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COMMENTARY

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Key Points:

- Policy advice in geohealth must acknowledge health and non-health tradeoffs
- Health is governed by complex social as well as natural/engineered systems
- Funding agencies can improve the quality of policy advice from geohealth by allowing or promoting a health nexus in funded projects

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Geohealth Policy Benefits Are Mediated by Interacting Natural, Engineered, and Social Processes

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Abstract Interest in health implications of Earth science research has significantly increased. Articles frequently dispense policy advice, for example, to reduce human contaminant exposures. Recommendations such as fish consumption advisories rarely reflect causal reasoning around tradeoffs or anticipate how scientific information will be received and processed by the media or vulnerable communities. Health is the product of interacting social and physical processes, yet predictable responses are often overlooked. Analysis of physical and social mechanisms, and health and non-health tradeoffs, is needed to achieve policy benefits rather than "policy impact." Dedicated funding mechanisms would improve the quality and availability of these analyses.

Plain Language Summary The Earth sciences can produce information of direct relevance to human health, for example, on the cycling of contaminants. Researchers provide policy advice in published articles with the goal of reducing health impacts. Many proposed policies, such as food consumption advisories, introduce complex tradeoffs that are rarely directly analyzed. Others, such as investments in pollution control technologies, have opportunity costs. This article encourages researchers to interrogate possible unintended consequences or tradeoffs. This is likely to involve social as well as natural or engineered processes. This article identifies possible barriers to effectively implementing this thinking, notably, funding mechanisms that exclude study of health endpoints.

1. Introduction

Recent years have seen great increase in interest in the health implications of Earth science research among geoscientists, policymakers, and others. Of all geochemistry-geophysics papers indexed by Web of Science since 1987 mentioning "health" in the abstract, roughly half have been published since 2015. This interest has been reflected in the proliferation of publications (e.g., GeoHealth by the American Geophysical Union) and professional societies (e.g., Geology for Global Development) devoted to mobilizing Earth science expertise to improve human health and wellbeing. This research has the potential to be highly convergent (NRC, 2014), linking physical models developed at large spatial and temporal scales (e.g., multi-decadal global climate models) to individual- or community-scale socio-environmental models for human exposures and health outcomes.

Geohealth research products most often characterize a natural process (e.g., environmental contaminant cycling) and make inferences about risks to human health by drawing on the health sciences literature. Policy recommendations tend to represent humans as receptors whose overall health will be improved or impaired by simple policy or behavioral levers. For example, the geohealth literature is replete with calls for fish consumption advisories, emissions controls, capital investments, and other interventions intended to achieve a human health benefit. Implicit in these recommendations is a single causal chain between natural system, human exposures, and health outcomes. Whether or not proposed interventions would minimize human health impacts, cost-effectiveness, feasibility, or potential tradeoffs are rarely directly interrogated in articles providing policy advice.

Advice on increasing the "policy impact" of environmental research has traditionally focused on study design and publication practices (Bilotta et al., 2015) and has even encouraged authors to recast policy debates around existing research agendas (Rose et al., 2020). This is problematic because it reinforces monodisciplinary models of health and the environment and encourages decision-making based on the persuasive power of individual scientists or research groups. In reality, net health impacts of policy interventions are determined by interacting natural, engineered, and social processes, which are currently poorly represented in geohealth research. Scientific

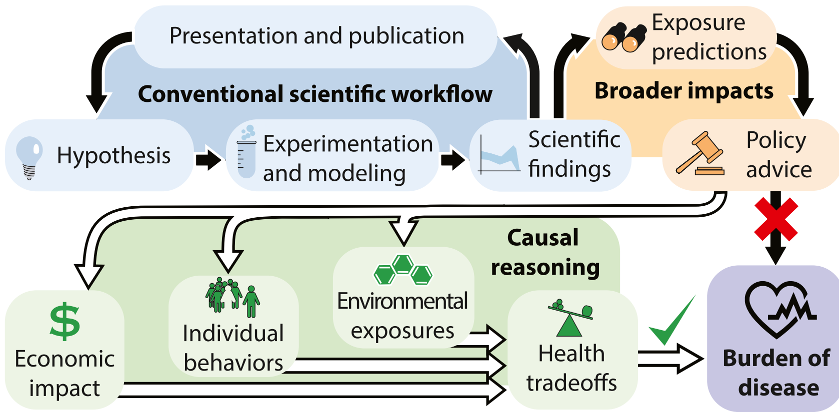

Figure 1. Earth science investigations frequently conclude with policy advice that anticipates a straightforward impact on human health (black arrows). We call for analysis that considers the diverse mechanisms by which advice may pose health tradeoffs instead (white arrows). The conventional scientific workflow (top left) can also be enhanced by greater knowledge co-production and other strategies discussed in Section 4.

research thus has greater policy *benefit* when it provides a structured analysis of tradeoffs actually confronted by policymakers, which frequently cross traditional disciplinary lines, and when it seeks to "inform, not persuade" (Blastland et al., 2020).

In Figure 1, we illustrate how policy advice may emerge as a byproduct of the traditional scientific workflow in the Earth sciences. In the United States, policy insights from geoscience work frequently emerge as co-benefits of traditional scientific activities, for example, as a "broader impact" in the terminology of the National Science Foundation. Findings from a well-defined geoscience hypothesis are often interpreted in the context of risks to human health, and corresponding advice is issued to reduce those risks. Ultimately, we call for geohealth research that identifies potential policy interventions carefully and with consideration of the range of likely mechanisms that could pose, at a minimum, health *tradeoffs*, if not tradeoffs across health and non-health outcomes. A full policy analysis is understandably outside the scope of most Earth science research. However, a lack of causal reasoning around proposed policy interventions may lead to adverse consequences for communities who may otherwise benefit most from scientific research.

There are many examples of adverse outcomes from geohealth interventions linked to inadequate consideration of the interacting social, natural, or engineered processes in which they are embedded. These include rebound effects, where efficiency improvements designed to arrest depletion of environmental resources instead accelerate their depletion by lowering costs (Berbel et al., 2014; Wheeler et al., 2020); the adverse impacts of green infrastructure on ground-level air quality via perturbations to local atmospheric chemistry and physics (Wang, 2021; J. Zhang et al., 2019; Y. Zhang et al., 2020); changes to drinking water sources made to avoid pathogen exposures or reduce costs increasing exposures to other contaminants (Escamilla et al., 2011; Masten et al., 2016); and fish consumption advisories that reduce contaminant exposures but also nutrient intakes, and which often affect dietary patterns of individuals other than those targeted (Calder et al., 2019; Shimshack et al., 2007; Stone & Hope, 2010).

We use the example of fish and seafood consumption advisories as a case study to demonstrate how seemingly simple policy advice is complicated by tradeoffs across life science disciplines and uncertainties across natural and social systems. We continue with a generalizable discussion of how geohealth research is complicated by patterns of information diffusion, including the role of the media. We close with a set of recommendations to scientists and policymakers.

2. Case Study: Fish and Seafood Consumption Advisories

Fish and seafood bioaccumulate chemicals such as polychlorinated biphenyls and methylmercury (MeHg), and consumption advisories are a commonly advocated and deployed tool to control human exposures (Fair et al., 2018; Ghoshdastidar et al., 2018; Imm et al., 2005; Li et al., 2022; Ni et al., 2021; Sundseth et al., 2015).

Yet fish and seafood are also low-fat, high-protein foods rich in micronutrients, and there is a rich evidence base for the cardiovascular and neurodevelopmental health benefits of fish and seafood consumption (Ruxton, 2011). In practice, consumption advisories are designed to contain human exposures to contaminants within the range of reference doses (levels judged unlikely to result in excess risk) or, for carcinogenic/genotoxic contaminants, a dose associated with an acceptable excess lifetime cancer risk (often 1 in 100,000) (U.S. EPA, 2000).

Interventions to lower contaminant exposures to a risk-based target are not necessarily health-protective if there is a countervailing impact on nutrient intake, particularly if baseline contaminant exposures are near or below reference doses (Hellberg et al., 2012; Stone & Hope, 2010). For example, MeHg and ω-3 long-chain polyunsaturated fatty acids (ω-3 PUFAs) from fish and seafood exert opposite effects on common cellular mechanisms that influence cardiovascular and neurodevelopmental risks such that most fish are likely to present net benefits over wide ranges of intakes (Ginsberg & Toal, 2009; U.S. FDA, 2014). However, risk-benefit models vary widely in assumptions over plateaus in benefits, dose-response shapes for both MeHg and ω-3 PUFAs, the range of endpoints considered, approaches to weight the importance of each endpoint, and assumptions about counterfactual dietary patterns (Calder et al., 2019; Groth, 2017; Rice et al., 2010; Stern & Korn, 2011). Thus, even idealized models of likely health impacts of changes in fish consumption necessarily embed subjective professional judgments of the strength of diverse lines of epidemiological evidence and the relative importance of different risks and benefits.

These uncertainties are compounded by unpredictable responses to fish consumption advisories. Targeted individuals may be unaware of advisories (Anderson et al., 2004) or ignore them (Burger, 2000). Conversely, advisories can also lead to reduced consumption of species not targeted by an advisory and/or among individuals not within the scope of the advisory (Shimshack et al., 2007). Among individuals who reduce consumption of fish and seafood, net health benefits are extremely sensitive to what foods are substituted in diets; even modest increases in red meat consumption are likely to have significant net negative effects on cancer and cardiovascular risks, and there are substantial uncertainties associated with patterns of diet switching (Calder et al., 2019; Cohen et al., 2005). There is a literature on improving the understanding of consumption advisories (Burger, 2000; Tan et al., 2011), but ultimately there is no predictive model for the social responses to these interventions.

Overall, calls for fish and seafood consumption advisories, like other geohealth interventions, are only justified following a comparison of risks of action versus inaction. This calculation is often made successfully in cases of urgent hazards with well-understood solutions (e.g., changing water sources, repairing treatment infrastructure, or distributing bottled water following an outbreak of waterborne disease). Conversely, smaller risks are often understood using inferential techniques such as low-dose extrapolation, introducing substantial uncertainties and subjective elements that complicate a comparison with the risks of intervention. Many geohealth interventions anticipate a response from individuals, but these are unpredictable and interact with uncertainties in natural or engineered systems in subtle ways as the above case study demonstrates.

3. Geohealth Is Complicated by Patterns of Information Diffusion

Geohealth interventions are complicated by information diffusion patterns beyond the control of scientists, notably, among the media, individuals within affected communities, and groups with an interest in scientific findings. In most sciences, individual researchers have great latitude to decide how much to engage with the media, the public, or policymakers as a function of their own perceptions, incentives, priorities, and aptitudes (Besley & Nisbet, 2013; Corley et al., 2011). Conversely, geohealth research often addresses questions of high public salience and may spawn media coverage and sustained discussion in affected communities; in these cases, researchers may have a responsibility to engage with media to ensure coverage and perceptions are consistent with actual scientific findings.

Research with a health nexus receives vastly more media attention than other areas of scientific inquiry, for example, >90% of U.S. mass media articles in 1990 and 2001 (Suleski & Ibaraki, 2009). Traditional and social media coverage drives awareness of environmental risks in settings ranging from Indigenous communities in Canada (Furgal et al., 2005; Wheatley & Paradis, 1996) to the general populations of diverse countries where studies have been conducted, including the U.S., Italy, and China (Maran & Begotti, 2021; Ragain, 2009; Tilt & Qing, 2010). Scientists have little control over media representation or interpretation of published findings, which can lead to unexpected complications: media coverage of health research is prone to sensationalism, can overstate confidence in, and generalizability of, findings, and tends to focus on adversarial dynamics of scientific debates rather than critically evaluating the strength of evidence on either side (Chang, 2015; Nabi & Prestin, 2016; Shuchman & Wilkes, 1997). Implications for individual decision-making (e.g., whether to eat less fish) presented by research articles may thus be magnified or distorted by media coverage regardless of the intent of the authors. Authors may minimize the potential for misrepresentation of research findings by actively engaging with media and addressing and confronting likely misunderstandings directly with reporters.

The communities most vulnerable to environmental hazards tend to be the ones most vulnerable to incomplete, misleading, or alarmist information. For example, Indigenous communities in the Arctic face high contaminant exposures due to patterns of global contaminant cycling and deposition and diets rich in predatory fish and mammals (Bard, 1999; Van Oostdam et al., 1999). Communicating scientific information on environmental risks to Indigenous communities is however complicated by language barriers, differences in conception of risk, and the potential for distortion of scientific information across large social networks (Arquette et al., 2002; Furgal et al., 2005; Mercer et al., 2010). Individuals from different backgrounds may have attachments to foods, traditional medicines, and other cultural products that represent genuine hazards (e.g., heavy metals in traditional cosmetics) but that also fulfill culturally specific psychosocial roles (Ernst, 2002; King & Furgal, 2014; U.S. EPA, 2023). Potential health gains from interventions in culturally specific practices should be weighed against impacts of disruption, ideally, in close collaboration with representatives from the affected communities (IARPC, 2018).

Finally, geohealth findings and policy advice may be used in unanticipated ways by special interest groups. For example, our own work characterizing health impacts of new hydroelectric reservoirs in Canada has been cited by U.S. environmental groups opposed to expanding cross-border electrical interties (Birchard, 2017; Calder et al., 2016; Riverkeeper Inc., 2019). Because such interties usually draw from existing rather than new generation, different environmental risks and benefits are relevant to the policy debate around intertie expansion. We thus did not anticipate that our research would be used to lobby against deeper integration of the electrical grid, which is widely considered to be a key pathway to decarbonization (Dimanchev et al., 2021). We have since countered these arguments through media outreach and an expanded research agenda that characterizes social costs and benefits of hydropower exports in the broader context of the renewable energy transition (Calder, 2019a, 2019b; Calder et al., 2020b, 2022; Matson, 2022; Willson, 2023).

4. Strategies to Increase the Policy Benefits of Geohealth Research

The convergent nature of geohealth research creates unique opportunities to use scientific analysis to support decision-making around complex policy challenges. However, as described above, policy recommendations that do not adequately reflect the interactions of social, natural, and engineered systems, or that do not appropriately reflect uncertainties, may be counterproductive.

Knowledge co-production has emerged as a set of practices to build communities affected by environmental (and other) risks into the research process, from hypothesis generation to articulation of scientific findings, and, if justified by the scope of the analysis, policy advice (Armitage et al., 2011; Woodall et al., 2021). Early and active involvement of members of the public, community activists, policy experts, and/or other stakeholders from a variety of backgrounds increases the likelihood that research will reflect relevant tradeoffs. Funding the participation of community members and organizations to the extent possible is crucial given their time and resource constraints. This is especially the case for organizations serving historically marginalized or disadvantaged communities, which may face the greatest constraints while engaged with the most vulnerable groups.

There is a growing literature providing guidance on community-engaged science, with models varying according to timeline, whether a project is community-led or researcher-led, and whether the primary outcome of interest is generalizable knowledge or site-specific decision support or interventions (David-Chavez & Gavin, 2018; Hayhow et al., 2021). This adds to emerging guidance from the U.S. Government, for example, the Interagency Arctic Research Policy Committee Principles for Conducting Research in the Arctic (IARP, 2018). These strategies are essential for creating informative and policy-relevant science and also for using science to meaningfully advance environmental justice (Hoffman-Hall et al., 2022).

Graphical modeling tools, known variously as "results chains," "logic models," "Bayesian networks," and other terms, have emerged as a set of methods to structure relationships among interventions and responses among social and physical systems (Calder et al., 2020a; Tallis et al., 2019). Graphical models can be used to identify potential synergistic or antagonistic processes and areas of uncertainty in order to inform new research questions or identify the possibility for unintended consequences. Development of these models also encourages interdisciplinary collaboration and community engagement to ensure that all relevant pathways and concepts have been incorporated. Policy advice based on a detailed graphical model is likely to be more nuanced and comprehensive than one that emerges as a byproduct of a relatively narrow geoscience investigation.

Graphical models have found some use in international development and other social sciences, in environmental health, and in the rapidly growing field of planetary health, but are still rare in the Earth sciences. Interest in these methods may rise after COVID-19 demonstrated the need to balance spread of infectious disease with countervailing economic, psychological, and other impacts of concern (Alexander & Shareck, 2021; Calder et al., 2021; Diallo et al., 2023). Overall, there is a growing literature from which geoscientists can draw to better align scientific research with policy impact to the benefit of communities facing environmental risks and policymakers facing poorly elucidated tradeoffs.

Barriers to effective practice of convergent geohealth remain. Perhaps most significantly, geoscience and health research funding is directed overwhelmingly at basic science, while policy transferability and community engagement are often considered a "broader impact," at least in the United States (Figure 1) (Seitter et al., 2022). A recent analysis by the American Meteorological Society concluded that research advancing best practices in U.S. geohealth is likely to fall outside the scope of the primary federal funders of both geoscience (National Science Foundation) and health (National Institutes of Health) (Seitter et al., 2022). Likewise, major funders of interdisciplinary research often specifically exclude research with a health nexus (Alfred P. Sloan Foundation, 2022). Funding opportunities dedicated to convergent geohealth research such as NASA's Health and Air Quality program are rare (NASA, 2021). We note positive developments, for example, a recent NSF call for applications to supplemental funding for graduate students whose work links geoscience to human health (NSF, 2023). Still, despite significant emerging interest in geohealth, it is often pursued, by necessity, on an ad-hoc basis as allowed by available time and money. The lack of institutional structure around geohealth research is almost certainly impairing development of consensus around research priorities and the dissemination of best practices.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data were not used, nor created for this research.

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