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

Web Appendix

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

Introduction

There are various classifications, categorisations and frameworks used to map climate change mitigation actions and their health impacts[15,60,260,261] These are not designed for research focussing on implementation, political economy aspects and on *how* actions work, and for whom. For example, it is often unclear what constitutes an action or intervention and its main components, and inequalities in outcomes are often neglected. The lack of a comprehensive framework hampers mutual learning and research that engages with context and implementation aspects. As part of the Pathfinder Initiative a framework was developed that was designed to capture evidence from across all sectors with a focus on implementation of climate change mitigation actions and its impacts on health.

Aims

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

Methods

To design this process, we have developed a set of steps combining framework synthesis and participation from experts and stakeholders, in an approach similar to those adopted by recent studies. For the elements of the framework involving discussion and consultation, we were able to draw on a large international network of project partners and participants in the Lancet Pathfinder Commission. The main methodological steps are shown in Table A1.1

Table A1.1 Steps in the elaboration of the framework

Steps	Methods	Outputs
Step 1. Provisional Framework and classification	• 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 (see **Error! Reference source not found.**). When this was not available, we relied on national-level or research classifications. Organisations: IPCC, Drawdown, Ocean Panel, EU commission, OECD, C40, WHO These were selected based on the researchers' and partners' expertise. • Feedback from partners and Commissioners (1 session each, done in 2020)	- Provisional classifications of actions (what is implemented), strategies (how) and outcomes (with emphasis on distribution) (DONE)
Step 2 Academic framework review and synthesis	Additional review of recent academic frameworks and typologies incorporating both climate and health – (to be completed) See Appendix1 for search strategy Comparison between institutional (Step 1) and academic (Step 2) frameworks and typologies. Synthesis of existing frameworks and typologies	- Provisional framework
Step 3. Piloting and structured expert feedback	Partners to map evidence from 2 or 3 of their own (or provided) case studies each into proposed categories and give brief written feedback on • Perceived usefulness of framework • Unclear concepts or categories • Suggested changes Potentially: Volunteer commissioners to give brief structured feedback as well	- Summary of suggested changes
Step 4. Preliminary framework	Researchers to discuss feedback from exercise and reach a consensus on a preliminary (as opposed to "provisional") framework, which will support screening and mapping of evidence gathered from a call for "case studies" or examples on mitigation and health	- Preliminary framework, to support screening and mapping of evidence
Step 5. Reliability assessment and final framework	Re-assess framework and check inter-reliability. When enough case studies have been analysed to provide codes for each of the main domains, inter-rater reliability can be assessed and any adjustments can be made. (Eg. Categories can be combined or other categories can be added)	- Reliability assessment. - Final classification and mapping framework.

Provisional framework

The provisional framework is described in Figure 3 of the Commission report. The different concept and basic typologies are described in this section.

Context

Given the focus of this framework, we consider context to include drivers of climate change action and structural determinants of health based on WHO CSDH expanded to include environmental aspects[262]:

Context includes:

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

We are interested in how the context generates

- Barriers and opportunities
- Context-intervention interactions

Actors

This category reflects **<u>who</u>** is influencing, designing, implementing the action and strategy. It is kept provisionally but might be removed if not judged useful for evidence mapping.

Climate change mitigation action: Solutions and strategies

Mitigation solutions

This category reflects **<u>what</u>** is being done to mitigate climate change and improve health.
We define mitigation solutions as broader categories (See Table A1.2), each containing broader specific solutions, for example:

- Summary solution category: Shift to renewables.
- Specific solution: Small-scale solar panels and wind farms.

A summary classification of mitigation solutions has been elaborated based on a list of specific decarbonisation solutions, as described in this section. This bottom-up approach to defining categories allows for added flexibility and re-definition, for example in cases where specific solutions within a category have substantially different health impacts, or where additional detail might be wanted.

Mitigation strategies are also classified according to the sector they target, and whether they are primarily "demand-side" (aiming to change consumption patterns), or "supply-side", addressing production processes. Systemic solutions are classified separately. These are actions that adopt a system-wide or sectoral approach. This can be the case of a cross-sectoral carbon tax, or a package of interventions that complement each other across housing, transport and green spaces, for example.

The provisional detailed list of specific solutions for climate change mitigation has been compiled drawing on key existing resources which complement each other in terms of coverage. Development of the research framework was based on a review of existing classifications and frameworks for climate change mitigation actions and health outcomes used by institutions involved in designing or influencing climate policy at an international level including IPCC[60], Drawdown[263], OECD[61] and WHO[62]. The framework also draws on specific resources for classification of behavioural solutions[63], ocean-based solutions[64], the health and education sectors[65,66] and urban nature-based solutions[67].

The resulting list is broad and comprehensive but not meant to be exhaustive. It is used as the basis of the summary classification of climate mitigation solutions, described below. The detailed solutions list will be retained in the framework to provide examples for users and illustrate the scope of each broader "strategy". The (non- exhaustive) list of mitigation solutions used to compile the Mitigation Strategies classification is in the supplementary file 1 [Tab 3, Col G]. In the "framework synthesis" step, the current provisional classification will be compared and combined with existing typologies developed in peer-reviewed publications.[260,261]

Table A1.2. Summary classification of mitigation solutions.

Coverage	**Solution categories*** (*Some of these might have potential negative health impacts)
System-wide and cross-sectoral interventions	
Energy	Renewable energy technologies
	Improved energy storage, use and distribution
	GHG capture and storage
	Increased energy efficiency of buildings and appliances
	Clean cookstoves
	Replace fossil fuel energy by Nuclear
Transport	Alternatives to cars
	Reduced demand for travel
	Energy-efficient transportation
	Electric/Hydrogen transportation
	Biofuel, Diesel, (CNG)
AFOLU-Oceans	"Sustainable" intensification of agriculture/aquaculture/fisheries
	Agro-ecology
	Nature-based solutions/non-urban (E.g. Restoration and conservation of forests and other ecosystems, peatland rewetting, tree plantation in degraded land, protecting indigenous peoples' forest tenure)
	Low-emissions diets-Incl. plant-rich diets (within recommended dietary guidelines), dietary shift towards low-carbon ocean-based products,
	Reduced household food waste
	Use of e-commerce food delivery
Industry	Switch to materials less intensive in GHG emissions
	Improved resource management, including recycling
	Reusing and managing industrial process emissions incl. carbon capture and storage
	Reduce consumer waste
	Reduced product demand
Human Settlements	Infrastructure changes enabling behaviour change
	Nature-based solutions for urban areas

Health-care and Education	Promote voluntary family planning
	Education for climate empowerment
	Women's access to education
	Sustainable health care

Strategies for implementing solutions

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

Table A1.3. Types of mitigation strategies

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

Health impact pathways

Pathways are the mechanisms through which the solutions and strategies described above (which we can jointly refer to as "climate mitigation actions") affect human health.
Health impact pathways result from implemented actions, directly or indirectly and inc[262]lude unintended consequences (trade-offs or spill-over effects). They can be initially hypothesized as resulting from the interaction between climate mitigation action, contextual structural factors and intermediate determinants of health, resulting in a specific pattern and magnitude of health outcomes. These are classified and completed based on the social determinants of health framework,[262] combining to an extent with the OECD Wellbeing framework.[61]

Impact pathways include effects through:

a) Environmental quality and fragility (See Section 1. Context)
b) Other structural determinants of health (See Section 1. Context)
c) Social inequities (See Section 1. Context)
d) Intermediate determinants of health (See section 5. Outcomes)
e) Health feedback loops (from health outcomes and health inequalities to stratification and social determinants of health)

*Intermediate determinants of health are included as outcomes, as we probably have data to extrapolate health outcomes from them. In cases where they don't qualify as an outcome they can still be included as part of the hypothesized pathway.

Outcomes

This section refers to environmental, socioeconomic and health outcomes. (Socioeconomic outcomes are of interest particularly as mediators of physical and psychological health). The resources summarised in **Error! Reference source not found.** are used to inform a preliminary classification of outcomes and risk factors. The typology of environmental outcomes will be further disaggregated following the framework synthesis step. Specific health pathways, risk factors and outcomes can be mapped onto this:

a) Environmental Impacts (typology to be developed)
    - Mitigation effects
    - Implications for climate change adaptation (not within the scope of the study but identified as crucial trade-offs, synergies or constraining factors)
    - Other significant environmental impacts. These can include, for example, biodiversity loss or change, waste, water, air and soil quality.
    - Basic environmental justice principles ("polluter pays")
b) Intermediate determinants of health (Combining CSDH and OECD while maintaining theoretical coherence)
    - Material and environmental circumstances – Capabilities
        - Income and wealth/poverty
        - Work and Working Conditions
        - Housing
        - Nutrition Security
        - Environmental quality
        - Safety
    - Psychosocial Factors

Measuring climate change mitigation action and health

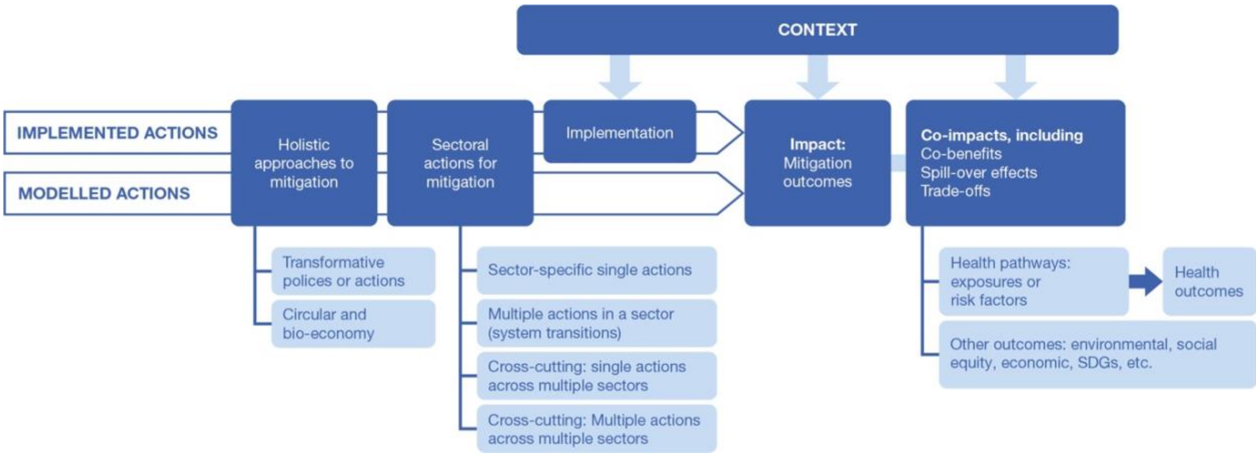

Figure A1. GHG mitigation and health research framework. Climate change mitigation efforts can affect health through complex mechanisms, involving ancillary effects of mitigation (e.g., improvements in air quality), as well as other impacts resulting from the regulations, instruments and strategies employed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

A2: Implemented Actions to Reduce GHG Emissions and Benefit Health

Partnership with existing data holders and an open call for evidence

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

Drawing on the systematic search of two studies

Our second source of documentary evidence came from two systematic searches that were conducted for two studies that aimed to systematically review the evidence for related aims. The first was the umbrella review discussed above, developed by the Pathfinder Initiative. We reviewed the reference lists and data extracted for the umbrella review to identify relevant primary studies that could serve as further examples. The second was a systematic review conducted using machine learning, which employed a broad search strategy to identify all the literature that discussed climate and health. The search yielded more than 16,000 studies and included studies on the impact of climate change on health, as well as health as co-benefits to climate change adaptation and mitigation actions. Studies were given a relevance score from zero to one for each of the three categories, zero being of least relevance and one being of highest relevance. We ordered the relevance score and began screening studies from highest to lowest relevance. No new studies were identified beyond the relevance score of 0.5, and a decision was made to stop screening at relevance score 0.3.

Hand search

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

A3: Expanded harmonisation from Umbrella Review.

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

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

For NOx and PM2.5 reported in change in kg, we used an adapted version of the CaRBonH tool also developed for WHO Europe. This tool is able to convert emissions of NOx and PM2.5 directly to deaths and YLL by estimating changes in exposure not only in the emitting country but also neighbouring countries in 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 60 primary studies (mostly agricultural studies) which were initially extracted were removed from the analysis at this stage due to the available tools not being able to model NO and NO_3.

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

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

Additional information we collected was:

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

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

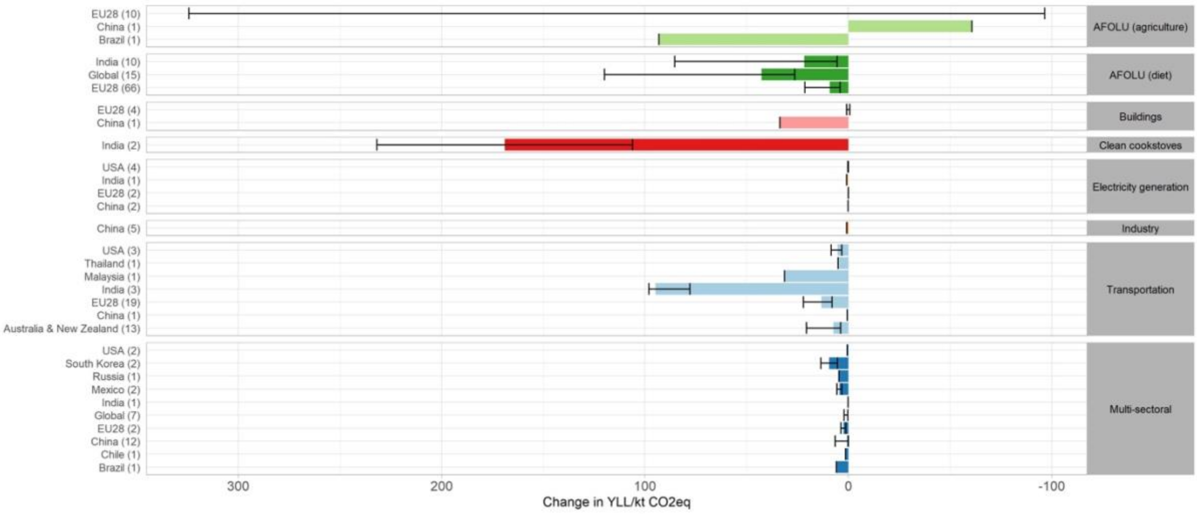

Figure A3.1. ratios of health co-impacts to mitigation potential for each action, i.e. the amount of years of life gained per tonne of greenhouse gas emissions avoided

A4: Umbrella Review - Excluded Studies

78 studies were excluded after data extraction for either not having enough information to scale up to the National level (e.g. small-scale soil incubation studies), not having a clear 'business as usual' (such as a standard fertiliser level), or for having health data that we could not model to YLL (such as NO and NO3). Of these, 58% were from HICs, 35% were from UMICs (primarily agricultural studies from China focusing on the release of NO or NO3), while only 3% were from LMICs (Table A3.1 and A3.2). None were from LICs, reflecting the wider lack of evidence available from, and lack of inclusion in systematic reviews of, LICs. Compared with the proportion of UMICs included in our review, a large proportion were excluded after data extraction. However, this is likely due to the type of data they collected – mostly farm level studies measuring gases like NO and NO3 (69% of UMICs which were excluded), which we could not model to health outcomes.

Table A4.1

Sector and Scale	Count of excluded studies
Global	**3**
AFOLU	2
energy	1
HIC	**45**
AFOLU	43
Transport	2
LMIC	**2**
AFOLU	1
human settlement	1
OECD	**1**
AFOLU	1
UMIC	**26**
AFOLU	18
energy	1
industry	1

Transport	2
Transport, industry, building	4
UMIC* in 2020	**1**
AFOLU	1
Grand Total	**78**

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

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

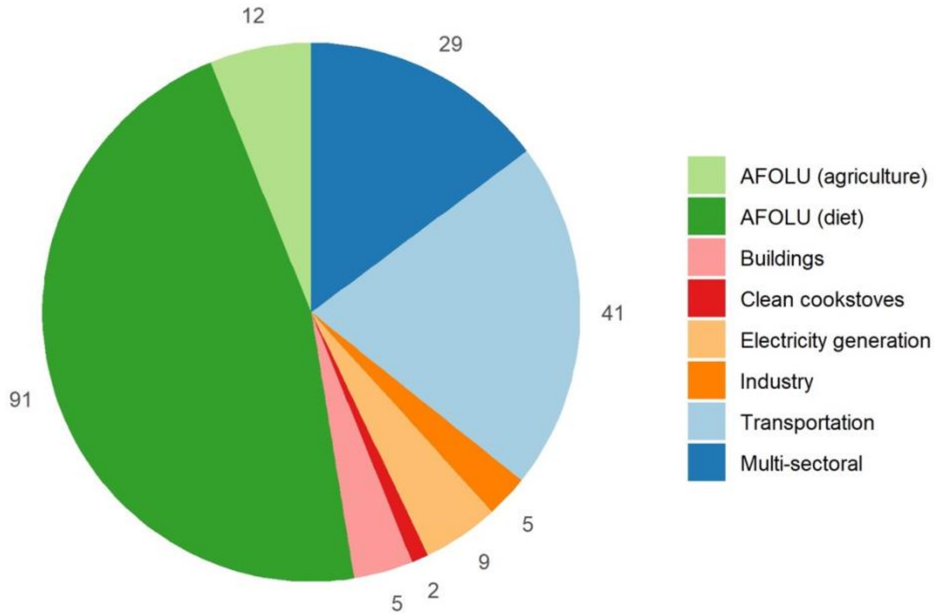

Figure A4.1. Proportion of unique mitigation actions from each sector.

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

Pathway to health	**Country income level***	**YLL/100,000/year**		**Pathway to health**	**Country income level***	**YLL/100,000/year**

Air pollution	LIC	4,540		Low physical activity	LIC	53
	LMIC	3,260			LMIC	140
	UMIC	1,882			UMIC	197
	HIC	533			HIC	219
	Global	2,482			Global	164
Dietary risks	LIC	1,093		Road injuries	LIC	929
	LMIC	2,135			LMIC	718
	UMIC	2,595			UMIC	803
	HIC	1,916			HIC	444
	Global	2,163			Global	724

A5: Example Exposure-Response Functions

Despite the large potential for GHG mitigation and health co-benefits from reduced air pollution in China,[82,236,264] our included studies did not show large reductions in YLL. Markandya (2009), however, found a health co-benefit intensity of -79 YLL/100,000/year for policies aimed at decarbonising the electricity generation sector[265] (Figure 9 Main Report). They used a stepwise log-linear and log-log model to estimate the effect of PM2.5 on mortality as in the WHO's Comparative Risk Assessment (CRA) method (this would result in over 500,000 fewer YLL country-wide at the time of study). Log-log models were proposed to avoid unrealistically high health impacts at high levels of pollution, however Pozzer et al. (2023) noted that these functions may not be representative for highly polluted regions, like China, thus underestimating the health benefits to reductions in air pollution.[80]

Peng et al. (2018), who estimated the impact of air quality measures, electrification, & decarbonised electricity across the electricity generation, transportation, and building sectors of China (Main Report Figure 10), uses ERFs based on the GBD.[266] In line with recent literature on the potential for the GBD to underestimate air pollution impacts,[80] it is likely that this, too, is an underestimate. A national energy efficiency policy in China considered by He et al. (2010) found relatively small health co-benefits[267] (Figure 10). They used the US-EPA's BenMAP model to estimate health benefits, where the ERFs were linear or log-linear.

A6: Nature Based Solutions – Methods and Full Results

This is a review of publications that conducted primary analysis to examine the mitigation potential of nature-based solutions (NBS) alongside health and socio-economic co-benefits. We used the IUCN working definition of NBS *'actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits'* (Cohen-Shacham, 2016). Natural Climate Solutions (NCS) are a subset of NBS that can be employed to limit warming by reducing atmospheric greenhouse-gas concentrations (Girardin, 2021, Griscom, 2017). They form the three steps to cooling marked by: i) protecting ecosystems and thus reducing carbon release for example by halting deforestation ii) restoring ecosystems so that they sequester carbon and iii) sustainable landscape management to reduce emissions and increase sequestration (Girardin, 2021). These solutions work alongside ambitious decarbonisation solutions discussed elsewhere in this report, offer the greatest contribution to carbon mitigation to limit temperature rise and achieve the Paris Agreement target of 1.5c (UNEP, 2021).

Background

This was a scoping review of publications that conducted primary analysis to examine the mitigation potential of nature-based solutions (NBS) alongside health and socio-economic co-benefits. We used the IUCN working definition of NBS *'actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits'* (Cohen-Shacham, 2016). All study designs (quantitative and qualitative) were included in the screening, as were studies where the reported outcomes were modelled or observed.

Table A6.1 summary of the source databases for NBS studies screened and manuscripts reviewed for data extraction.

Source	Screened	Full text reviewed	Included for data extraction
DFID	6	5	2
Umbrella review	24	8	0
C40	28	1	0
NBI	14	9	7
Ignition project	35	8	6
Grey literature, current reviews (tree review), WHO Evidence Synthesis	43	16	15

We identified relevant publications in the following way:

- by searching through pre-existing databases (DFID and C40) that have collated studies on actions to reduce greenhouse gas emissions. We then filtered out publications where the focus was on nature-based solutions and systematically screened for papers that reported health and/or socio-economic impacts
- by searching databases that collate studies related to NBS or the natural environment (Ignition Project and Nature Based Initiative online tool). Here we filtered out publications that reported reduction in greenhouse gas emissions as an outcome.
- by contacting specific authors to request recent updates to studies that we thought were relevant, but there was scope for more analysis to be done – for example, some of the urban ecosystem studies had quantifies a reduction in Ozone and it was plausible that follow-up studies could have also quantified CO2 reduction. Similarly, for studies that conducted qualitative assessments we inquired complementary quantitative measures.
- by following up on relevant references from the studies obtained using the above processes as well as other key publications that were deemed relevant by the project team and the commissioners (such as the WHO Synthesis of Evidence)
- the literature search was concluded when we reached a point of saturation whereby further literature search did not yield any additional studies

All manuscripts were double screened to check for measured or modelled greenhouse gas outcomes and one of more of the following: measured or modelled health outcomes, or health exposures such as air quality, or socio-economic determinants of health such as livelihood. Greenhouse gases other than CO2 were considered for in this review, in particular, Ozone mitigation potential of urban ecosystems was quantified in several studies and this was included in our synthesis under both impact on health and impact on GHG reduction. The final manuscripts were reviewed and data was extracted for a narrative synthesis. The range of study designs and inclusion of both modelled and evaluated examples precluded the possibility of conducting a meta-analysis.

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

Modelled or evaluated		Study	NBS and method of measuring mitigation	GHG Mitigation	Units	Health/SE outcomes	Notes
1	URBAN	Soares, 2011	41,247 trees in Lisbon	CO2 storage	21,030 tonnes	1) Air quality benefits from pollutant uptake (NO2, SO2, O3, and PM1O) given in kgs removed 2) decreased pollutant emissions from power plants as a consequence of energy savings 3) potential disbenefit of BVOC emissions from trees on ozone air quality 4) Increase in property value	Reduction of air pollutants = 25.6 t annually, valued at $222,738 or $5.40/tree [estimated as value that society places on clean air, as indicated by its willingness to pay for pollutant reductions]
Mixed - field inventory (tree species) and modelling			i-tree tool	CO2 sequestered	1776 tonnes per growing season		
				CO2 avoided	633 tonnes		
				Carbon released e.g. during tree maintenance or decomposition	549 tonnes (maintenance and decomposition)		

						(trade-off) 5) storm run-off reduction	
2	URBAN	Sunderland, 2012	818,000 trees in Torbay	CO_2 storage	98,1000 tonnes or 15.4 tonnes/ha	1) Air quality benefits from pollutants uptake (O_3, PM10, NO_2, and SO_2) tonnes/per year	health/well-being impacts estimated as £1.33 million per year [unclear how this was estimated]
Modelling			i-tree tool	CO_2 sequestered	3,320 tonne/year		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	959 tonnes/yr due to tree death		
3	URBAN	Millward, 2017	309 urban trees in Toronto	CO_2 storage	not reported	1) Air quality benefits from pollutant uptake (O_3, NO_2 , PM10, and SO_2) in kg/year? 2) energy savings from tree shading and wind breakers	air pollutant reduction valued at $1520 annually [estimated using the marginal cost of controlling different pollutants required to meet air quality standards] energy savings valued at $36/tree ($1190 for electricity and $9914 for natural gas)
Mixed - field inventory (tree species) and modelling			i-tree tool	CO_2 sequestered	27,201 kg/year		
				CO_2 avoided	32,193 kg/year e.g. from power plants		
				Carbon released e.g. during tree maintenance or decomposition	7500 kg/year		

4	URBAN	Flynn, 2013	bioinfiltration on rain garden Villanova Uni, # of trees not provided	CO_2 storage	490 kg per year?	1) air pollutant removal (NO_2, PM10, SO_2, 03, CO) in kg 2) negative human health impacts during construction phase which are positive during operation phase: Global warming potential (kg CO_2 eq.), human health – cancer (kg benzene eq.), eutrophication (kg N eq.), eco-toxicity ((kg 2,4-D eq.), respiratory effects (kg PM2.5 eq.),	
Implemented - Mixed - field inventory (tree species) and modelling				CO_2 sequestered	40 kg per year		
				CO_2 avoided (Annual avoided global warming potential)	1943 kg CO_2 eq/year		
			i-tree tool	Carbon released e.g. during tree maintenance or decomposition	not reported		

						smog formation potential (kg Nox eq.)	
5	URBAN	Szkop, 2016	932 trees in Warsaw park	CO_2 storage	not reported	Air pollutant removal (NO_2, PM2.5, 03, and SO_2) kg/year	Air pollution benefits [estimated as avoided health costs] $5857/year. PM2.5 accounting for 69% of this
Mixed - Field inventory (tree structure and species) and modelling			tree inventory and algorithm	CO_2 sequestered	not reported		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
				O3 removal	149.9 kg/year		
6	URBAN	Nowak, 2006	All urban trees in the US	CO_2 storage removal?	not reported	Air pollutant removal of NO_2, O_3, SO_2, PM10 and CO	Total pollution air removal (5 pollutants) by **urban** trees in coterminous United States is estimated at 711,000 t, with an annual value of $3.8 billion
Modelled				CO_2 sequestered	not reported		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
				O3 removal	305,100 t/ year		
7	URBAN			CO_2 storage	not reported		

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

9	URBAN	Naumoski, 2016	Hypothetical scenario of planting 555 trees in Skopje, Macedonia	CO_2 storage	548.86 kg/ year	Air pollutant removal of O_3, PM10, SO_2, NO_2 and PM10 and avoided VOCs Emissions of harmful BVOCs Rainfall interception Energy savings	
Modelled				CO_2 sequestered	not reported		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
10	URBAN	Pothier, 2013	Eight contiguous city blocks located in the downtown core of Toronto (584 trees)	CO_2 storage	55,005 kg/ year	Air pollutant removal of O_3, PM10, SO_2 and NO_2 Storm water run-off mitigation Energy savings from buildings	Air pollutant removal was estimated to total 136 kg per year. There were variations by species and by pollutant The urban trees intercepted an estimated 1435 m^3 of storm water runoff in 2009. The urban forest was estimated to have conserved 1093 GJ/yr of energy in 2009 through shading, evapotranspiration and windbreak. Natural gas savings were estimated at 1015 GJ/yr, and conserved electricity totalled 78 GJ/yr
Mixed - Field inventory (tree structure and species) and modelling				CO_2 sequestered	9.98 tonnes/ year. Norway maple trees, green ash and crab apple were the most important carbon-sequestering species		
				CO_2 avoided	not reported		

				Carbon released e.g. during tree maintenance or decomposition	not reported		
11	URBAN	Derkzen, 2015	Urban trees in Rotterdam, Netherlands	CO_2 storage	41.97 kg/ m2	Air pollutant removal Storm water run-off mitigation Energy savings from cooling Noise reduction Recreation	
Modelled				CO_2 sequestered	not reported		
				CO_2 avoided (through energy savings)	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
12	URBAN	McPherson, 2017	Urban trees in California	CO_2 storage		Air pollutant removal of O3, PM10, SO2, NO2 and PM10 and avoided VOCs Emissions of harmful BVOCs Stormwater run-off mitigation Energy savings	
Mixed - Field inventory (tree structure and species) and modelling				CO_2 sequestered			
				CO_2 avoided			
				Carbon released e.g. during tree maintenance or decomposition			

						(cooling and heating) Increase in property value	
13	URBAN	McHale, 2007	Urban trees in four Colorado cities	CO2 storage		Energy savings	
Modelled				CO2 sequestered			
				CO2 avoided			
				Carbon released e.g. during tree maintenance or decomposition			
14	URBAN	McPherson, 2005	5 US cities: Ft. Collins, Cheyenne, Bismarck, Berkeley and Glendale	CO2 storage	158,483 ??		
Mixed - Field inventory (tree structure and species) and modelling				CO2 sequestered	not reported		
				CO2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
15	URBAN	Grzędzicka, 2019	Urban trees in Silesia park, Poland	CO2 storage		Air pollutant removal of PM2.5, PM10	
Field experiment				CO2 sequestered			
				CO2 avoided			
				Carbon released e.g. during tree maintenance or decomposition			

1	URBAN AND RURAL	Nowak, 2014	Trees and forests in the conterminous US	CO_2 storage	not reported	Air pollution removal of NO_2, O_3, $PM_{2.5}$ and SO_2	Trees and forests in the conterminous United States **(both rural and urban)** removed 17.4 million tonnes (t) of air pollution in 2010 with human health effects valued at 6.8 billion U.S. dollars. Health impacts included the avoidance of more than 850 incidences of human mortality and 670,000 incidences of acute respiratory symptoms. Most of the pollution removal occurred in rural areas, while most of the health impacts and values were within urban areas.
Modelled				CO_2 sequestered	not reported		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
				O_3 removal	14,330,000 tonnes pe year		
1	RURAL	Pandey, 2015	105 community forests in Nepal ~10K ha	CO_2 storage	increased by 5.1 MgC/ha/yr as a result of sequestration	fodder and grass for livestock timber to build houses, fuel wood for household energy consumption of wild food (fruits, vegetables and meat) income from selling	
Mixed - Tree data modelled and health outcomes obtained through FGDs				CO_2 sequestered	48.2–129.9 MgC/ha (between 2010 - 2013)		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		

						nontimber forest products	
2	RURAL	Mekuria, 2015	11 community enclosures in Ethiopia - 1483 ha tree inventory and algorithms	CO_2 storage	not reported	Community revenue from carbon market. The net present value (NPV) of the abovegroun d carbon sequestered in exclosures ranged from US$6.6 to US$37.0 per hectare and increased with exclosure duration. At a watershed level, 51.4 Mg C ha-1 can be sequestered , which represents 188.6 Mg CO_2 ha-1, resulting in temporary certified	Other associated benefits: reduced land degradation and soil erosion increased food production, fodder availability and improved livelihood
Implemented - Field experiments (tree inventory) modelled across years and household surveys (historical recall)				CO_2 sequestered	51.4 MgC/ha sequestered from the 11 exclosures, representing 188.6MgCO_2 /ha		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		

						emission reductions (tCER) of 139.4 $MgCO_2$ ha-1 and NPV of US$478.3 per hectare.	
3	RURAL	West, 2018	513 ha deforestation frontier, Amazon	CO_2 storage	not reported	Equity implications scenario 1- increased farm-based profits by average of 8% (0% in the poorest and 25% in the wealthiest) scenario 2- increased farm-based profits by an average of 335% (79% in the poorest to 617% in the wealthiest).	
Modelled				CO_2 sequestered and CO_2 avoided - simulated the potential impacts of REDD+ payment scenarios on net CO_2 not emitted or removed from the atmosphere (Mg CO_2^{-1}), and community welfare (farm-based household profits)	scenario 1 - \$15 Mg CO_2^{-1} which equates to preserving 70% of mature forests scenario 2- \$30 Mg CO_2^{-1} which assume preserving virtually all (97%) mature forests		
			modelled scenarios	Carbon released e.g. during tree maintenance or decomposition	not reported		
4	RURAL			CO_2 storage	not reported		

Mixed - Tree data modelled across time, and health outcomes obtained through stakeholder workshops		Pauydal, 2016	Phewa watershed in Nepal	CO_2 sequestered	not reported		
				CO_2 avoided	not reported		
				Carbon stocks	100 m3/ ha-1		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
5	RURAL	Fedele, 2018	Land-use changes in West Kalimantan and Central Java - Indonesia	CO_2 storage	not reported		
Mixed - Tree data modelled across time, and health outcomes obtained through FGDs (histprical recall)				CO_2 sequestered	not reported		
				CO_2 avoided	not reported		
				Carbon stocks	198 tC/ ha		
				Carbon released e.g. during tree maintenance or decomposition	not reported		

6	RURAL	Wood, 2016	Climate Compatible Development projects in Malawi	CO_2 storage savings?	4,475,744 t/ 50-years		
Implemented - Mixed, GHG modelled and health outcomes via stakeholder surveys and interviews (historical recall)				CO_2 sequestered	not reported		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
7	RURAL	Brown, 2010		CO_2 storage	not reported		
Implemented - mixed (GHG modelled, health outcomes via personal communication)				CO_2 sequestered	165,000 t/ 10 years		
				CO_2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
8	RURAL	Peh, 2014	Converting drained, intensively	CO_2 storage	not reported		
Implemented - modelled				CO_2 sequestered	not reported		

ecosystem services assessment			farmed arable land to a wetland habitat in the UK				
				CO2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		
9	RURAL	Scriven, 2012	REDD plus in the Peruvian Amazon	CO2 storage	not reported		
Implemented - GHG modelled, health outcomes via household surveys				CO2 sequestered	not reported		
				CO2 avoided	not reported		
				Carbon released e.g. during tree maintenance or decomposition	not reported		

A7: Case Study: Sanitation – Surat, India

Between 1995 and 2011, the Surat Municipal Corporation (SMC) made large investments in the water supply infrastructure in Surat, India. The city expanded the coverage of the piped water supply network and the sewerage network including upgrading existing treatment plants. The upgraded plants use an anaerobic sewage treatment that enables the capture and use of methane for power generation. The project resulted in a reduction of 80,000 tonnes of CO_2eq emissions per year from four sewage treatment plants.[268] It has also resulted in improvements in the water quality, measured in terms of declines in the Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD) and Suspended Solids (SS) indicators. However, the Total Dissolved Solids (TDS) remained high, which was likely to be due to chemical treatment (chlorination) of water before discharging it to the water bodies. In addition, from 2009, the four sewage treatment plants produced 3000 to 5000 tonnes of organic manure per year, generating a total revenue of approximately 2.5 million Indian Rupees (INR) per year and a total of 32 new jobs were created across the four plants.

An investigation in India found that the most important driver for wastewater treatment and water reuse is water scarcity, indicating a need for water reuse solutions to help meet population demands for water supply.[269] In contrast, important barriers include inadequate collaboration between central and state governments and between different water-related ministries; lack of an umbrella directive for integrated water resources management, with no clear action plans to operationalise policies promoting wastewater management; and finally, weak enforcement and monitoring mechanisms. A few Indian states, such as Maharashtra, Punjab, or Gujarat (where Surat city is located), have been able to define reuse standards and establish successful wastewater treatment and reuse approaches supported by long-term financing mechanisms. They established an effective governance structure, which ensures that regulations are enforced and monitored.

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

A8: A systemic lens for opening the door to sufficiency

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

International experience suggests that the implementation of the type of policies identified as transformative via the Irish case study can indeed trigger large behavioural change and with this bring large climate and health benefits.[221] For example, in Pontevedra, a small Spanish town, road reallocation and street redesign, in tandem with a change towards mixed land-use planning has reduced car traffic by 69% in the town centre and 90% in the downtown core. Air pollution and GHG emissions were reduced by 61% and 70% respectively. In addition, while in 1996–2006 30 people died in road accidents in main streets, only 3 have died since 2006 (with no road fatalities after 2009).[213]

For example, Barcelona's Superblocks reorganise the city into polygons of approximately 400 m x 400m. Inner roads are not closed to motorised vehicles, as these can enter the Superblock but they cannot cross it. Cars also have to stay within a speed limit of 10 km/h within Superblocks. The Superblock model liberates 70% of space dedicated to cars while reducing traffic in 15% (by 2024 the aim of the municipality is that traffic reductions could be 21%).[213] Estimates in Barcelona also suggest that if implemented at scale (in the whole of the municipality) the Superblock model could bring relevant results. It is estimated that by adopting this new model in the whole of the municipality, the city could eliminate 36% of GHG transport emissions by 2024 and 45% by 2030. Improvements in air quality would allow 96% of the population to be exposed to air pollution below 40 micrograms / m3. In addition, the model would allow 76% of the population to be exposed to noise below 65 dBA (rather than only 54% of the population).[270]

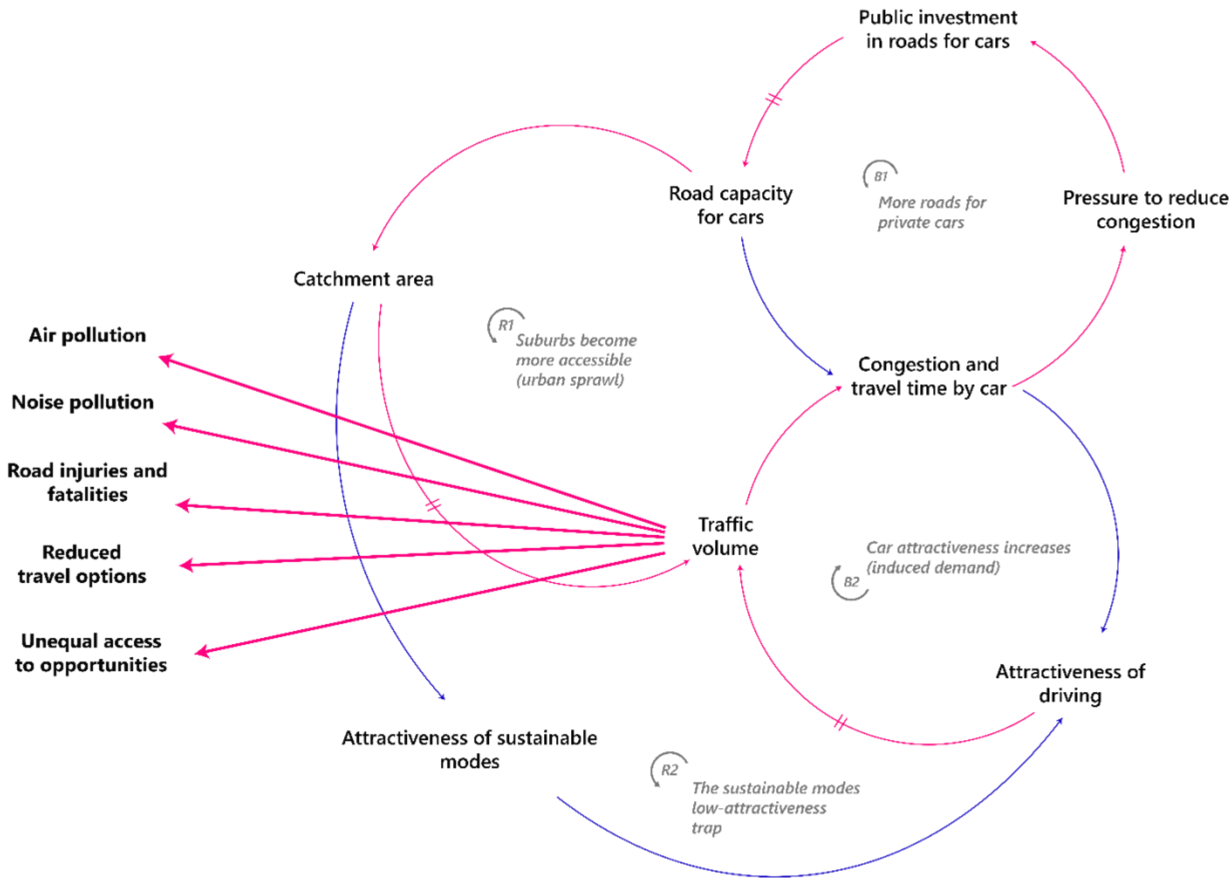

Figure A6.1 System dynamics underlying the car-dependent system and its effects.

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

A framework for categorising policies

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

As illustrated in Figure A7.2 reactive and anticipatory policies have low to medium transformative potential since they do not in reality aim to address root causes. The transformative potential of policies with a transformative intent ca however be low, medium, or high depending on the state of the system (e.g. the levels of different stocks) the policy is trying to influence and the policy's scale or level of ambition.

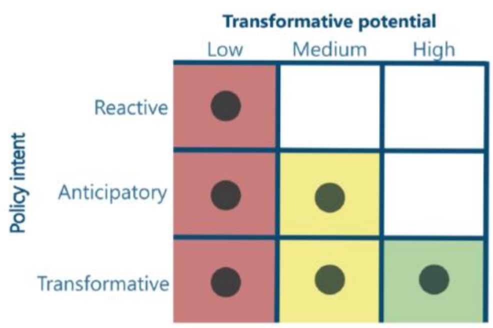

Figure A6.2 Framework for categorising policies according to their transformative potential and intent. Source [221]

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

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

- Causal loop diagrams (CLDs) can be seen as a deep dive into the iceberg model's "structure" level, enabling the analyst to better understand the interconnections or causal relationships that produce the results at the tip of the iceberg.
- Stock and flow analysis complement CLDs in the study of policies' transformative potential by helping policy makers understand the system's physical lock-in. Stock and flow analyses shed light on the magnitude of the stocks – one indication of a system's physical lock-in – and the magnitude and speed of change variations in flows may trigger in existing stocks. Stocks and flows are the elements of a system; stocks (e.g. vehicle fleet, public transport infrastructure) change over time due to inflows and outflows, and are the "system memory".
- Meadows leverage points framework combines insights from CLDs and stock and flow analysis to identify 12 places to intervene in complex systems, referred to as "leverage points".[271] High-leverage points are places in which a small intervention may lead to large behavioural changes. Low-leverage points are places in which small interventions lead to small changes.

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

Some countries have been able to achieve high levels of healthy life expectancy at relatively low environmental footprints including GHG emissions. For example, a recent study showed that at levels of average national primary annual energy use between 10 and 75 GJ per person, eight of nine metrics, including life expectancy, infant mortality, happiness, food supply, and access to basic sanitation services, improve steeply and then plateau[272] Air pollution is the one exception as it plateaus at an energy threshold of 125 GJ person^{-1} across 133 countries. Equitable distribution of current average per capita global energy use of 79 GJ annually could allow the whole world population to achieve 95% or more of maximum performance across all metrics, assuming no other barriers.

Assessment of national data between 1990-2016 also shows that increased environmental footprint and CO_2 emissions appear associated with higher levels of human health and development (measured by healthy life expectancy HALE and human capital HC respectively) up to a certain level of income after which the association is weakened and may reverse.[54] In low- and middle-income countries health outcomes tend to improve with increased resource use, while in high-income countries HALE and HC tended to decline with increasing environmental footprint and CO_2 emissions.

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

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

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