Commentary

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Guidelines for Modeling and Reporting Health Effects of Climate Change Mitigation Actions

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BACKGROUND: Modeling suggests that climate change mitigation actions can have substantial human health benefits that accrue quickly and locally. Documenting the benefits can help drive more ambitious and health-protective climate change mitigation actions; however, documenting the adverse health effects can help to avoid them. Estimating the health effects of mitigation (HEM) actions can help policy makers prioritize investments based not only on mitigation potential but also on expected health benefits. To date, however, the wide range of incompatible approaches taken to developing and reporting HEM estimates has limited their comparability and usefulness to policymakers.

OBJECTIVE: The objective of this effort was to generate guidance for modeling studies on scoping, estimating, and reporting population health effects from climate change mitigation actions.

METHODS: An expert panel of HEM researchers was recruited to participate in developing guidance for conducting HEM studies. The primary literature and a synthesis of HEM studies were provided to the panel. Panel members then participated in a modified Delphi exercise to identify areas of consensus regarding HEM estimation. Finally, the panel met to review and discuss consensus findings, resolve remaining differences, and generate guidance regarding conducting HEM studies.

RESULTS: The panel generated a checklist of recommendations regarding stakeholder engagement: HEM modeling, including model structure, scope and scale, demographics, time horizons, counterfactuals, health response functions, and metrics; parameterization and reporting; approaches to uncertainty and sensitivity analysis; accounting for policy uptake; and discounting.

DISCUSSION: This checklist provides guidance for conducting and reporting HEM estimates to make them more comparable and useful for policymakers. Harmonization of HEM estimates has the potential to lead to advances in and improved synthesis of policy-relevant research that can inform evidence-based decision making and practice. https://doi.org/10.1289/EHP6745

Introduction

In 2015, 196 countries outlined their Nationally Determined Contributions (NDCs) as part of the 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), with the goal of avoiding dangerous climate change of 2°C over preindustrial levels (The Paris Agreement). The scientific community has since reiterated that holding warming below 1.5°C could avoid key environmental tipping points and prevent substantial climate-related risks to natural and human systems (Rogelj et al. 2018; UNFCCC 1992). Current climate change mitigation efforts, however, fall far short. Greenhouse gas emissions (GHGE) reached a record high in 2018 globally, which also saw continuing expansion of fossil fuel use and reduced rates of renewable energy installation (IEA 2019). Further, the operational guidelines outlined in the Katowice Package (UNFCCC n.d.b) set out the undertaking of a Global Stocktake that will make use of the "best-available science" for mitigation (and other Paris Agreement thematic areas) (UNFCCC n.d.a). For studies of the health effects of mitigation (HEM) to make a meaningful contribution to this global effort, common standards are needed to facilitate synthesis through meta-analysis and other approaches (Chang et al. 2017).

Although climate change mitigation is an urgent priority, policy implementation has been limited, often due to associated short-term financial costs (Workman et al. 2018). However, cost assessments rarely account for concomitant impacts (generally subdivided into co-benefits and co-harms), i.e., "the . . . effects that a policy or measure aimed at one objective might have on other objectives" (Allwood et al. 2014). Comprehensive accounting of co-benefits and adverse side effects is essential (Zenghelis 2006) because beneficial mitigation externalities may enhance the economic case for pursuing aggressive mitigation action (Rogelj et al. 2018). (Haines et al. 2009). Systematic reviews of HEM studies estimating actions, policies, interventions, and technologies have found that mitigation can lead to near-term changes in local and regional air quality, transportation behaviors, and dietary intake that have significant health benefits, with broader benefits accruing in the longer term (Chang et al. 2017; Gao et al. 2018) (See Figure 1; note this is not intended to be comprehensive). In most cases these health effects are beneficial, and their economic valuation could

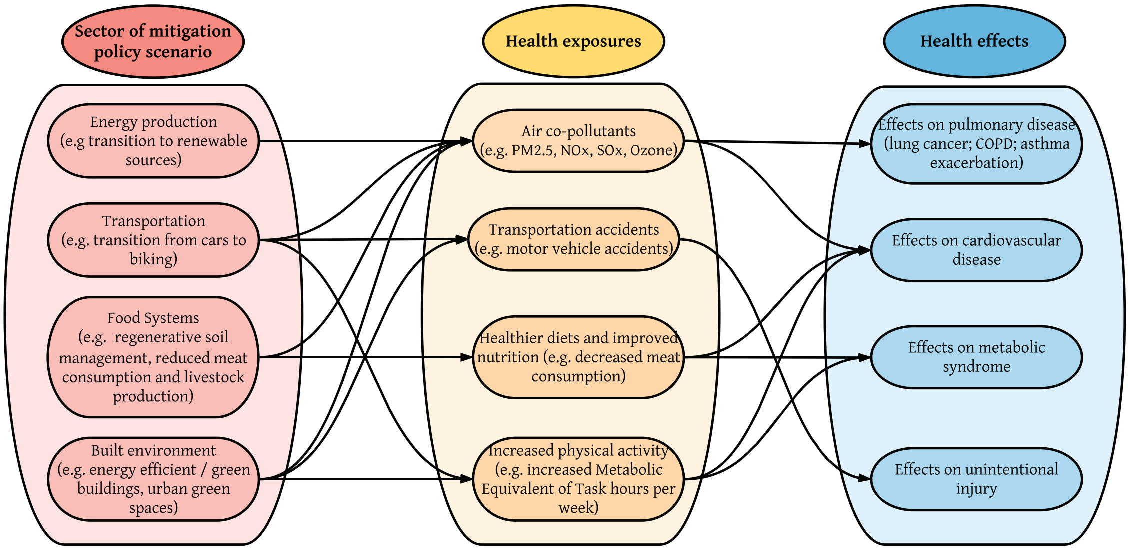

Figure 1. A conceptual framework that provides sector-specific examples of the multiple mechanisms and pathways through which climate change mitigation policies can affect human health. This figure is not intended to be comprehensive.

offset a substantial proportion of mitigation costs, particularly in emerging economies (Smith and Haigler 2008).

Despite this, HEM research appears to have had limited policy impact. Evidence of mitigation co-benefits outside of health, e.g., for development (economic and scientific advancement) and for benevolence (a more moral and caring community) has motivated support for mitigation actions (Bain et al. 2016). But HEM research has gained minimal political traction and to date has done little to influence climate change policy (Workman et al. 2018). Influencing policy making with research evidence is a complex process (Cairney and Oliver 2017; Oliver and Cairney 2019). Experience with other population health challenges such as air quality and tobacco abuse suggests that important elements include developing a consistent and compelling body of evidence, linking research with a coalition or network approach to advocacy, being prepared to take advantage of windows of opportunity, and developing an understanding of how the ideological beliefs of decision makers influence the framing of policy proposals (Rose et al. 2017; Smith 2013).

Increasing the policy influence of HEM research necessitates reducing potential barriers and promoting potential facilitators of its uptake. Two previously identified barriers are resistance from powerful vested interests and structural challenges that limit cross-sectoral collaboration between the health sector and climate change decision makers (Workman et al. 2018). Another barrier is the lack of a compelling, harmonized evidence base because current evidence consists primarily of heterogeneously modeled HEM estimates. Although there is broad agreement about the general approach to modeling HEM (Remais et al. 2014; Smith and Haigler 2008), the broad array of mitigation actions and wide variety of specific modeling approaches taken have precluded meta-analysis (Chang et al. 2017; Gao et al. 2018). There is currently no clear framework for advancing HEM research methods and results reporting, and compelling examples of how concomitant impacts on health (beneficial and adverse) have accrued from mitigation activities are still needed. In sum, basic guidance that would enhance the policy utility of HEM estimates are lacking, including for scoping, estimating, and reporting research on HEM.

With these concerns in mind, the Wellcome Trust, the World Health Organization (WHO), and the University of Washington coconvened a workshop to identify strategies for enhancing the policy utility of HEM estimates, with a focus on developing guidance that could help improve the applicability and comparability of HEM evidence. Shortcomings in current research and reporting practices were identified, and a consensus process was undertaken to arrive at a minimal set of reporting guidelines to promote transparency, interpretability, and uptake of HEM estimation. Herein we present the methods used to generate consensus regarding these issues as well as the resulting practice and reporting guidance that emerged.

Methods

Several methods across multiple stages were used to develop this guidance, including a review and synthesis of the literature, assembly of an expert panel, a modified Delphi consensus-building process, an expert workshop to develop preliminary guidance, and postworkshop guidance refinement (Figure 2).

Literature Review

A literature review was conducted to provide material for the expert panel and the modified Delphi process. The review covered

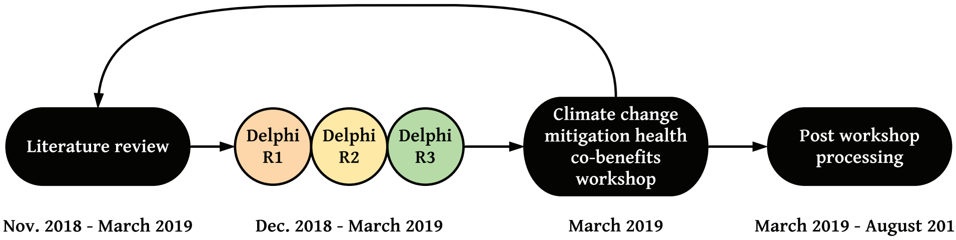

Figure 2. Timeline and process for developing guidance document. R1, R2, and R3 were successive rounds.

HEM studies published between 1 February 2017 and 1 February 2019, building on prior reviews of studies conducted before that period (Chang et al. 2017; Gao et al. 2018). Papers were classified according to mitigation scenario and sector, geographic scale, health metrics used, health outcomes estimated per CO_2 equivalent averted, monetized benefits, and treatment of uncertainty. The papers identified were provided to the expert panel, along with a narrative synthesis of the review findings.

Expert Panel Assembly

An expert panel was assembled based on researchers identified in the literature review. Experts were contacted via electronic mail and asked to participate in the panel. First contact was made with first and senior authors; substitutions were allowed upon mutual agreement between the organizing team and the initially contacted expert. Panelists were asked to participate only if they could engage through the entire process. Sixty-four panelists were recruited. All panel members were invited to the workshop and to participate in editing the guidance document. All participating panelists are included as authors.

Modified Delphi Process

The Delphi process is a general method designed to measure and reach consensus. Our modified Delphi consisted of three rounds of anonymous, online surveys with two categories of predefined questions, similar to those of other Delphi processes (Boulkedid et al. 2011). The first category consisted of affirmatively phrased declarative statements related to HEM estimation practices and to the potential utility of guidance from the EQUATOR Network (an international initiative to promote reporting guidelines for published health research) (EQUATOR Network n.d.) and elsewhere on modeling studies (Bennett and Manuel 2012; Stevens et al. 2016), observational studies (von Elm et al. 2007), and health impact assessments (HIAs) (Bhatia et al. 2014). Panelists were asked to express the degree of agreement on a scale of 1 to 9, with 1 indicating strong disagreement and 9 indicating strong agreement, and to provide a narrative justification for their responses. The second category of questions was exploratory and meant to prioritize topics for further discussion and to generate additional areas in which to seek consensus. Between survey rounds, panelists were given descriptive analyses of responses and summaries of narrative comments from the prior round. Each survey is included in the Supplementary Materials. Panelists also had full, anonymized access to all raw data and responses. Consensus was determined by measures of central tendency and spread in the third round of questioning, with a mean score and interquartile range (IQR) between 1 and 3 indicating consensus against and a mean and IQR between 6 and 9 indicating consensus for a given statement.

Guidance Refinement

Panelists convened in London in March 2019 in a workshop sponsored by the Wellcome Trust and coconvened with WHO and the University of Washington. The overarching goal was to reach consensus on key issues surrounding health co-benefits research. Building from and guided by the modified Delphi process, the 3D workshop used small group discussions combined with report-back presentations to discuss key elements of the survey and, when possible, reach consensus. In total, 53 researchers encompassing a range of expertise on climate change mitigation health co-benefits research attended the workshop (Table S1). Small group discussions were moderated by preselected facilitators, and discussion notes were taken and summarized by rapporteurs.

Small group discussions were held on the following issues: stakeholder engagement, modeling approaches, model parameterization and treatment of uncertainty, and reporting. Due to the current state of the literature, which disproportionately focuses on air pollution and active transport, workshop discussions were largely focused on these areas, with a secondary focus on food systems, the built environment, and urban form. The workshop concluded with a plenary discussion of consensus guidance statements, including the type of studies for which the guidance should be designed. The guidance statements were assembled into a draft document after the workshop and circulated to the group, including those panelists who were unable to attend the workshop, for review and refinement prior to publication.

Discussion

Here we present the consensus findings of the author panel reflecting the outputs from the expert consensus process outlined above. We first present "Practice and Reporting Guidance" and then conclude with a "Discussion" section reflecting the perspective of the panel regarding the context for this guidance and its implications for HEM estimation and reporting.

Practice and Reporting Guidance

The material in this section is the consensus recommendation of the panel, unless noted in the text or otherwise attributed with a citation. This statement begins with a brief discussion of guidance scope and application. Next, there are three sections of recommended guidance: "Stakeholder Engagement," "Modeling Approaches," and "Parameterization and Reporting." A schematic of the overall process to which the guidance applies is presented in Figure 3.

Scope and Application

Given the wide range of HEM research, it is important to delineate the activity for which this guidance is designed and how the guidance is intended to be implemented.

As noted earlier in the "Introduction," prior research on HEM determined that mitigation actions may result in substantial health co-benefits, but the policy potential of this research has not been fully achieved, partially as a result of wide variability in methods and reporting as well as the nonsystematic nature of previous approaches (Remais et al. 2014; Gao et al. 2018). This guidance is meant to encourage specific modeling practices, methods, and results reporting to maximize the likelihood of implementing the most beneficial mitigation actions and maximize the likelihood of avoiding adverse side effects. As such, this guidance is particularly relevant to HEM research focused on quantitative estimation of mitigation health co-benefits via modeling of population health impacts associated with specific mitigation actions. It is likely of less relevance where the primary aim of a policy is not climate change mitigation, but both health and carbon impacts are modeled. Practically, these guidelines are likely to be most relevant to modeling efforts scoped for national and international efforts, but they could also be applied subnationally in large countries such as the United States, China, and India. It may be more challenging to implement the guidance at local levels due to resource constraints or lack of relevant downscaled modeling inputs.

The guidance is meant to be comprehensive and provide a checklist of standard practices and analysis reporting that can be used by funders, researchers, reviewers, and journal editors in scoping, preparing for, conducting, reporting, and reviewing HEM research. Guidance recommendations are listed below,

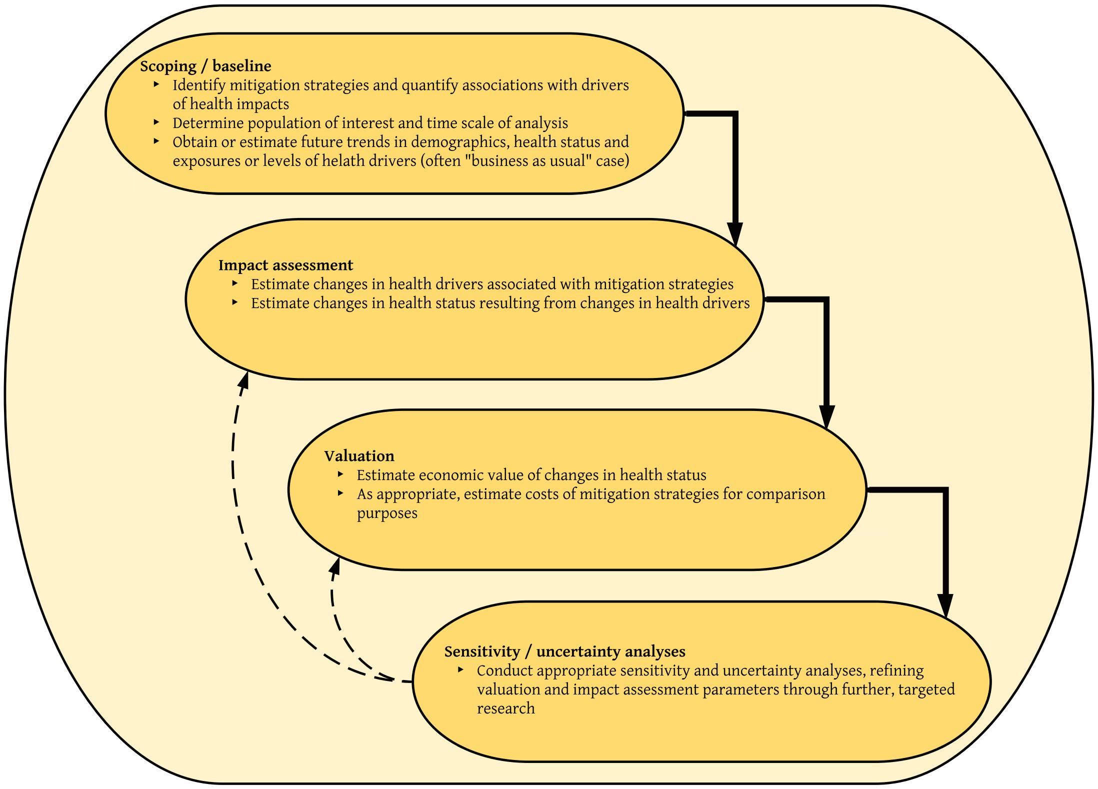

Figure 3. Engagement, modeling, parameterization, reporting, and synthesis considerations for health effects of mitigation policies (HEM) studies, building on figures originally published by Remais et al. (2014) and Gao et al. (2018).

preceded by accompanying (and less prescriptive) background text. Although we encourage following the guidance to maximize comparability across studies and policy impact, we are not advocating that adherence be required as a test of study quality or asserting that studies that do not adhere to the guidelines necessarily lack quality or rigor. Further, we acknowledge the need for flexibility in modeling approaches, to avoid stifling both innovation and research output from resource-poor settings where full adherence to this checklist may not be feasible. Finally, we acknowledge the importance of good modeling practice, including the need to maintain a humble approach to modeling complex systems, to frequently revisit modeling assumptions, and to consistently seek to incorporate new evidence.

Stakeholder Engagement

As noted in the HIA literature (Bhatia et al. 2014) and other pertinent work on environmental health policy noted above (Rose et al. 2017; Smith 2013), a fundamental prerequisite of policy relevance is stakeholder engagement, particularly with policymakers, during research planning to improve usefulness of model inputs, improve relevance of study design to policy context, and encourage policy uptake. The panel strongly encourages use of transdisciplinary and interdisciplinary stakeholder teams (including nonhealth disciplines) to reflect the broad range of methodological, sociological, and other considerations. Modeling efforts should consider including government policy makers, the public and civil society, the private sector, and scientists from a variety of relevant disciplines (e.g., health, mathematics, statistics, ecology, economics, and other social sciences), as needed. Such efforts could help lessen barriers to policy uptake and allow researchers, decision makers, and funders to anticipate policy resistance; encourage policy uptake; and account for variable uptake of policy scenarios in analysis. Stakeholder engagement may take multiple forms (Bhatia et al. 2014), employ a range of tools (e.g., mapping, review of specific cases), and occur over a variety of administrative and geographic scales. Expertise may need to be added to the research team on effective approaches to facilitating stakeholder engagement.

With these considerations in mind, the panel recommends the following Engagement Guidelines:

1. Specify the primary decision maker(s) and/or target audience(s).
2. List and describe strategies used to facilitate stakeholder engagement and communication with the target audience throughout the HEM development and dissemination process.
3. As relevant, describe involvement with knowledge brokers, research uptake officers, policy advisors, and other stakeholders at multiple stages of planning and implementation (e.g., their role in selecting model inputs such as health metrics).
4. As relevant, describe collaboration(s) with stakeholders (whether at the affected community level, in academia, or in government) in health-determining sectors (e.g., finance, energy, transportation, housing, industry, food systems, and agriculture).
5. As relevant, describe engagement between mitigation and adaptation experts relevant to various phases of effort, from planning to implementation and dissemination, including any efforts to avoid unintended consequences.

Modeling approaches. There is clear value in different modeling approaches, and our guidance does not prescribe specific modeling approaches as long as the approach allows for incorporation of baseline population health information, demographics, and evaluation of counterfactuals (i.e., what could happen without the mitigation scenario). HEM models generally take the approach shown in Figure 3 and draw from a variety of methods, including comparative risk assessment, complex mechanistic modeling, and microeconomic and behavioral modeling, though other approaches are sometimes employed (Remais et al. 2014). Comparative risk assessment approaches allow for standardization and comparison of risk, whereas mechanistic and behavioral modeling can provide insights into systems dynamics and questions of how individuals, households, and other economic units may respond to various policy options.

The panel recommends that modeling choices should be made based on assessments of which approach is most appropriate for the research question of interest and stakeholder input, as relevant. We also recommend that counterfactual scenarios, exposure–response functions (ERFs), health metrics, and study time frames should be selected based on stakeholder input, the research question posed, and health focus. In addition, we encourage modelers to be explicit regarding the rationale for these selections. For instance, although disability-adjusted life-years (DALYs) may be appropriate for some international studies, quality-adjusted life-years (QALYs), mortality rates, and loss of life expectancy (LLE) may, depending on the context and stakeholder needs, be more applicable at national and subnational scales. Additionally, the conversion of health metrics into monetary measures is a valuable approach if conducted transparently because it may be particularly compelling for policymakers and allows for the comparison of impacts across several dimensions (e.g., financial costs vs. health benefits).

For global and regional assessments, the panel recommends that ERFs should generally be selected from systematic reviews and meta analyses. However, when local evidence is of primary importance to stakeholders or when there is reason to believe that evidence generated elsewhere may not be generalizable to the study setting (e.g., applying ERFs from high-income countries to low-income countries or applying in a different climate region), ERFs may be based primarily on local evidence. The STROBE reporting guidelines for observational studies (von Elm et al. 2007) and PRISMA statement for systematic reviews (Moher et al. 2009) can be useful in selecting which studies to incorporate. Time horizons should be similarly justified and selected based on context. For example, time horizons for national studies could be made congruent with national governmental policy cycles, whereas time horizons for regional studies could align with the sustainable development goals (United Nations n.d.). In any case, researchers should clearly describe and justify the parameterization choice.

We encourage, where possible and relevant, the use of ensemble climate model projections that follow the Representative Concentration Pathways (RCPs), the Shared Socioeconomic Pathways (SSPs), or other globally agreed-upon scenarios. We also encourage characterization of the uncertainties inherent in scenario choice, temperature projections, model structure, and internal variability (Deser et al. 2012; Hawkins and Sutton 2009). The RCPs include four emissions pathways developed primarily by the integrated assessment modeling (IAM) community (van Vuuren et al. 2011). The SSPs are a set of five reference scenarios that capture plausible trends in "the evolution of society and natural systems over the 21st century" by incorporating a range of socioeconomic and environmental conditions (O'Neill et al. 2014). Taken together, the SSPs and RCPs can be used to explore uncertainty in outcomes and projections, with one axis representing plausible socioeconomic and environmental conditions and the other representing emissions pathways (O'Neill et al. 2014). The use of the RCPs and SSPs would align the efforts of HEM researchers with those of the larger climate modeling community, although some HEM studies will be scoped and scaled such that these scenarios will not be particularly relevant. For instance, in a study aimed at evaluating the health impacts of changes in transportation policy at a city scale or over a relatively short (i.e., decadal) time span, neither the RCPs nor the SSPs are likely to add perspectives that will be useful to stakeholders. The SSPs can also be used, where relevant, to incorporate other drivers of health outcomes, such as urbanization and inequity.

With these considerations in mind, the panel recommends the following Modeling Approach Guidelines:

Mitigation Policies

1. Describe mitigation policies and scenarios and their relevant sectors (e.g., finance, energy, transportation, housing, industry, food systems including agriculture).

Geographic Area and Scale

2. Specify the geographic scale (international, regional, national, subnational, city) and geographic area of interest.

Population and Demographic Considerations

3. Describe populations (size and other characteristics) for model baseline and counterfactual scenarios.
4. If applicable, account for equity and describe socially and economically marginalized populations.
5. If applicable, account for and describe populations that are most likely to experience adverse consequences or benefit the most.
6. List and describe data sources used for population and demographic projections.
7. Describe the degree of congruence between population and demographic data and emissions projections in terms of time frame, underlying assumptions, and other factors deemed relevant.
8. Describe why target population and demographic choices for the baseline and counterfactuals are appropriate to the policy decision(s) being considered.
9. Describe how the analyses will account for projected demographic changes.
10. Describe whether and how the analyses will account for feedbacks between and within models and across drivers of population/demographic projections. If feedbacks are not addressed, state why.

Counterfactual Scenarios

11. Describe how exposure(s) to the mitigation action(s) and related downstream exposure(s) is assigned, including, as appropriate, the proportion of the population that is exposed over time as a function of implementation.
12. List and describe counterfactual scenarios, ensuring that these reflect current realities in the absence of strong mitigation policies. As appropriate, list and describe other mitigation policies used in the model.
13. Describe any potential correspondence between mitigation and counterfactual scenarios with SSPs, RCPs, and/or other globally agreed-upon scenarios, either qualitatively through narrative linkages (e.g., if the mitigation and counterfactual scenarios are characteristic of particular scenarios) or quantitatively (e.g., using specific combinations of RCPs and SSPs with numerical correlates for emissions, demographic shifts, etc.).
14. Describe data sources used for counterfactual scenarios (for example, emission scenarios).

Time Frames and Horizons

15. Specify and justify the baseline year for data sources used in the model.
16. Clearly define and justify time frames and projected time horizons.

Exposure–Response Functions

17. Describe and justify exposure–response functions used.
18. If applicable, describe how exposure–response functions may vary among vulnerable and disadvantaged populations.
19. Describe health response studies used for modeling (e.g., description of sample size, location, timeframe) and justify if health responses were not obtained from systematic reviews or meta-analyses (e.g., use of local studies).

Health Metrics

20. Define and justify metric(s) for measuring the health of populations (e.g., health metrics such as DALYs, years of life lost (YLL), years lived with disability (YLD), mortality, LLE, hospitalizations, emergency department visits, among others) appropriate for the specified causal pathways and target audience/decision makers.
21. Describe and justify data sources used for health metrics (examples as above).

Baseline Health Estimates

22. Describe baseline population health estimates.
23. Describe and justify sources used for baseline health estimates and demographics (e.g., national vital statistics, the Global Burden of Disease study, etc.).

Parameterization and Reporting

We recommend quantitative analysis of uncertainty despite the complications involved in doing so. In instances where sources of uncertainty cannot be quantified, we recommend additional qualitative discussions. HEM researchers should also conduct sensitivity analyses to quantify (if possible, using value of information or other methods) how input uncertainties, model parameters, and model structure drive variability in model outputs. Both sensitivity and uncertainty analyses should be conducted for the following: exposure, economic valuation of health effects, the role of adaptation in exposure–outcome associations, the magnitude and functional form of exposure–outcome associations, and other inputs such as demography and policy uptake. Researchers are also encouraged to consider discounting intervention costs and impacts if appropriate to the decision and decision-making context.

We encourage working with IAM and other modeling communities to develop realistic rates of implementation for key policies. IAM is a commonly used approach in the climate science community to integrate aspects of human systems (demography, energy use, and the economy, among other features) with aspects of the climate system (Moss et al. 2010). It has allowed for the development of emissions scenarios such as the RCPs (van Vuuren et al. 2011) and can be used to simulate feedback loops, evaluate uncertainties, and provide insight into the benefits of climate change mitigation (Moss et al. 2010).

With these considerations in mind, the panel recommends the following Parameterization and Reporting Guidelines:

Health Outcome Reporting

1. Report elements of component health metrics used (e.g., number of deaths or disease cases, baseline rates, percent attributable, health events per capita, change in life expectancy).

2. Describe extent to which environmental exposures (e.g., air pollutants), vs. demographic change, resulted in health impacts.

3. Conduct a sensitivity analysis and describe methods used.

4. Describe general study limitations qualitatively (e.g., describe potential sources of bias and likely impact on findings) and quantitatively (e.g., describe limitations in valid parameterization of model).

5. Where feasible, conduct quantitative uncertainty analysis, particularly value of information methods to prioritize data and research needs.

6. Discuss sources of uncertainty that could not be addressed quantitatively.

7. Discuss potential and/or actual (social, political) resistance to policy uptake either qualitatively or quantitatively (e.g., through incorporation of a step function for policy implementation over time).

8. Discuss adverse consequences of mitigation actions (potential, hypothetical, or those observed in results) either qualitatively or quantitatively.

Accounting for Variable Policy Uptake

9. Differentiate scenarios between thought experiments ("first best world"), maximum credible rates of implementation ("second best world"), and realistic rates of implementation.

10. Describe equity impacts of policy uptake.

11. If possible, qualitatively discuss nonlinear dynamics (e.g., delays and thresholds) associated with intervention implementation and expected outcomes using empirical data.

Discounting

12. For discounted valuation estimates, justify choice of fixed vs. variable (e.g., certainty-equivalent) rates, specific rates chosen, and conduct sensitivity analyses, including at least rates of 0% (with a 100-y time horizon) and 3%.

Data and Code Transparency

13. When legally and ethically possible, openly and publicly share data and code used for HEM studies to facilitate model validation of models by external researchers, collaboration between investigators, and the production of meta-analyses (including through retrospective harmonization), and new studies. If there are legal or ethical limitations to data sharing, these should be explicitly stated.

Discussion

The guidance, which addresses stakeholder engagement, modeling approaches, parameterization, and reporting, is aimed at quantitative modeling scoped to provide policy-relevant insights that facilitate the selection and implementation of mitigation policies based both on mitigation potential and on anticipated health impacts. This guidance may be most relevant to efforts at the national or international level, although the guidance is also likely relevant for subnational efforts in large countries and for settings such as megacities. The ultimate aim of the guidance is to generate estimates that are responsive to stakeholder needs and that can be compared and combined to support policy decisions.

This guidance includes several departures from previous work. First among them is the emphasis on stakeholder engagement, which is a fixture of other policy-oriented activities such as HIA (Lock 2000). This guidance reflects and underscores the priority of policy relevance in HEM research. Although we stop short of stipulating that stakeholders always be engaged in HEM efforts as stipulated in HIA guidance (Bhatia et al. 2014), consensus nonetheless emerged among the panel members that stakeholder engagement, including engagement of potentially affected civil society and community members and sectors outside health, would likely enhance evidence uptake into policy. Resources from the HIA practice community (SOPHIA Stakeholder Engagement Working Group 2015; SOPHIA n.d.) may be relevant for stakeholder engagement in future HEM efforts.

Another departure is the emphasis on using common scenarios in modeling efforts. Socioeconomic and development trends will affect baseline mortality rates over the coming decades, and adopting the SSPs as a standard set of reference pathways can enhance comparability across studies. Relevant quantifications of the SSPs are available (Dellink et al. 2015; Jiang and O'Neill 2017; Kc and Lutz 2017; Li et al. 2019; Marangoni et al. 2017; Nepal et al. 2019; Rao et al. 2019), and there is increasing application in the health sector (Markandya et al. 2018; Sellers and Ebi 2017). Using the SSPs, Sellers projects different burdens of noncommunicable disease (NCD) mortality as a proportion of all deaths, particularly in low- and middle-income countries (LMICs), depending on development pathways (Sellers 2020), a relevant trend for future baseline population health estimates in HEM studies.

A third departure is the encouragement to incorporate demographic projections and more realistic assumptions regarding policy implementation. Many HEM studies made the simplifying and unrealistic assumption that the mitigation action of interest is imposed on today's world immediately and uniformly worldwide, with a constant population, despite the presence of a wide range of possible population distributions over coming decades, both in terms of numbers of people (6.9–12.6 billion in the year 2100, depending on socioeconomic development pathway) and in terms of the age structures and health status of populations (Kc and Lutz 2017).

Less of a departure, but still an important practice innovation, is the emphasis on *a*) standardized metrics of health impacts, *b*) more comprehensive causal pathways linking exposures and health impacts, and *c*) incorporation of climate change into projected changes in exposure. Air pollution provides an example of the importance of these issues. As understanding of the wide range of health impacts of exposure to fine particulate matter ($PM_{2.5}$) continues to increase, it has become clear that some recent HEM studies underestimated the ancillary health benefits of reducing $PM_{2.5}$ exposure. A 2019 review by five national academies of science and medicine concluded that associations were unequivocal between $PM_{2.5}$ and heart disease, stroke, chronic obstructive lung disease, lung cancer, premature birth, dementia, and brain development (Academy of Science of South Africa, Brazilian Academy of Sciences, German National Academy of Sciences Leopoldina, U.S. National Academy of Medicine, U.S. National Academy of Sciences 2019), with additional adverse health outcomes reported in individual epidemiology studies. A 2017 review of projections of health risks from ozone and particulate matter under different climate change scenarios concluded that climate change is expected to worsen air quality by changing atmospheric processes and chemistry, resulting in increases in mortality, with results differing by region, scenario, and other factors (Orru et al. 2017). Since the preindustrial period, climate change already increased the global population-weighted fine particle ($PM_{2.5}$) concentrations by 5% and the near-surface ozone concentrations by 2% (Fang et al. 2013). Projections should take into account the complex interactions between climate change and air pollution, such as climate change constraining improvements in air quality in some regions (Trail et al. 2014). Incorporating the interactions among air pollution, climate change, health, and demography into HEM analyses and expressing these impacts using standardized metrics inclusive of morbidity and mortality would increase the accuracy and comparability of the estimates.

If implemented widely, we expect that the recommended guidance would lead to increased methodological harmonization in HEM studies and thereby enhance comparability and synthesis. As several reviews of mitigation health co-benefits literature highlighted (Chang et al. 2017; Gao et al. 2018; Haines et al. 2009; Remais et al. 2014; Smith and Haigler 2008), the variety of methods used to quantify mitigation health co-benefits has limited the extent to which results can be synthesized, particularly through meta-analysis. These reviews codified the HEM process but stopped short of providing prescriptive guidance. Implementation of this guidance should facilitate combining future HEM research estimates using meta-analyses and other approaches such as multicriteria decision analysis (Huang et al. 2011; Linkov et al. 2006; Wilson 2015; Yokota and Thompson 2004; Zhang et al. 2016). We recognize that the selection of modeling techniques will be context-specific, at the discretion of study groups, and scaled to a level that is relevant to decision makers. However, harmonization of modeling methods where appropriate and explicitly reporting the rationale for modeling approaches will facilitate synthesis, modeling at global scales, and greater policy impact, and allow for integration with other evidence from controlled and observational studies. As a corollary, the emphasis on open source data and code sharing for modeling, echoing other relevant EQUATOR Network guidance, will also facilitate comparison, retrospective harmonization, and understanding of the implications of methodological choices and untangling of differences due to use of different data sources, assumptions, and scenarios.

The panel notes that this guidance will likely require additional resources to implement and build global capacity to support stakeholder engagement, incorporation of additional team members, broader uncertainty analyses, and transparency regarding source data and model code. Identifying the needed resources may be a challenge because HEM research is already inadequately funded (Ebi et al. 2009) and more limited in scope than models of the economic costs and benefits of climate change mitigation. An implication of the guidance related to engagement is that additional investments are needed specifically to support transdisciplinary and interdisciplinary teams (e.g., funding for economists on teams of health researchers; improved stakeholder/decision maker engagement; strengthening partnerships and capacity of LMICs; increasing access to data sources, particularly in LMICs; and research on highly exposed and/or highly susceptible populations with lower adaptive capacity). Although some federal funding supports such efforts, such as the National Science Foundation's Convergence Research efforts, further investments are needed to update models as new insights are gained, for instance, into causal pathways. Investments by national funding agencies, foundations, and nongovernmental organizations would lead to better-informed mitigation decisions, building a more resilient and sustainable future.

A final point bears mention. This guidance is particularly relevant to large-scale HEM modeling efforts aimed at prioritizing mitigation investments and highlights the importance of considering implementation in modeling mitigation actions. Our expert panel was unanimous in highlighting the need for concomitant, parallel discussion of implementation, to include developing implementation case studies and other approaches to building the evidence base related to recognition, documentation, maximization, and publicization of mitigation health co-benefits—both to inform HEM modeling efforts and to facilitate rapid, effective implementation, of the policies that have been assessed to effectively promote optimal population health.

The guidance provided here can, with modification, be applied to other questions, such as the health effects of strategies to reduce urban heat islands through greening programs. As noted above, the potential relevance of such interventions for local population health and policy may justify their study despite a likely smaller global mitigation impact.

The need for better understanding, estimation, and reporting of the health effects of mitigation is clear. These guidelines have been developed to help improve the quality of modeling studies to inform mitigation policies. Improving this evidence base is critical to ensuring health is fully considered in mitigation strategies, encouraging both more mitigation and better design of mitigation to minimize negative health effects and maximize positive health effects. It is our hope that harmonization of health co-benefits studies will help inform better policy and thus improve public health outcomes.

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