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Integration of Multiple Climate Change Mitigation Actions and Health Co-Benefits: A Framework Using the Global Calculator

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Background: The Global Calculator is an open-source model of the world's energy, land, and food systems. It is a pioneering online calculator to project the impact of interventions to mitigate climate change on global temperature. A few studies have been conducted to evaluate the health co-benefits of climate change mitigation, though they are still fragmentary.

Objectives: Our objectives are to identify which sectors could yield the greatest results in terms of climate change mitigation and suggest whether existing evidence could be used to weight mitigation actions based on their ancillary impacts on human health or health co-benefits.

Methods: Using the International Energy Agency (IEA) 4DS scenario as a referent (i.e., the "4-degree Celsius increase scenario"), we simulated changes in different policy "levers" (encompassing 43 potential technological and behavioral interventions, grouped by 14 sectors) and assessed the relative importance of each lever in terms of changes in annual greenhouse gas emissions in 2050 and cumulative emissions by 2100. In addition, we examined existing estimates for the health co-benefits associated with different interventions, using evidence from the Lancet Pathfinder and four other tools.

Discussion: Our simulations suggest that—after accounting for demographic change—transition from fossil fuels to renewables and changes in agriculture, forestry, land use, and food production are key sectors for climate change mitigation. The role of interventions in other sectors, like carbon capture and storage (CCS) or nuclear power, is more modest. Our work also identifies mitigation actions that are likely to have large health co-benefits, including shifts to renewable energy and changes in land use as well as dietary and travel behaviors. In conclusion, some of the sectors/interventions which have been at the center of policy debate (e.g., CCS or nuclear power) are likely to be far less important than changes in areas such as dietary habits or forestry practices by 2050. https://doi.org/10.1289/EHP14906

Introduction

Under the Paris Agreement, countries develop and communicate their plans to meet greenhouse gas (GHG) emission reduction targets through their nationally determined contributions (NDCs). To date, the NDCs from all countries combined will not be sufficient yet to meet the least ambitious Paris Agreement target of achieving a 66% chance of staying below 2°C by the end of this century.[1] Incremental, sector-by-sector changes are insufficient in delivering required emission reductions. In addition to sectorial mitigation actions, what is needed to meet the Paris Agreement targets are wide-ranging, large-scale systemic transformations.[1] Before the Ukraine war-related energy crisis in 2022, the energy supply sector was responsible for $\sim 34\%$ of the total net anthropogenic GHG emissions worldwide [20 gigatons of CO_2-equivalent per year ($GtCO_2$-eq per year)]; industry accounted for 23% (14 $GtCO_2$-eq per year); agriculture, forestry, and other land use (AFOLU) for 22% (13 $GtCO_2$-eq per year); transport for 15% (8.7 $GtCO_2$-eq per year); and the remaining 6% (3.3 $GtCO_2$-eq per year) was attributable to buildings.[2]

Opportunities for mitigation vary according to sector and country though they are not necessarily proportional to the GHG emissions released by each sector. Feasibility of mitigation differs widely across sectors, being highly feasible in the case of transition to renewable electricity production or electric mobility (despite the well-known challenges in meeting peak demand and adequate storage of electricity in systems that rely exclusively on renewables).[3] Other sectors are more problematic. The transition in AFOLU depends on the opposing driving forces caused by population growth and urbanization rates while also increasing food productivity, reducing waste production, and increasing waste collection and recycling. Interventions should also encompass enhanced carbon sinks including sequestration in soil.[4] Among the manufacturing sectors, mitigation is technically complex for high-intensity energy sectors (cement, steel) and—in transport—for aviation.[5–7] Finally, progress in all mitigation strategies is impacted by unpredicted, and often negative, events like global crises, political turmoil, or local conflicts such as the wars in Ukraine and the Middle East. Other similar catastrophic events include those caused by climate change itself, since extreme weather events can damage infrastructure and disrupt energy systems, transportation, and food systems, including impacts on crop yields and food supply. Additionally, long-term consequences of climate change should be considered, such as loss of habitability, mass migration and even an existential threat to billions of people. However, here we consider only short-term effects.

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Apart from the global pledges to reduce GHG emissions, as stressed by the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (AR6), "policies implemented by the end of 2020 are projected to result in higher global GHG emissions than those implied by Nationally Determined Contributions (NDCs) (statement with high confidence)."[8,9] This statement remains valid in 2024. Thus, we face two gaps: one is the "implementation gap" between actual reductions and what was pledged by each country in their NDCs; the second is that the level of ambition of the NDCs themselves is far from being sufficient to meet the Paris targets ("ambition gap").[1]

The main objective of this paper is to test if the Global Calculator (GC) could be used to prioritize and integrate mitigation interventions and to discuss the role of health co-benefits in the choice of interventions. Here, we define health co-benefits as the ancillary health benefits of policies with the primary goal of mitigating climate change.[10,11] It is not the purpose of this paper to examine the cost-effectiveness of each intervention (estimates have been proposed by IPCC in their latest report) or to discuss the necessary political leadership.

Methods

The Global Calculator (GC) is an online open-source simulation model of the world's land, food, energy, and manufacturing systems that allows the user to design their own version of the future and see the implications of modelled technological and behavioural changes on the climate. With this interactive tool the user can explore all the options available for reducing emissions through changing our energy sources and behaviours, including diets, and technology, up to the year 2050. It is aimed at businesses, NGOs, people in government, and anyone who has an interest in how the world can tackle climate change. The GC is a follow-up to the country and regional-level 2050 Calculator projects that include the UK, China, India, Nigeria, Kenya, South Africa, the European Union, and many others. The GC is based on a system dynamics approach, that has been developed to estimate the impact of mitigation interventions on the achievement of the Paris Agreement targets.[12] The GC model (version 23), including supporting documents and programming code, is available in full open access at https://www.globalcalculator.net. Experts from nine leading international organizations [UK Department of Energy and Climate Change, EU Climate-KIC, the World Resources Institute (US), Energy Research Institute of the National Development and Reform Commission and Energy R&D International (China), E&Y (India), the London School of Economics, Imperial College London, Climact (Belgium), the Climate Media Factory (Germany), and the International Energy Agency] came together to build a model of the world's energy, land, food, and climate systems projected through 2050. The team built the GC to model what lifestyle is physically possible (i.e., compatible with existing technologies) for the world's population—from kilometers travelled per person to dietary calorie and protein consumption—and the energy, materials, and land requirements to satisfy the resulting demand. The impacts on GHG emissions of different pathways or scenarios are illustrated by linking the model to the IPCC climate science and other sources. The model has been tested with experts from more than 150 organizations around the world. It builds on previous experiences based on the UK government on 2050 calculators and encouraged the development of several national calculators. Further information on these models is available on the Imperial College website at https://www.imperial.ac.uk/2050-calculator.

To adjust the parameters of the GC, one can modify the values of 43 different levers (Supplementary Excel Table S1). Each lever represents a specific intervention or mitigation action, corresponding to the implementation of specific policies or lifestyle changes. These levers are grouped by 14 sectors and have four different

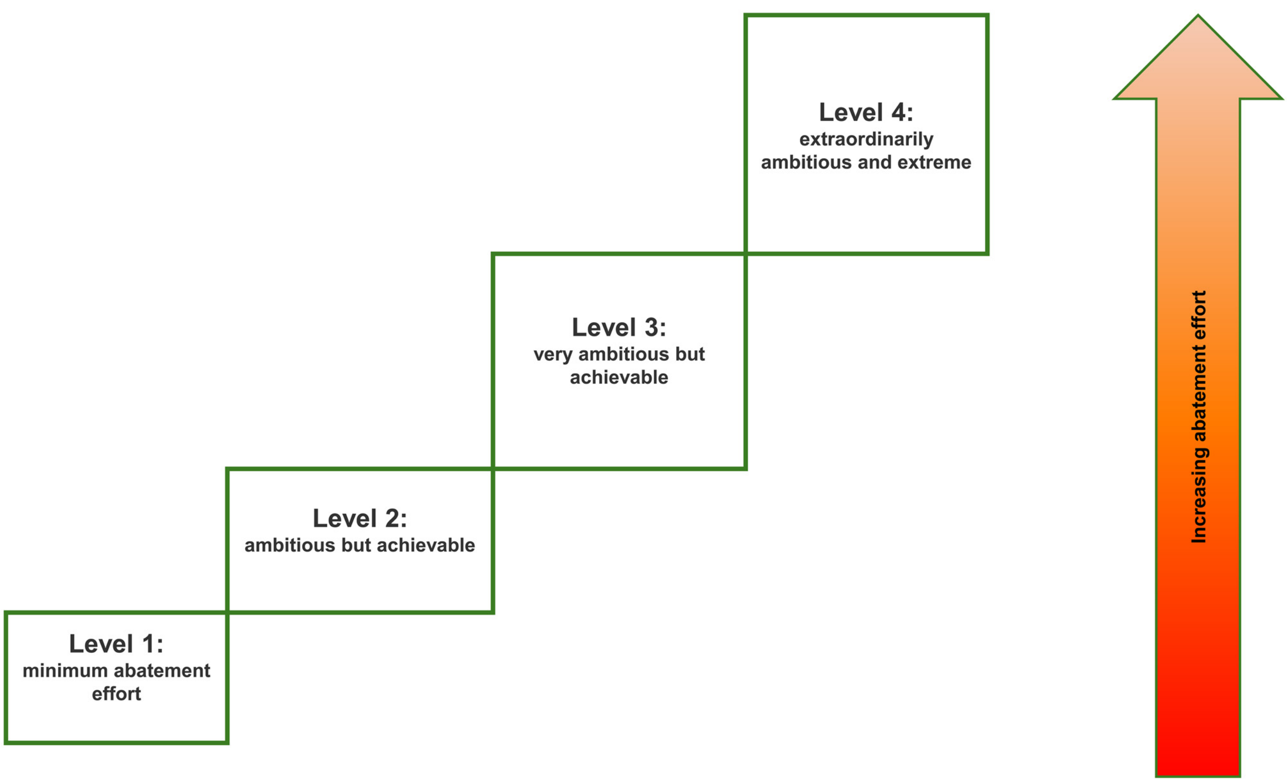

Figure 1. Four levels of carbon abatement effort by 2050 used for each sector of the Global Calculator. Source: Prepared by the authors, based on the Global Calculator. From: Imperial College London (2015), The Global Calculator. Available at http://tool.globalcalculator.net/globcalc.html?levers=22rfoe2e13be1111c2c2c1n31hfjdcef222hp233f211111fn2211111111/dashboard/en.

degrees of stringency or ambition "levels" (Figure 1). The possible levels of ambition span from business as usual (BaU) (usually corresponding to level 1) to extremely ambitious interventions, corresponding to level 4.[12–14] More granular details of the sector metrics are contained in GC technical documents.[15]

Combinations of interventions have been modeled according to predefined policy sets including for example the scenarios developed by the International Energy Agency.[16] In this work, we compare rates of GHG emissions measured as $GtCO_2$-eq per year in 2050 under three scenarios of increasing mitigation ambition levels across sectors' levers, relative to a BaU scenario:

- For the purposes of this study, BaU is approximately represented by the level of ambition settings across all levers under the International Energy Agency (IEA) four degree scenario (IEA4DS), which is available among "example pathways" on the Global Calculator webtool. The 4DS scenario is represented by a combination of levers with a specific set of levels of ambition; it mirrors the original IEA4DS scenario previously developed by IEA.[16] Supplementary Excel Table S2 explains how the global calculator levers were used to approximate the 4DS scenario.
- IEA4DS +0.5: mitigation ambition increases in each of the levers by 0.5 points, in each individual lever and in all levers grouped in the same sector (where 1 point is equivalent to an additional ambition level), up to a maximum cap of 4.0 (considered the upper limit for extremely ambitious but theoretically still achievable scenarios).
- IEA4DS +1.0: increases in ambition for each lever by 1.0 point.
- IEA4DS +1.5: increases in ambition for each lever by 1.5 points.

These are unitless mitigation levels that can be interpreted by referring to Supplementary Excel Table S1 and to further details of the underlying sector metrics as reported.[14] It must be noted that usually the progress from 1.0 to 4.0 is not linear and that a change in a specific lever is modulated by the value of others, since the GC considers how levers interact with each other (based on the concept of systems dynamics).

Our estimates of the contribution of mitigation actions in different sectors are incremental and therefore extend the IEA4DS pathway. The 4DS pathway already significantly increases renewable energies and is less intensive in fossil fuels compared to the six-degree scenario (IEA6DS); our calculations investigate to what extent other interventions would additionally contribute. IEA4DS has been chosen, instead of more updated trajectories, because it is an approximate expression of the current global GHG emissions trend (business as usual).

The Global Calculator simulates emission pathways only until 2050, but it offers a number of possible scenarios between 2050 and 2100, including flat emissions, in order to estimate the global cumulative carbon dioxide emissions and therefore temperature changes expected by the end of the century. The levers refer to policy interventions implemented between 2015 and 2050. To facilitate interpretation of our findings, GHG emissions are presented in CO_2 eq. It is useful to recall that the potency of individual GHGs varies widely, and there is not always a clear consensus on the precise global warming value of a specific GHG. For example, IPCC AR5 used a global warming potential (GWP) between 28 and 34 for methane at 100 years. The GWP is a measure of how much energy the emissions of 1 ton of gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more a given gas warms the Earth's atmosphere compared to CO_2 over that period. In the Global Calculator, the GWP used for methane was 29. The calculator also includes N_2O emissions, which are significant in agriculture, and the GWP used for N_2O was 265, slightly different from AR6.[2]

The Fossil Fuel Sector

The fossil fuel sector in the GC refers to policies concerning the efficiency of electricity generation in fossil fuel-based power plants, not all of the policies contributing to decarbonization. Most of the policies concerning replacing fossil fuels with other sources for electricity generation are included in the renewables sector, while policies concerning decarbonization in other sectors, such as reducing fossil fuel–based transport or fossil fuel usage for heating, are included in the levers of those specific sectors.

Human Health Co-Benefits

Each lever in the GC can have ancillary effects (positive or negative) beyond reducing GHG emissions in areas such as human health, biodiversity loss, water conservation, migration, inequalities, and social justice. An exhaustive evaluation of health co-benefits of different mitigation policies is still lacking, and methodological differences (e.g., baseline, time horizon) across studies make direct comparisons of health co-benefits difficult, even for the same type of co-benefit.[17]

We considered here how evidence from synthesis reports (principally the Lancet Pathfinder)[18] could be used to guide the selection of those mitigation actions that are the low-hanging fruit and bring greatest returns in terms of health and GHG reductions, as well as facilitate the effectiveness of subsequent interventions in other sectors. In addition to Pathfinder, we also included: *a*) a website based on a systematic review of the literature plus expert judgement [the "Climate (Co)benefits portal" developed at the University of Leeds Priestley International Center for Climate],[19] that provides estimates of health co-benefits (also risk of trade-offs and mix of co-benefits and trade-offs) for a number of different mitigation actions, under different levels of confidence; *b*) the Global Burden of Disease (GBD) that is not specifically targeted to co-benefits and is described in detail below[20]; *c*) a specialized calculator for co-benefits associated to changes in transportation in Australia[21]; and *d*) some additional papers in the scientific literature, including reviews.[22] We have excluded other specialized calculators focused for example on energy and pollutants, like the Long-range Energy Alternatives Planning-Integrated Benefits Calculator (LEAP-IBC) (https://www.sei.org/mediamanager/documents/Publications/SEI-Factsheet-LEAP-IBC-2.pdf).

Results

Based on the GC, it has been previously estimated that to achieve the Paris Agreement's goals, one needs the following interventions (among other possible scenarios): the amount of CO_2 emitted per unit of electricity globally needs to fall by at least 90% by 2050; the proportion of households that heat their homes using electric or zero-carbon sources should rise from 5% today to 25–50% globally by 2050; buildings in 2050 must be 50–65% better insulated; appliances should be more efficient than today (for example, refrigerators should be 40% more efficient); cars should be around 50% more efficient (for an explanation of the calculations and assumptions, see https://www.globalcalculator.net/). Here, we compare the impact of changes in different sectors.

Mitigation Potential of Different Interventions

Table 1 and Supplementary Excel Table S1 show, with different levels of detail, the emission reductions due to changes in any

Table 1. Contribution of improvements across different sectors on yearly greenhouse gas (GHG) emissions (CO_2eq) in 2050 and cumulative emissions in 2100 compared to a reference scenario (International Energy Agency IEA4DS model), calculated using the global calculator by increasing the level of ambition by 1 level (IEA4DS +1.0 scenario). Please note that estimates were produced via systems dynamics models; thus, due to interactions across sectors, contributions from different sectors cannot be summed up.

	% Reduction in yearly emissions, 2050	% Reduction in cumulative emissions, 2100	Health co-benefits according to the Climate (Co) benefits Portal[a]	Health co-benefits according to the Global Burden of Disease[b]	Health co-benefits according to the Low Carbon Living Co-benefits Calculator[c]
Travel	12.7	8.6	Yes	Not measured	Yes
Home	19.4	12.2	Yes (energy efficient infrastructure)	Not measured	Not measured
Diet	39.2	22.4	Yes	Yes	Not measured
Transport	3.4	2.3	Yes	Yes	Yes
Buildings	10.1	6.4	Yes	Not measured	Yes
Manufacturing	11.6	7.2	Not measured	Not measured	Not measured
Carbon capture and storage	5.4	3.5	Yes, if trade-offs are considered	Not measured	Not measured
Bioenergy[d]	1.9	1.3	Yes, with trade-offs	Not measured	Not measured
Characteristics of fossil fuels	8.6	5.5	Yes	Not measured	Not measured
Nuclear	3.5	2.8	Yes, with trade-offs	Not measured	Not measured
Transition to renewables	21.6	13.3	Yes	Not measured	Not measured
Food	39.2	25.1	Yes, for diet	Not measured	Not measured
Land use[d]	36.0	23.2	Yes	Not measured	Not measured
Demography[d]	39.7	24.8	Not measured	Not measured	Not measured

Note: For details, see excel Table S1 and GC technical documents.[15] BMI, body mass index; CO_2eq, carbon dioxide equivalent; IEA4DS, International Energy Agency (IEA) four degree scenario.
[a]From the Climate (Co)benefits Portal.[19] Details can be found at https://priestleycentre.shinyapps.io/climatecobenefitsportal/.
[b]From the Global Burden of Disease.[20]
[c]From the Low Carbon Living Co-benefits Calculator.[21] Only related to built environment and transportation. Outputs in the model include BMI, feel safer after dark, trust, general health, life satisfaction, mental health, time spent sitting, time on public transport, time spent walking, multiculturalism, social relationships, social capital, take away, time in car, vegetables servings, and walked over 10 minutes. Inputs include density of dwellings, bus stops, land use diversity, train stops, sporting facilities, number of intersections, and others.
[d]These sectors contained at least one lever for which the level of ambition for the improvement would have exceeded the boundaries of reasonable expectations. We provide the results of the most ambitious improvement that was considered possible.

specific lever grouped by sector, referring respectively to the yearly emissions in 2050 or to the projected cumulative emissions by 2100, under the mitigation scenarios relative to the reference. The cumulative emissions in 2100 according to the reference scenario would be 5,512 $GtCO_2$-eq; and annual emissions in 2050 would be 53.6 $GtCO_2$-eq.

More detailed explanations on sector metrics can be found in Climate-KIC.[23] Just as examples, in the GC the diet sector includes caloric intake, meat consumption levels, and types of meat consumed; the food sector includes crop yields, livestock feeding methods (e.g., grain/residue-fed or pasture-fed), and waste and residues; the transportation sector includes transport efficiency and electric and hydrogen-powered cars, while emissions from transport are mostly included in other sectors. Excel Table S1 shows in the left column the base level of each lever, while the following columns to the right show the proposed level and the resulting changes in emissions: for each change (+0.5, +1, +1.5), we indicate the total cumulative GHG emissions by 2100, the yearly emissions in 2050, and the percent reduction in cumulative and in yearly emissions in 2050 compared to BaU. Table 1 is a simplified version, i.e., shows the effects of a 1-point increase by sector, that is the comparison between the IEA4DS scenario and a scenario in which all the levers belonging to each specific sector are increased by 1, including the percent reduction in yearly emissions in 2050 and in cumulative emissions in 2100. This approach allows quantification of the potential contribution of each intervention to any mitigation strategy. Please note that estimates were produced via systems dynamics models; thus, due to interactions across sectors, contributions from different sectors cannot be summed up.

Table 1 shows that under the IEA4DS pathway +1 scenario, interventions achieving the highest reduction in yearly GHG emissions by 2050 are those related to food (−39%), diet (−39%), land use (−36%), and transition to renewables (−22%); travel accounts for −13%, home for −19%, buildings for −10%, and manufacturing for −12%; while interventions in the bioenergy (−2%), transport other than travel (−3%), nuclear (−3.5%), carbon capture and storage (−5%), and changes in fossil fuels (−9%) lead to lower reductions in emissions. The ranking of the sectors is the same for cumulative emissions by 2100.

Similar estimates are provided under the IEA4DS pathway +1.5 scenario; just as an example, transition to renewable energies would lead to a 31% reduction in yearly emissions in 2050. This corresponds to major changes in wind, hydroelectric, marine, solar, and geothermal energy and in changes in the global electricity storage capacity. Estimates for the IEA4DS +0.5 scenario are also given in Supplementary Excel Table S1. It is important to stress that the reduction in yearly emissions in different sectors is not addible due to the interconnected nature of the calculator and the fact that different interventions often result in changes to a parameter that has clear upper boundaries (e.g., the percentage of land designated to agriculture or reforestation projects). Interventions described in levers such as "food" and "diet" ultimately are interlinked and, hence, will produce a smaller net result than the arithmetical addition of the reduction in emissions generated by changes in each single lever.

Inclusion of Health Co-Benefits

The *Lancet* Pathfinder Commission was set up to assess the evidence on the short-term health impacts of greenhouse gas mitigation, including modeling studies and implemented actions.[18] Pathfinder is based on specific mitigation actions that were either modeled or implemented in specific geographic areas and could be associated with health impacts; data were harmonized to increase comparability between studies. Their work incorporates an umbrella review of 57 original studies that were captured by 26 published systematic reviews. These studies assessed 196 mitigation actions in terms of both their health impacts and GHG emission effects. As a part of the umbrella review, the published estimates of health and GHG emission effects were harmonized into comparable estimates of changes in kilotons of greenhouse gases per 100,000 of the national population per year in CO_2 equivalents (CO2 eq), and changes in years of life lost (YLL) per 100,000 population per year. The mitigation actions described came mainly from high-income settings (129 actions, 65%), with a further 30 (15%) from upper middle–income settings. The greatest contribution to mitigation came from electricity production, with a reduction of about 300 kt CO2eq/100,000/y, followed by AFOLU (about 100), and then multisectoral interventions (about 50). Most of the evidence on health co-benefits was from the AFOLU sector with 103 out of 200 unique co-benefit estimates of mitigation actions, almost all of which focused on dietary changes (see also the review by Jarmul et al.[24]); the next largest sector was transport with 43 actions (22%), followed by multisectoral interventions (i.e., interventions acting across multiple sectors). Pathfinder reported quantitative estimates in terms of years of life lost per 100,000 population per year: Air pollution was associated with 2,482 YLL/100,000/y, diet with 2,163, physical activity with 164, and injuries with 724. These estimates are valid for the mitigation actions and the countries for which evidence was available (see also https://climatehealthevidence.org/) and are not necessarily generalizable.

We also tried to identify sources of information on health co-benefits of mitigation interventions beyond specific experiences in certain geographic areas, in particular based on online calculators. While many papers have addressed single health co-benefits for air pollution in relation to transport[25,26] or diet,[27] none has been exhaustive in considering all potential interventions included in the Global Calculator. One tool is the Priestley Center portal[19] with estimates of health co-benefits for several sectors; some of the evaluations (particularly diet) differ from those provided by other sources. A second tool is based on a specialized calculator on the impacts of transportation changes in Australia.[21] It refers to transportation, use of land, built environment characteristics, and considers a large number of co-benefits related to health (see note in Table 1).

Another potential approach is through the GBD,[20,28] which estimates attributable mortality, years of life lost (YLLs), years of life lived with disability (YLDs), and disability-adjusted life-years (DALYs) for 87 risk factors and combinations of risk factors at the global level, regionally, and for 204 countries and territories.[20] The attributable burden of deaths and DALYs was estimated on the basis of counterfactual models. According to the GBD, a large number of deaths or DALYs (we only use number of deaths here) are attributable to avoidable exposures that can be reduced through the corresponding mitigation policies. In particular, abatement of air pollution would avoid 2,900,000 female deaths per year (11% of all deaths) and 3,750,000 in men (12%); a reduction in BMI (for example by promoting active transportation) would avoid 2,500,000 deaths in women and 2,500,000 in men; a reduction in LDL cholesterol would avoid 2,500,000 deaths in women and 2,300,000 in men; an increase in physical activity would avoid 400,000 deaths in women and as many in men; and prevention of nonoptimal temperature would avoid about 2,000,000 deaths per year overall. However, the GBD does not consider how these goals would be attainable, and their quantitative estimates are calculated in relation to target levels that were not established in relation to climate change mitigation goals. While mitigation policies may not fully eliminate the exposures modeled in GBD, further analysis of GBD data is necessary to produce estimates of the avoidable fractions of health impacts through relevant mitigation policies. The GBD could be a very useful baseline tool to estimate health co-benefits if included in a modeling exercise like an extension of the Global Calculator, but as such, it can only provide an upper estimate of potential co-benefits.

Another relevant paper is from Hamilton et al.[22]: Across the nine countries that they examined (Brazil, China, Germany, India, Indonesia, Nigeria, South Africa, the UK, and the US), they estimate that a sustainable pathways scenario would result in an annual reduction of 1.18 million air pollution–related deaths, 5.86 million diet-related deaths, and 1.5 million deaths due to physical inactivity by 2040, compared with the current (BaU) pathways scenario. Adopting a more ambitious "health in all climate policies" scenario would result in a further reduction of 462,000 annual deaths attributable to air pollution, 572,000 annual deaths attributable to diet, and 943,000 annual deaths attributable to physical inactivity in those nine countries.[22]

Comparisons across mitigation interventions could in principle allow assigning a weight to different sectors in relation to their associated co-benefits: In particular, they indicate that reduction of air pollution obtained with a transition to renewables and changes in transportation modalities would be associated with large health co-benefits, and the same appears for dietary changes (though not with all tools). However, no systematic estimation of co-benefits across a sizable number of sectors was identified, and estimates varied even in the same sector, given the different assumptions and baselines that were used. In addition, most studies on health co-benefits described local experiences not necessarily generalizable to other settings. Nothing comparable in design to the Global Calculator was identified, perhaps with the exception of Pathfinder, which draws comparisons of health co-benefit estimates across contexts and sectors.

Discussion

By using a calculator developed and tested by experts in several institutions, we have tried to rank interventions for the mitigation of climate change, using the IEA4DS pathway as a business-as-usual reference pathway; we have weighted each lever (grouped into sectors) for its contribution beyond the 4DS pathway. We considered also whether it is possible to weight the different interventions on the basis of their contributions to co-benefits for health (e.g., disease reduction due to decrease in air pollution, health improvements related to diet, and others). We have reached some preliminary conclusions: Beyond basic interventions included in 4DS, there are some sectors with more important contributions to the mitigation of climate change than others, in particular food, land use, and shift to renewables. Other levers lead to lower relative contributions: shift from fossils to nuclear, carbon capture and storage, and bioenergy with carbon capture and storage (BECCS) under the simulations here assessed. Transportation, as defined by the interventions proposed in the GC, is in a somewhat unique position, since it is responsible for a more modest decrease in emissions (though emissions related to transport are largely counted in other sectors, particularly travel) but is associated with important health co-benefits in the literature.

The inclusion of co-benefits in weighting the different interventions does not seem to be entirely feasible for several reasons: Systematic reviews are largely limited to air pollution, active travel, and food, considered separately; most of the empirical studies have local relevance and describe local contexts for both mitigation and health impact; and health impacts of interventions are not necessarily estimated in relation to assumptions on the extent and effectiveness of mitigation. Another limitation of the literature is that harms—in addition to benefits—are not consistently considered or sufficiently reported in evaluations.

The large contribution of diet to GHG mitigation reflects in particular the land use change driven by increased or decreased demand for pasture and cropland to supply the animal feed for livestock production for meat-based protein (with integrated counting in food and land use categories). The associated changes in deforestation rates when increases in crop yields are not sufficient to meet the projected food demand, as well as methane emissions from ruminant livestock drive very substantial increases in GHG emissions, including soil carbon impacts through land use change. Diet in the GC is characterized by human population dynamics and eating habits (calories consumed, quantity of meat, type of meat) while food reflects mainly agricultural production practices (crop yields, livestock—grain/residues fed and pasture fed, treatment of wastes and residues). Both diet and food include impacts of transportation and other sources of energy use.

Apart from the impact of land use, food, and diet (which are all interconnected), it seems that a transition to renewables would contribute considerably more to GHG emission reduction than the development of nuclear power or bioenergy, for example. There also appears to be a limited role for BECCS although the GC is constrained in simulating BECCS in detail. In contrast, BECCS and other carbon removal technologies could possibly play a role to help mitigate hard-to-abate sectors, as suggested by Vallejo et al.[29] It is worth noting that these GC simulations run to 2050 with simplified assumptions made from 2050 to 2100. Some technologies (e.g., CCS and negative emission technologies) may have greater contributions beyond this year target, not to mention other disruptive technologies that may evolve in the long-term, like fusion energy.

Our examination of health co-benefits associated with interventions in different sectors has been based primarily on the Lancet Pathfinder exercise,[18] which stresses the large contribution arising from abatement of air pollution and then diet, consistent with the contribution of energy production, AFOLU, and transport sectors in terms of GHG emissions. Otherwise, there are limitations in finding exhaustive evaluations of health co-benefits that correspond to all interventions available in the Global Calculator for climate change mitigation. Nevertheless, there are good reasons to believe that health co-benefits associated with GHG reduction could be very large and occur in the short-term, in some cases immediately, and the economic benefits may offset the costs of the GHG reduction measures as suggested by the latest IPCC report.[9]

Limitations

Our exercise provides a general framework but also has several important limitations. The main advantage is to try to include in a single picture the different sectors involved in the green transition and find criteria for prioritization. A second goal was to weight sectors on the basis of the health co-benefits. However, there are several limitations. The different levers are not comparable (though interlinked) because those related to the production of energy are overarching with respect to productive sectors such as manufacturing or agriculture. There is a high degree of sectoral interdependency; for example, most of the reductions in the use of fossil fuels is expressed in the contribution to other levers such as nuclear, renewables, and bioenergy (and fossil fuels were partially incorporated in the reference scenario IEA4DS). Bioenergy supply is, in turn, a residual outcome of agricultural productivity, land availability, and the preferential use of wastes and biological residues. The model gives priority to food production and forest conservation, i.e., bioenergy potential works as a consequential lever in the GC. It is not possible to expand bioenergy over forestlands or by aggravating food security in the GC: This was a modeling assumption based on consensus of expert opinion. In contrast, by increasing agricultural productivity and promoting more sustainable food consumption patterns in the GC, bioenergy may substantially increase by 2050.[13]

A few additional caveats are needed for the interpretation of the results. Our efforts were focused on identifying areas in which intervention generates the greatest results, but modifying a single lever is not a realistic option for policies, and interventions should be represented by synergistic changes in multiple levers. For example, if one selects the IEA4DS pathway, then the level of GHG emissions caused by hydrogen production (assumed to be done via electrolysis) will be calculated based on the global average emissions for electricity production (2011–2050 and on to 2100) as set by the IEA4DS pathway. This needs to be considered when comparing sectors. Certain sectors, such as transportation, might be particularly impacted by this approach since the most effective policies in this area are focused on synergistic approaches (e.g., increasing the number of passengers per car while replacing fossil fuels with electrical motors). Since we consider the potential of each intervention by itself, our approach might underestimate the potential reductions that multiple synergistic policies can achieve. Also, our changes of 0.5, 1, or 1.5 units in the lever ambition are relatively arbitrary, though we see no easy alternative to compare sectors. In addition, variability in the estimates needs to be considered in the update of the Global Calculator. Validation has been made against the existing body of literature plus expert judgment, but an assessment of the credibility of quantitative estimates has not been done systematically. This is even more true for the sources of health co-benefits.

A similar exercise, to our knowledge, has only been partially made in a publication on the use of the European Calculator (EUCalc)[14] and in a document by the UK Department for Business, Energy and Industrial Strategy (BEIS).[30] However, the basis for the calculations made in the UK BEIS is not completely clear. Also, recently, the latest IPCC report included a hierarchy of mitigation interventions that assigned a potential health impact to each of them.[9] Results are similar to ours, with a large contribution expected from renewables and changes in food production and agriculture, and limited contributions from CCS and nuclear power.

Our exercise should be considered together with other proposals, in particular a roadmap for the inclusion of co-benefits in mitigation strategies.[17]

Research is needed to provide evidence on health co-benefits that have been insufficiently considered beyond the usual categories (diet, active travel, and air pollution). Just to give an example, tobacco has large effects on health but also on greenhouse gas emissions and water consumption in cultivation.[31] The use of land for tobacco plantations is also not insignificant at a time when land for cultivation competes with forests. Tobacco production is, in fact, one of the most impactful and least sustainable agricultural activities.[32] This is particularly true for low-income countries where production is high.[33] We put tobacco under the spotlight because of its large health effects (and thus potential co-benefits), but little is known with reasonable accuracy about other sectors, for example the production of alcoholic beverages and ultra-processed foods, particularly for the planetary impacts in addition to health effects, including wrapping materials and logistics.

Conclusions

The use of the Global Calculator, a well-established source of scenarios for the mitigation of climate change, seems to suggest that—after accounting for demographic change—transition to renewables and changes in agriculture, land use, and food production are key priority sectors for policy making. The role of other interventions, like carbon capture and storage or nuclear power, seems to be more modest. In addition, the latter may be associated with limited co-benefits for health (except reductions in air pollution with greater use of nuclear power, as opposed to conventional thermopower), compared to land use repurposing and changes in food habits. Also, changes in transportation following the interventions proposed in the GC should be given greater importance due to the potential co-benefits they could generate.

In future work, data should be updated to more recent mitigation trajectories beyond the IEA4DS model and should be reproduced at the level of single continents, countries, or cities. The approach needs to be refined as far as health co-benefits and their weight in the choice of mitigation actions are concerned, and other (nonhealth) co-benefits should be better quantified and included in assessments, such as biodiversity conservation. Currently, there are several scientific papers on single health effects of mitigation actions but no systematic and comprehensive review or evaluation of them all, perhaps with the partial exception of Pathfinder. In spite of their limitations, analyses presented here are an attempt to quantitatively assess mitigation interventions to inform policy making and public understanding of policies that should be prioritized.

We stress that new instruments that might be developed in the future should consider the relationships between climate change mitigation and health co-benefits as bi-directional. This is the main limitation of some health-related metrics, like the Global Burden of Disease, in which none of the estimates have been inspired by mitigation actions. In practice, currently, we cannot say what proportion of attributable burdens (comparing observed exposure to a theoretical minimum) can be reduced by mitigation. Of course, the message that climate change mitigation would take care of all of a given burden is incorrect: We still need, in parallel, targeted public health actions that are not designed for climate change mitigation (including better food, physical activity, etc.).

Recommendations for Future Work

It is highly desirable that the Global Calculator be updated with the addition of health co-benefits using a similar system dynamics approach. Recommendations to homogenize the literature on co-benefits have been provided by Hess et al.[17]

Based on our experience with this paper, we suggest that:

1. Multiple health co-benefits should be considered; most of the literature has focused so far on transportation and partially on diet and energy, i.e. sectors including housing, land use, or agriculture have been covered only sporadically; in fact, the advantage of the Calculator approach is in allowing a joint consideration of a number of alternatives and their interactions.
2. Harms of mitigation interventions should be added to avoid a biased evaluation of co-benefits.
3. Data should be provided in a way that modeling is made possible; the advantage of the Global Calculator is that it is a flexible and open access tool in which assumptions can be easily translated into impacts and scenarios or modified to represent new understanding.
4. The Global Calculator reports the assumptions that have been incorporated into models; this should be done also for the modeling of co-benefits, and sensitivity analyses should be performed in order to test the impact of assumptions on estimates.
5. Most literature on health co-benefits, such as that summarized in Pathfinder, refers to local experiences whose generalizability is not very clear. Though co-benefits are by definition local, the goal of attaching health impact estimates to different mitigation interventions implies a certain degree of generalizability; this aspect needs to be refined by developing modeling capabilities of co-benefit calculations in response to different contextual factors (e.g., age and demographic structure of the population, nutritional requirements, some basic environmental factors, etc.), which require simulations and case studies.
6. Systematic evaluations of co-benefits could go beyond Pathfinder, including additional empirical and modeling studies that were not evaluated in their systematic reviews (e.g., papers that did not evaluate both health and climate mitigation impacts at the same time; papers of poor quality, or published too recently to be included in reviews or not meeting the review inclusion criteria, etc.).

In summary, a parallel, rigorous and systematic collection of data and modeling of both interventions for climate change mitigation and the associated co-benefits would be extremely useful for policy making. In the long run, this kind of modeling should also incorporate economic evaluations and be extended to "planetary boundaries" other than climate change (in particular to loss of biodiversity and ocean acidification).

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