions from management of solid waste: a systematic review. *Glob Chang Biol* 2015; **21**: 1313–27.
257 Cairncross S, Feachem R. Environmental Health Engineering in the Tropics, Third. Abingdon, Oxon; New York, NY: Routledge, 2018 DOI:10.4324/9781315883946.
258 The Global Commission on Adaptation. Adapt Now: A Global Call for Leadership on Climate Resilience. 2019.
259 Sachs JD, Schmidt-Traub G, Kroll C, Durand-Delacre D, Teksoz K. SDG Index and Dashboards Report 2017. New York, 2017.

Panels

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 are responsible for around 12% of all emissions in 2019. Even more strikingly the top 1% emit on average 110 tonnes annually and contribute 17% of all annual emissions.[230] 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, which may mean increased consumption by those in areas with currently low emissions.[231] Depending on how health benefits are valued by society, keeping global temperature rises to well under 2°C may 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 (e.g., USA, Europe, Japan) implement deep cuts in GHG emissions primarily for reasons of global efficiency or climate justice, while other nations (e.g., India and China) act primarily to capitalise on health co-benefits.[232] In practice nations are likely to act from a range of motivations, including near 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 relatively low environmental footprints (and see WebAppendix A9).[233] The policies and procedures implemented in these nations could help to guide equitable climate action and the lessons from their relative success should assessed.[193]

Vulnerability to the impacts of climate change is closely linked to gender inequality and so addressing this inequality can promote increased resilience for disadvantaged populations while making progress on global development and climate goals.[20] 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 certain climate mitigation actions. There is a growing body of evidence outlining how marginalised and vulnerable populations are at greatest risk of climate breakdown.[234] 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.[234] Policies must ensure that marginalised and vulnerable populations are protected and account for unintended consequences.

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.[235] Due to large scale phasing-out of coal plants across Europe, the United States, and China, over 4 million coal workers have lost their jobs.[236] 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.[236] A shift to renewable energies therefore has profound impacts on coal mine workers and communities, although such impacts are not always evenly distributed.[237] For example, in China, coal mine workers employed by state-owned companies were provided with relocation and retirement plans, whereas workers from private mine companies were made redundant without assistance or adequate compensation.[237] The negative consequences for employees can therefore 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.[238]

Panel 3. Tackling CH4 (methane) emissions while improving sanitation

Actions on sanitation were also absent from the umbrella review. Sustainable waste and sanitation actions are closely linked to the circular economy and urbanisation. Solid waste (refuse generated as a by-product of household, public and commercial processes) dumpsites are thought to contribute 20% of global CH_4 emissions and 11% of black carbon due to anaerobic decomposition and burning.[239] There is good evidence for health benefits arising from the adoption of household sanitation, including on-site waste-disposal (e.g. pit latrines) and off-site disposal (transport and storage through sewerage systems) or container based approaches[240] (and see sanitation case study – Surat, India in WebAppendix A7). Analyses of multiple large-scale trials, observational studies and natural experiments, suggest 30% reductions in reported diarrhoea from well-designed sanitation actions.[241,242] Sanitation promotion with a community-level component is able to significantly reduce levels of open defaecation by encouraging access to, and use of, latrines at the household level (household or unshared sanitation),[243] leading to 50% fewer diarrhoea deaths in childhood.[244] Other benefits from improved sanitation have been reported, especially for women and girls, including safety and psychosocial health,[245] improved menstrual hygiene reducing urinary tract infections[246] and improved school attendance.[247]

Choice of technology may have important implications for GHG 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.[248] However, concerns have been raised about the potential GHG emissions arising from standard pit latrines, which use anaerobic decomposition releasing CH_4, a major source of global heating, and may comprise 7% of emissions in India.[248,249]

One solution is to increase coverage of sewerage systems, which is a priority in many urban areas and known to be beneficial for health,[250] but limited by infrastructure costs of household sewer connections. Other solutions include composting, which uses aerobic decomposition,[251] and container-based sanitation, where container pits are transported off-site for central processing,[252] but is costly to scale up and requires road access.[253] CH_4 production can be reduced through source separation of urine and faeces, such as dry desiccating toilets (composting latrines with urine diversion).[115] Digestors (e.g. bacteria, macro-organisms) have been developed to prolong the lifetime of the pit, enhancing its use.[254] The CH_4 produced by these approaches can also be captured and stored as biogas, for use as a clean fuel.[248] 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 GHG and health benefits at scale in field trial settings, is under-researched.

Depending on the type of solid waste and context, sanitary management may 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.[255] 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 over 70% each.[256] The value to agriculture of composting 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.[257]

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

- Interventions assessed in reviews are highly heterogenous 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/exposure and may not include all GHGs, which prevents accurate quantification.
- Even where studies provide a baseline measure of GHG 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 GHGs such as N20 have relatively neglected in research[33] and further studies are required to improve dose-response relationships.
- Only a few studies assess synergies and trade-offs either within a sector, between sectors and on other environmental outcomes.
- There are major gaps in data (both modelled and implemented) from LMIC 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 GHG 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-benefits 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 (e.g. 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.[20]

Panel 5 - Principles of the proposed Coalition

1. Implementing rapid reductions in GHG emissions consistent with the Paris 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, 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 rulebook for emissions and standard approaches to estimating changes in health-related exposures, determinants, and/or outcomes as well as the costs of action and wider social impacts (e.g. employment, poverty).

4. Supporting mutual learning - e.g. Agreement to share lessons - including barriers and facilitators of success - and resources such as training materials and courses, technical manuals, decision support aids etc. Communicating lessons learnt to their constituents /members, combatting misinformation where necessary.

Figures

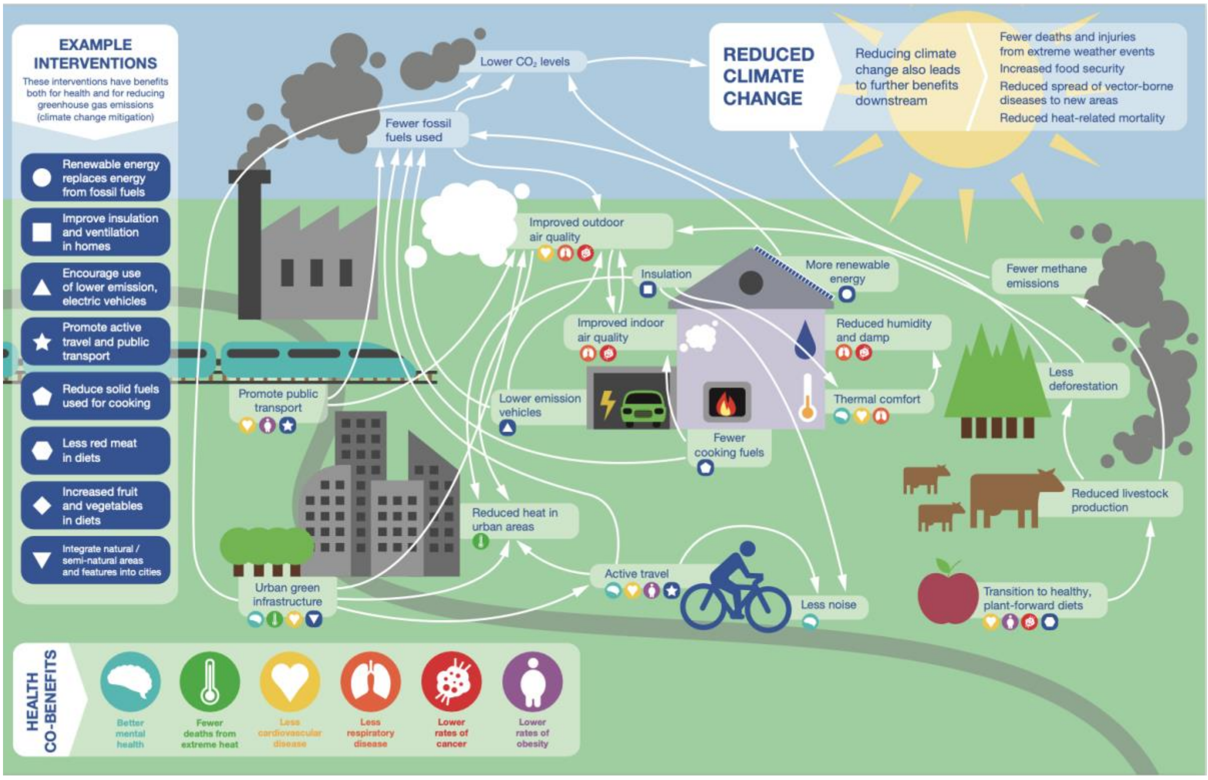

Figure 1 - Key pathways and connections between climate mitigation actions and health.

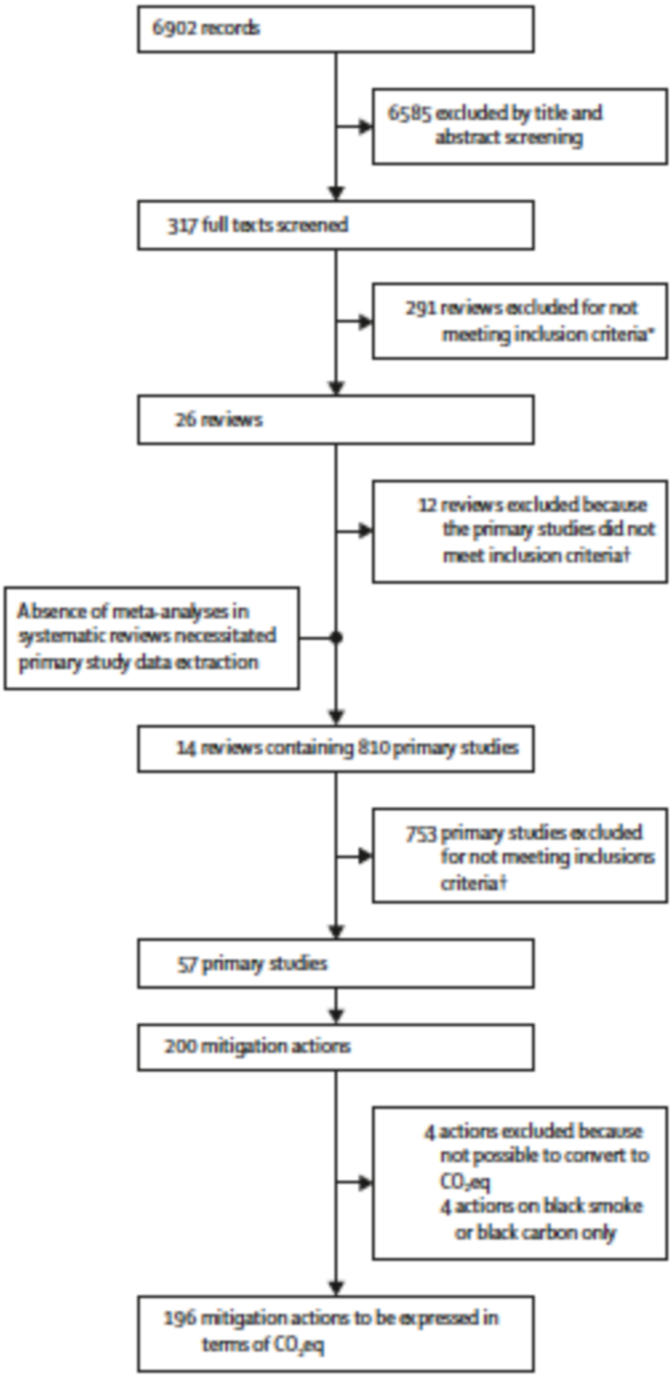

Figure 2. Flow diagram of search strategy from the umbrella review. *Excluded due to lack of quantitative estimates of both changes in GHG emissions and health outcomes. **Excluded due to insufficient context to enable scale up, lack of baseline measures, health measures which couldn't be converted to YLL, amongst other reasons.

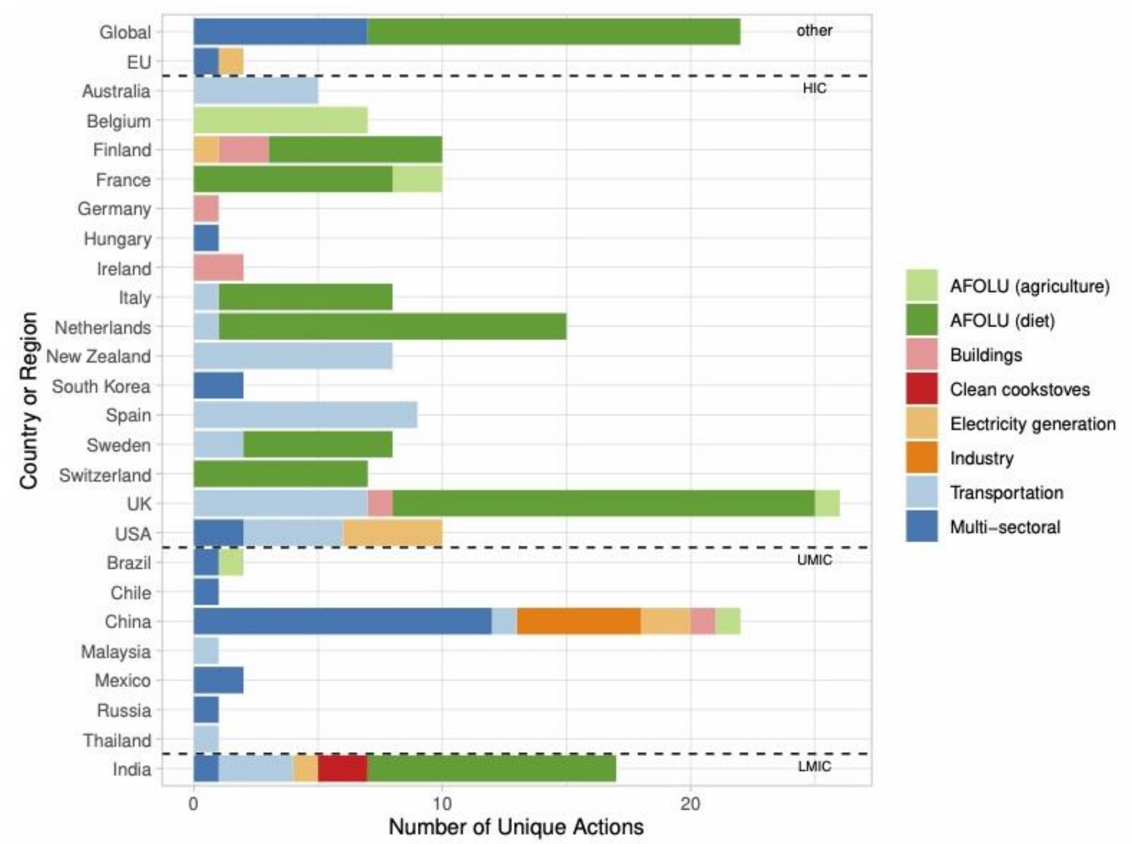

Figure 3. Number of unique mitigation actions studied in each country by sector. Note that these actions include those reducing black smoke and black carbon.

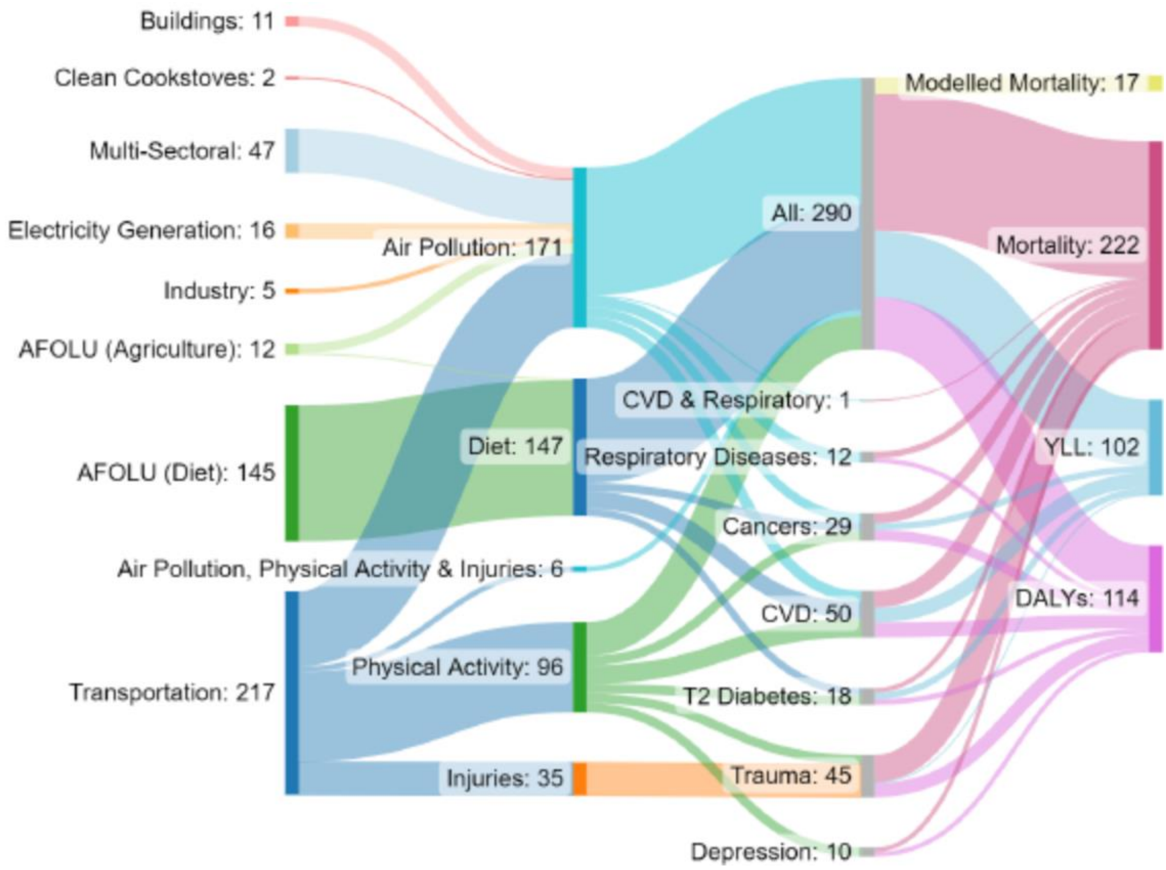

Figure 4. Numbers of mitigation actions across sectors (left) and their associated pathways (centre) to health outcomes (right). The figure shows all pathways to health outcomes, rather than unique actions. CVD = cardiovascular disease; DALY = disability-adjusted life-years. 'Air pollution, Physical activity & Injuries' is 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.

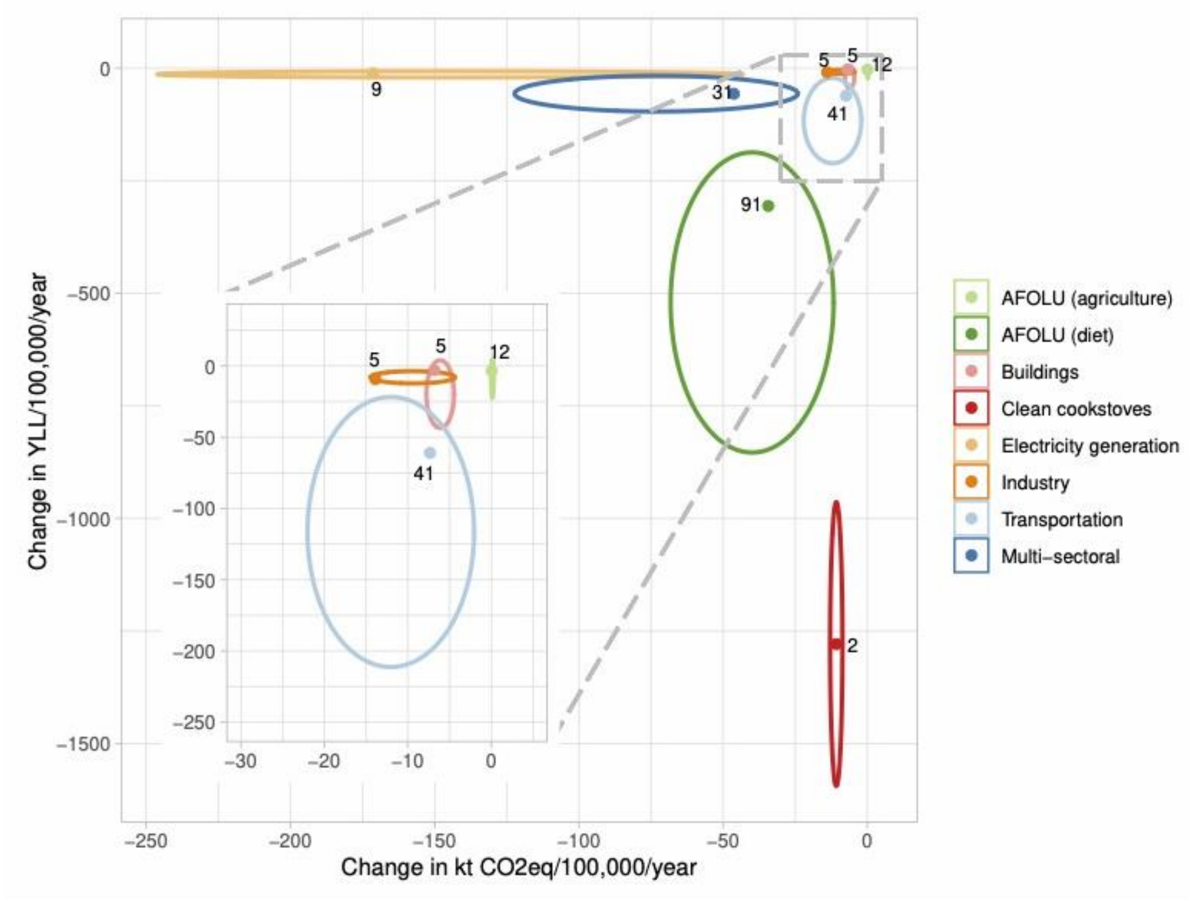

Figure 5. Climate and human health impacts of mitigation action by sector. Ellipse height and width corresponds to the interquartile range for each sector's change in health co-impact intensity (YLL/100,000/year) and carbon mitigation intensity (Kt CO_2eq/100,000/year), respectively, while the plotted points are the median, and the numbers indicate the number of actions. Annotated numbers represent the number of actions from each sector. Some estimates of environmental impact could not be converted to CO_2eq (e.g. black carbon and black smoke), hence fewer actions for the buildings and transportation sectors.

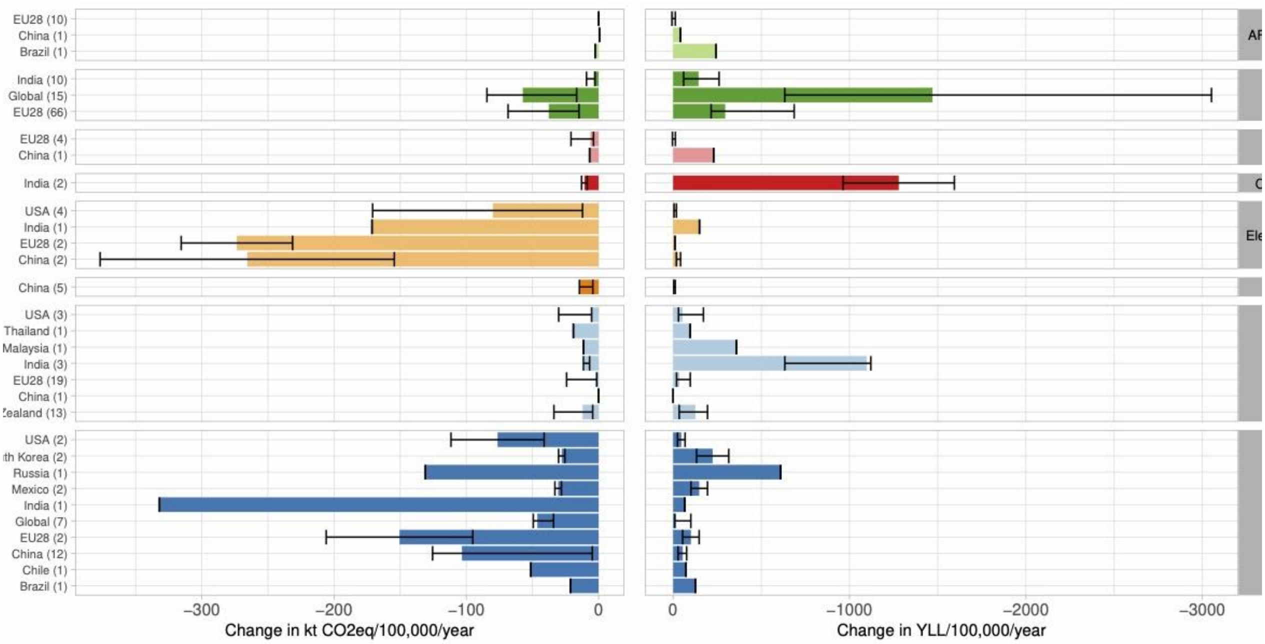

Figure 6. Variation in Carbon mitigation intensity across sectors. Median change in Kt CO_2eq /100,000/year and Health Co-Impact Intensity – change in YLL/100,000/year (i.e. Years of life gained), compared to business as usual, split by country context. The black bars represent the inter-quartile range for estimates. Number of actions given in brackets.

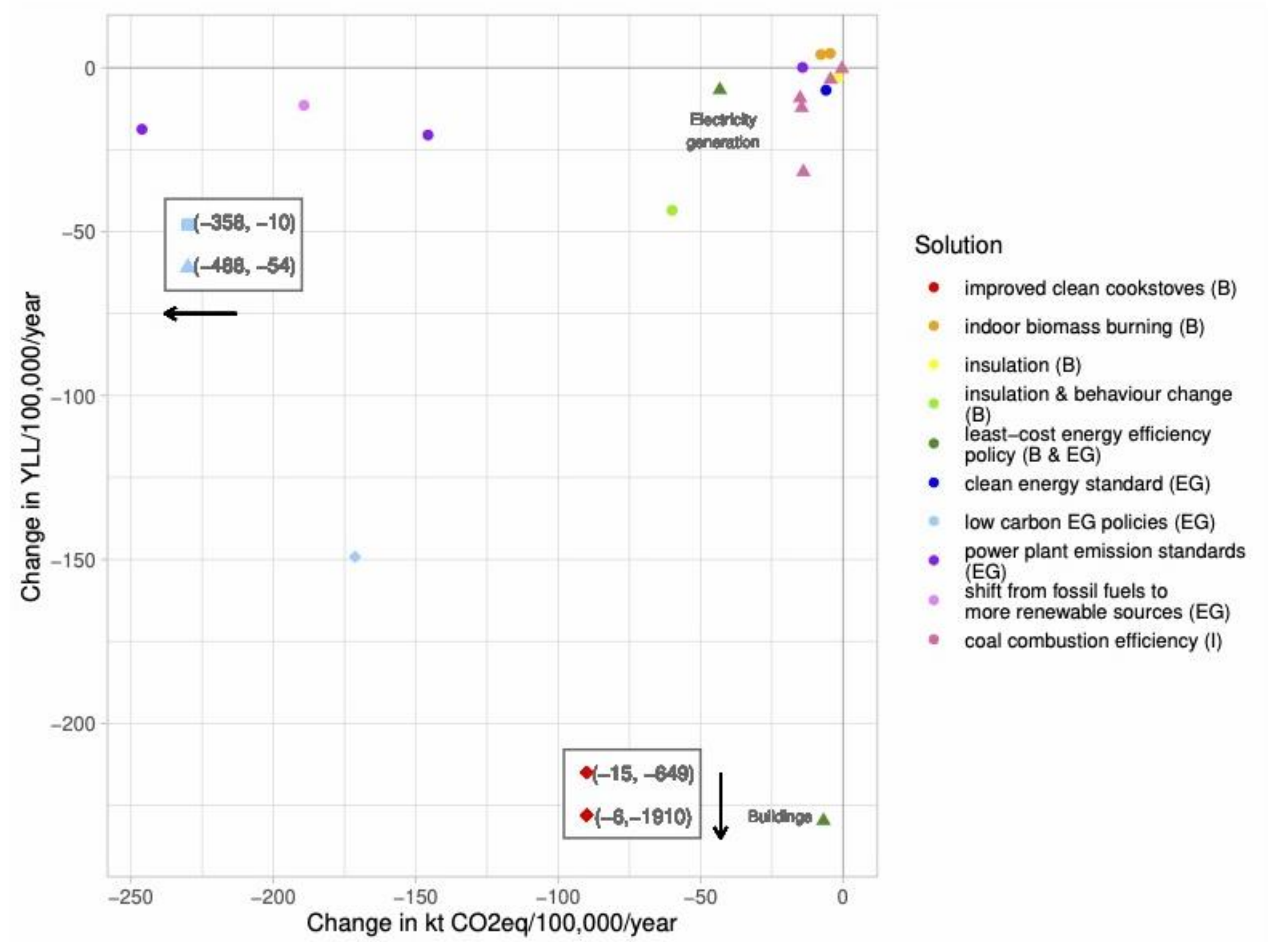

Figure 7. Climate and human health impacts of mitigation action in the electricity generation (EG), buildings (B), and industry (I) sectors. These sectors were grouped in one graph as they all actions involve changing energy use. The different shaped points represent different types of country: circle = HIC; triangle = China; diamond = India; square = EU. Note differences in the vertical scale for changes in YLL when making comparisons between sectors.

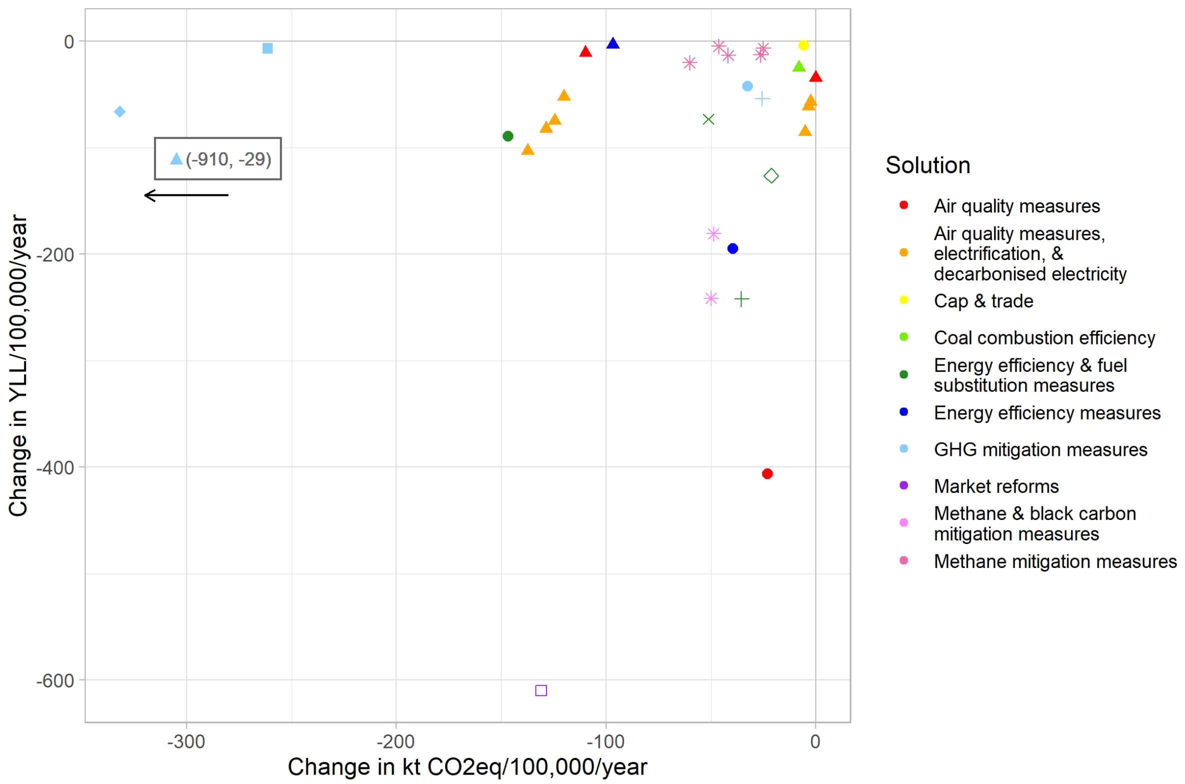

Figure 8. Climate and human health impacts of mitigation action from multi-sectoral actions. The different shaped points represent different types of country: circle = HIC; open diamond = Brazil; cross = Chile; triangle = China; plus = Mexico; open square = Russia; star= global; diamond India. Note differences in the vertical scale for changes in YLL when making comparisons between sectors.

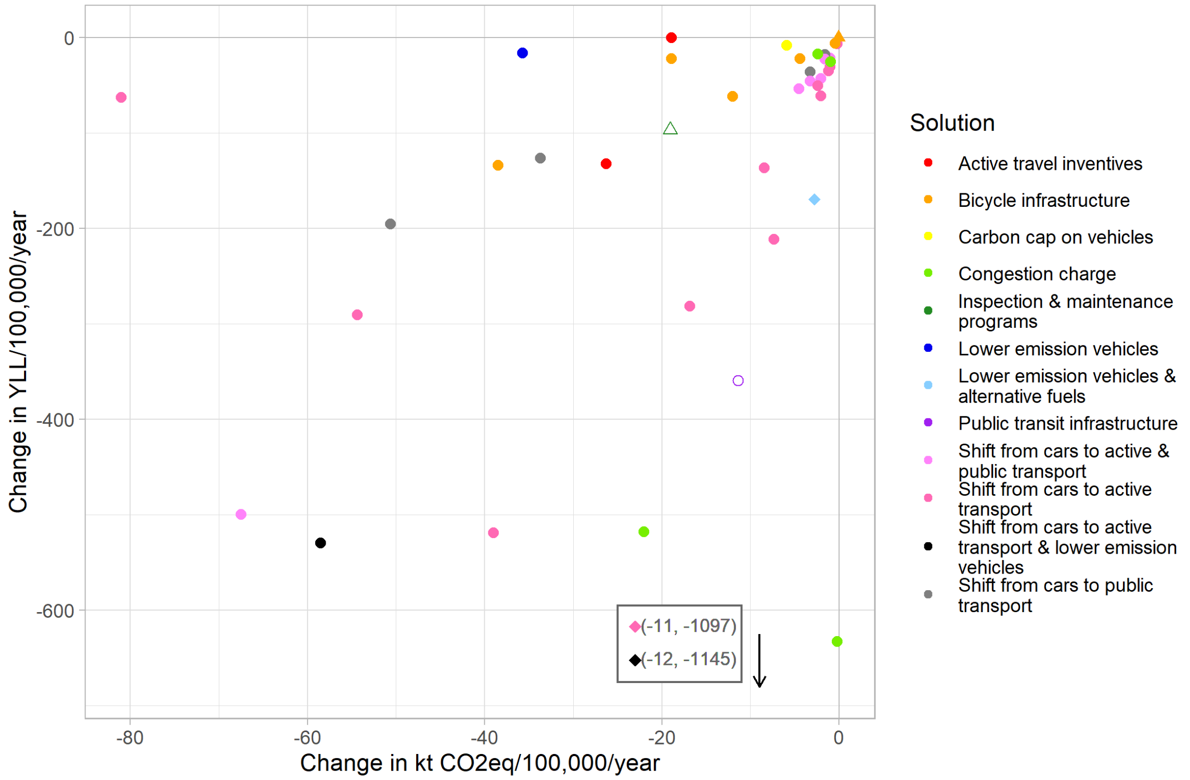

Figure 9. Climate and human health impacts of mitigation action in the transport sector; The different shaped points represent different types of country: circle = HIC; triangle = China open circle = Malaysia; open triangle = Thailand; diamond = India Note differences in the vertical scale for changes in YLL when making comparisons between sectors.

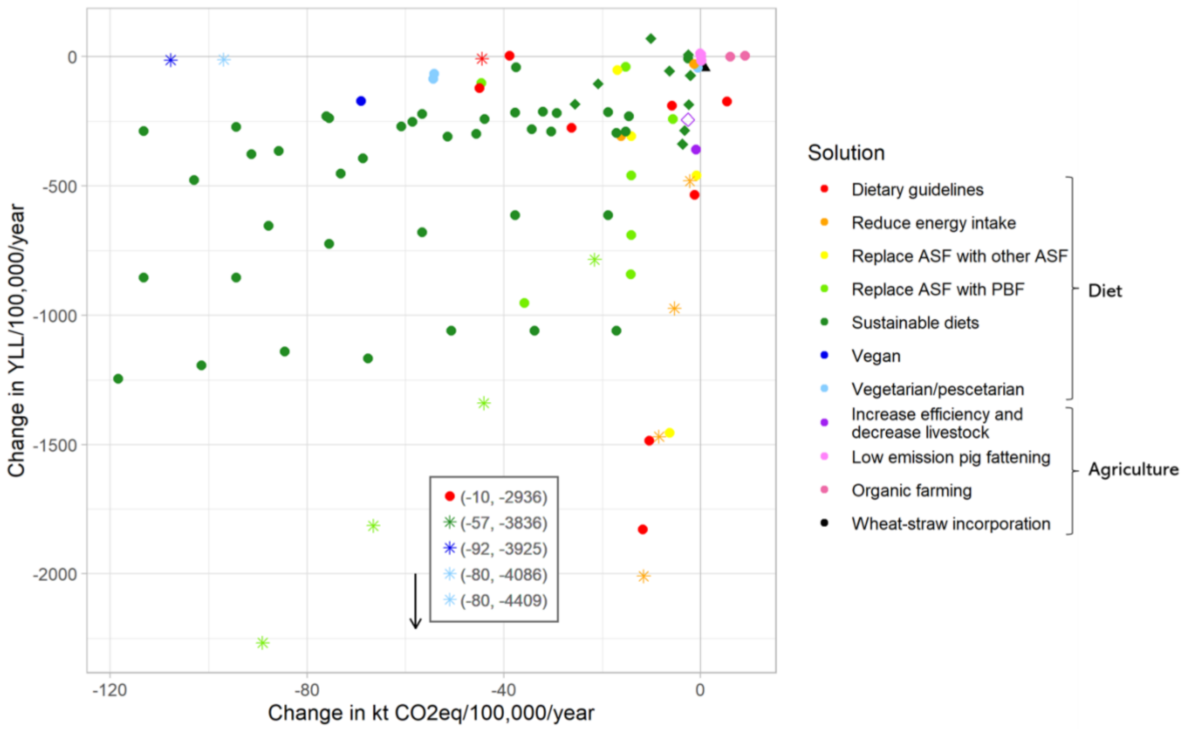

Figure 10. Climate and human health impacts of mitigation action in the AFOLU sector. The different shaped points represent different types of country: circle = HIC; open diamond = Brazil; triangle =

China; star= global; diamond = India. Note differences in the vertical scale for changes in YLL when making comparisons between sectors.

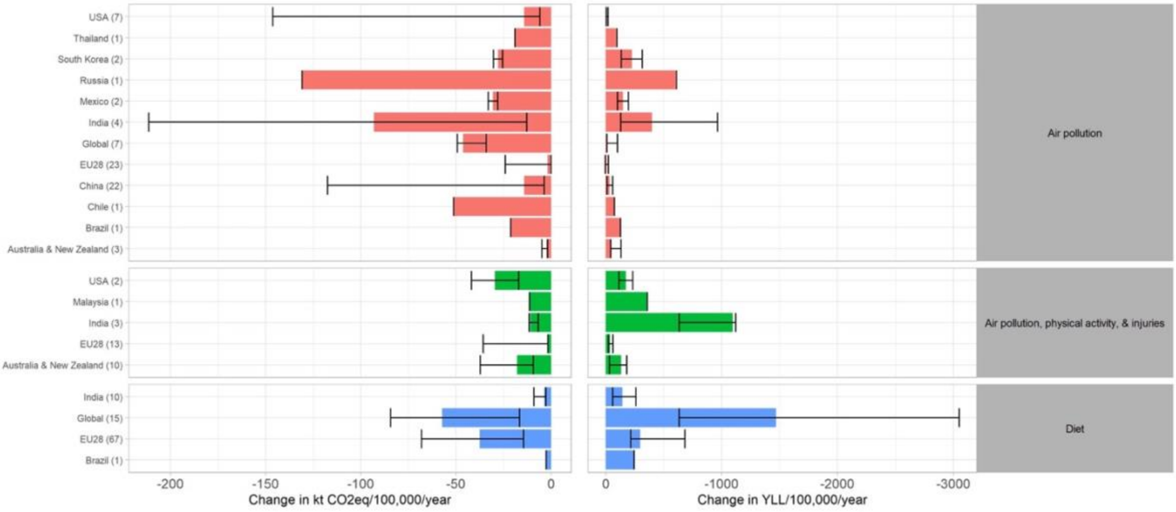

Figure 11. Variation in Carbon mitigation intensity across different health co-impact pathways. Median change in Kt CO_2eq/100,000/year and Health Co-Impact Intensity – reduction in YLL/100,000/year (i.e. Years of life gained), compared to business as usual, split by country context. Error bars represent the inter-quartile range for estimates. †Health pathway is a combination of two or more of: air pollution; physical activity; or injuries. Number of actions given in brackets.

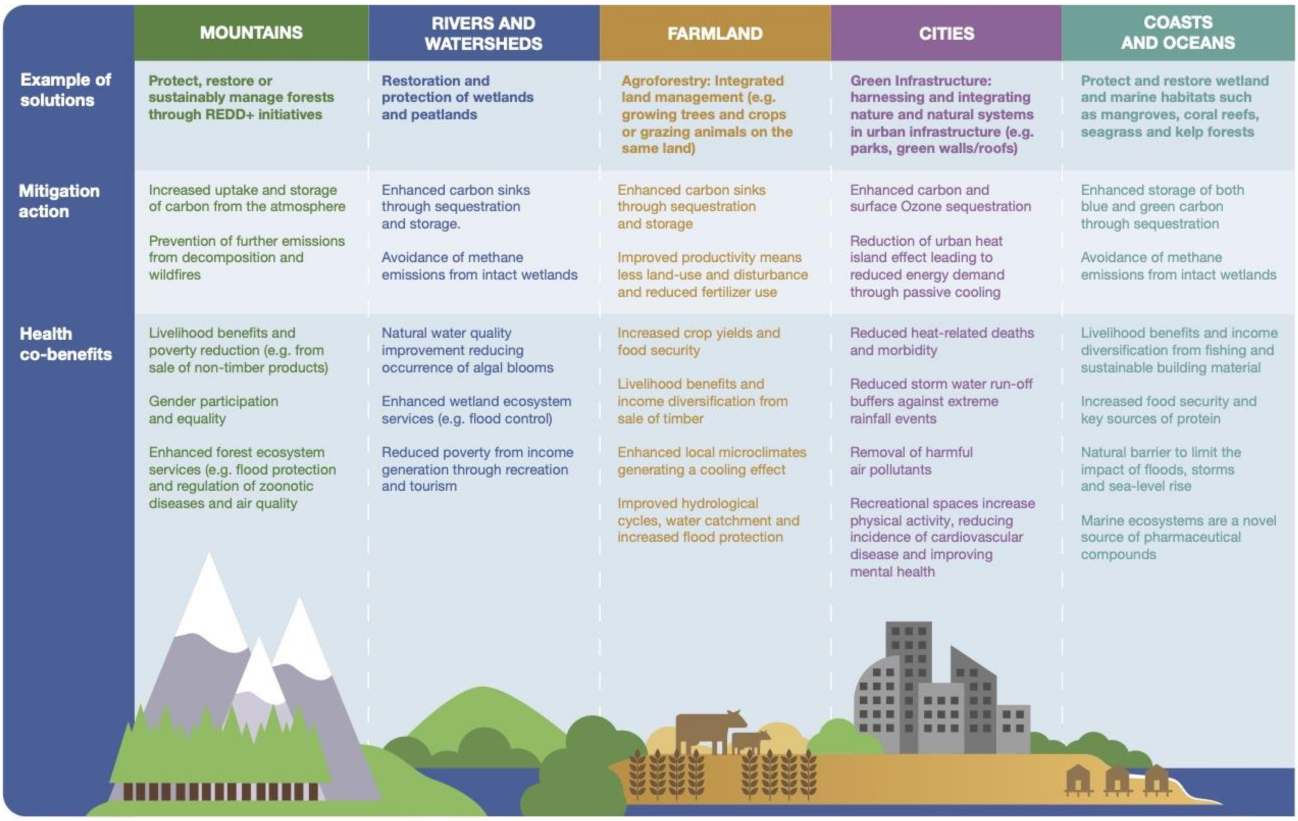

Figure 12. Pathways to health and equity from nature-based solutions adapted from The Global Commission on Adaptation.[258]

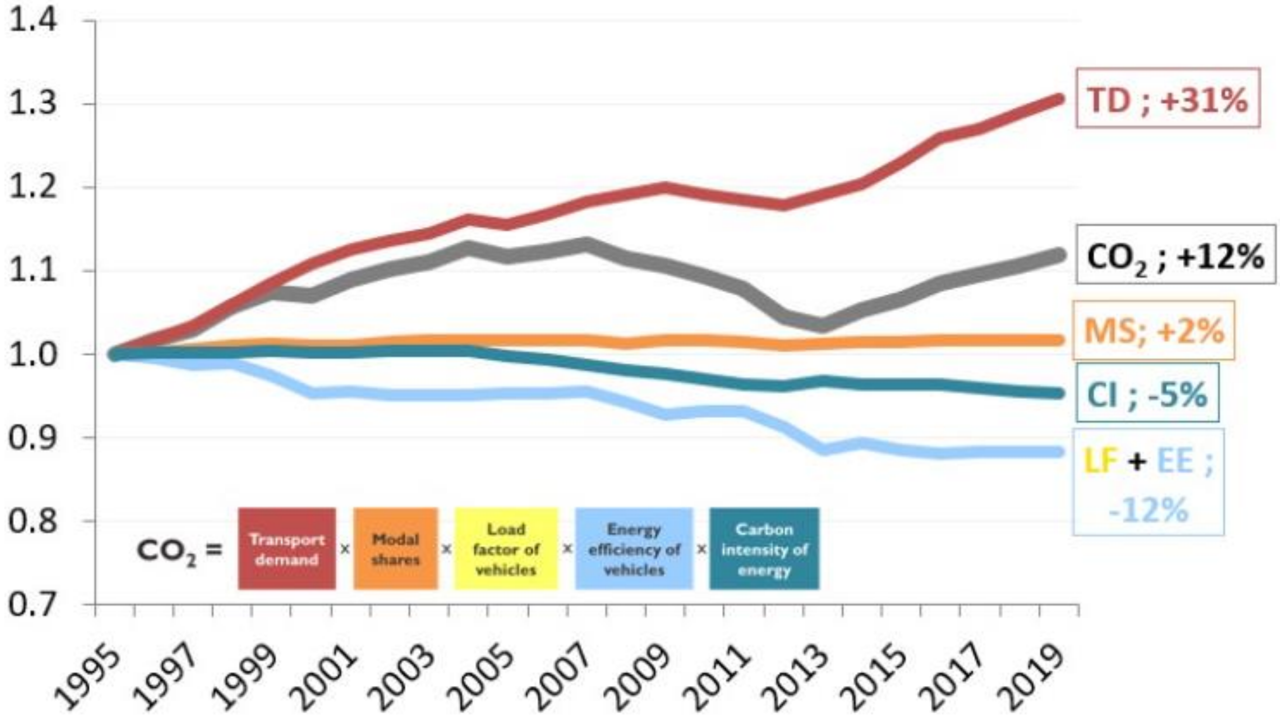

Figure 13. Drivers of emissions in the European transport sector. Decomposition of the evolution of CO2 emissions from EU passenger transport, from 1995 to 20196. CO2 = Transport Demand X Modal Share X Load Factor of Vehicles X Energy Efficiency (EE) of Vehicles X Carbon Intensity. Reproduced with permission from Enerdata[185]

Figure 14. Proposed Irish transport policies classified by transformative potential and intent using the Systems Innovation for Net Zero approach. In short this is a 3-point process to 1. *Envision* the goal(s) of a well-functioning system and challenge the mental models guiding systems towards

different ends. 2. *Understand* why the current systems is not achieving envisioned goals and assess the potential of implemented and planned policies to redesign the system. 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 OECD [192]

Glossary

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

- *Decarbonisation is technically just carbon reduction but often used to mean reductions of all GHGs here we use it in its widest context.*

- *Nature Based Solutions* - 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'[60]

- *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.[259]

- *Efficiency: is about the continuous short-term marginal technological improvements which allow doing more with less in relative terms without considering the planetary boundaries,*

- *Transformative change as "the situation in which – by changing its goals and dynamics – the system achieves different results than the system of the past"*

- *Incremental change as "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."*[184]