AGU Report to NSF on Accelerating Research and Impacts in GeoHealth

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Executive Summary

GeoHealth represents the critical intersection between the Earth and environmental sciences, and agricultural and health sciences. Following a specific request from the National Science Foundation (NSF; an acronym list is at the end of this Report) this report provides a series of recommendations aimed at empowering research, building fundamental workforce capacity, and improving communication around GeoHealth to the public and policy makers. This development is critical as a robust GeoHealth research enterprise is essential to global health, human and ecosystem well-being, and sustainability. The AGU community along with those from several allied societies provided the recommendations in this report; these were developed for a detailed survey and two workshops. The survey and other input revealed several broad challenges and needs, including highly siloed funding and support for researchers across institutions and societies, the inability to access or combine key datasets, and in particular the lack of clear career trajectories and support. The recommendations consist of: (i) six programmatic areas where significant attention to building a GeoHealth research enterprise is needed; (ii) approaches and concepts for four specific challenges in GeoHealth for which significant results could be enabled rapidly, within 2-3 years; (iii) ideas for developing an education/career path and for outreach; (iv) larger "moonshot" ideas that might yield very significant impacts over ca. 10 years. All of these have several common elements and themes: they leverage many directorates within NSF, including all within the GEO division; can build off of existing initiatives; are best developed through partnerships with other agencies and communities; and rely on open and FAIR data sets. Although the focus of these recommendations is toward and for the NSF, the suggestions are more general and hopefully will be considered by other funding agencies and other parts of the research enterprise in the U.S. and internationally.

Introduction

GeoHealth encapsulates the growing importance of the complex interactions between the environment (comprising Earth's surface and near surface, natural resources, water, soils, air, geologic processes including hazards and climate change, and ecosystems and other living organisms) and the health, well-being, and continued progress of human populations. It includes the interactions between climate change and health and diseases; acute and chronic pollution and health; the complex effects of natural disasters, including on mental health; as well as the relation of natural processes to ecosystems and agricultural systems—touching the food, energy, water nexus. Here, "Geo" refers to nearly all aspects of understanding Earth and Earth's systems, and "Health" similarly refers to agricultural and ecosystem health, which provide benefits to humanity and sustainability, as well as all of human health; for example, GeoHealth includes the often neglected mental and psychological health challenges of disasters, chronic pollution and environmental degradation, and migration forced by climate change. The social sciences and indeed most other sciences are closely connected as GeoHeath almost always bridges basic and applied research. While research in "GeoHealth" has a long history—for example, dealing with mining and health, environmental lead pollution, or improving water and air quality; and while some broader efforts have emerged over the past year–for the most part GeoHealth research has not been a priority for funding or institutional capacity building. There are few dedicated funding efforts, societies, or departments. This is a critical challenge because GeoHealth is central to nearly all major challenges in sustainability and providing for a healthy future for humanity. Air and water pollution are leading contributors to the global burden of mortality and morbidity; nearly every major pandemic and natural or human-caused disaster has a large environmental health component; and, climate change is a stress multiplier, impacting environmental quality, disaster risk, spread of infectious disease and vector habitats, and the capacity of communities to be resilient to these risk factors. Research at the intersection between the geo-environmental and health sciences has revealed systematic environmental and climate injustice and inequity challenges. There have been numerous calls for an expanded research effort around these topics (e.g., see Almada *et al.*, 2018; Colwell and Machis, 2019; Frumkin and Jackson, 2020).

Recognizing these critical needs, the National Science Foundation (NSF) reached out to AGU and other societies to provide ideas for expanding their portfolio around GeoHealth. Specifically, we were asked to convene our community to:

1. Identify the highest priority, most impactful, interdisciplinary/convergent challenges in GeoHealth that can be addressed in the next 2 to 3 years. Include a list of corresponding stakeholders, potential partners, and high impact deliverables to society and the economy. Do not limit your ideas to a single theme or topic. Longer-term topics are welcome and encouraged but should include what critical and impactful outcomes/products/concepts can be delivered in the 2–3-year timeframe.

2. For each idea, create a roadmap to address the identified challenges and provide solutions. If possible, provide timing of milestones and the delivery of high impact results and technology. Indicate partnerships required to deliver on the promise.

3. Provide ideas on the creation of an aggressive outreach/communications plan to inform the public and decision makers on the critical importance of geoscience to providing solutions, tools, utilities, and technologies to help overcome/address identified challenges/problems in environmental impacts on human health.

4. Identify information, training, and other resources needed to embed a culture of innovation, entrepreneurialism, and translational research in GeoHealth.

AGU approached this charge by first conducting a survey to gather input on challenges and the general state of GeoHealth research from key stakeholders—our members, as well as engaging leaders and members from several related societies including the American Public Health Association (APHA), Federation of American Societies for Experimental Biology (FASEB), and Society for Environmental Toxicology and Chemistry (SETAC). We received about 80 responses to a request for input and survey. We then held a virtual workshop, attended by about 30 of the respondents to develop key ideas and roadmaps, then held a smaller in-person workshop with key AGU GeoHealth leaders to organize and extend these ideas.

This report represents the synthesis of this effort and input, conducted over 1 month. Given the charge, we focus on immediate recommendations and several key example integrative programs that could have high impact for developing GeoHealth rapidly. We also provide some longer term "moonshot" ideas that likely need further development but would have a significant impact over the decade if appropriately resourced. The focus includes not just research ideas but developing the commensurate capacity—human and infrastructure and cross-disciplinary connections—and societal impacts, necessary for enabling the research and its benefits for humanity. The full set of input and survey results are included in the appendix. The listed authors are the steering committee; the AGU GeoHealth Advisory Board and all the participants (see Appendix) provided numerous inputs, edits, and comments.

Timeliness and Importance of GeoHealth

As noted above, GeoHealth has emerged as one of the critical convergent sciences of the 21st century (McNutt, 2018). Some discussion is provided above; several specific examples of recent research and challenges expand the perspective: Taking the COVID-19 pandemic alone, GeoHealth is central to questions regarding human-wildlife contacts leading to zoonotic spillover events (Tollefson 2020), the impact of air pollution on severity of disease symptoms, with associated environmental justice considerations (Wu et al. 2020), and the possible influences of meteorology, seasonality, and prevailing climate conditions on transmission risk (Kerr et al., 2021). More broadly, GeoHealth research has shed light on environmental drivers of infectious diseases, taking into account climate variability, local environmental conditions, and the ecology of waterborne, vector-borne, zoonotic, and direct transmission diseases (e.g., Colston et al., 2022, Moore et al., 2017, Gorris et al., 2019, Wimberly et al., 2014, Tamerius et al, 2013, Mordecai et al., 2020).

Despite this importance, GeoHealth's development faces major challenges because it falls between both the mandates and missions of major funders in the U.S. and worldwide, as well as between the physical and biological and health sciences in institutions and societies. It also embodies such diverse overlapping issues and topics that it requires interdisciplinary knowledge, thinking, and tools. Addressing the challenges (some listed below) invariably requires a multi- or trans-disciplinary team approach. This requires building networks and teams across disciplines, and thus across departments, societies, and funders. These challenges are reflected in the survey results: researchers perceive that funding is siloed and find it difficult to gain support for GeoHealth research, there are few clear career paths for students, and GeoHealth is not a central area of focus in many societies. Publications are scattered across many disciplinary titles. GeoHealth research is ideal for identifying solutions to societal problems, providing societal benefits, enabling community science, and improving environmental justice, but these are difficult to manage, and few researchers are well-trained or incentivized to engage in this work. Some recent progress has been made: AGU started a GeoHealth section in 2018 which has grown rapidly to close to 1000 affiliated members, and AGU and Lancet journal titles covering this topic also started in 2018. But much more attention is needed to develop a thriving cross-disciplinary community. NSF can play a key role.

Six Immediate Steps NSF Could Take to Catalyze GeoHealth by Fostering an Enabling Environment

Community input through our approach helped identify several recommendations to NSF (and other agencies, societies, and universities) that are programmatic and thus at a higher or organizational level than the charge for fostering and enabling specific interdisciplinary and convergent challenges around GeoHealth. These are indeed critical for enabling any and all of the solutions to these challenges, and we hope that these will garner close attention. Many of these recommendations turned out to be very similar to the high-level, integrative recommendations in the report on climate change solutions provided last year to NSF (https://doi.org/10.1002/essoar.10507256.2). Here are six important high-priority steps that NSF could take to catalyze GeoHealth. For each of these (and all of them collectively), it would be reasonably straightforward to develop metrics that measured demonstrable impact around, e.g., communities engaged, number and progression of students, data sets available, etc.).

1. Enable interoperable GeoHealth data and software across NSF

As an example of convergent science, progress on GeoHealth depends on available, interoperable data from many disciplines. This is a particular challenge for GeoHealth because it requires bridging across the physical and biological and health sciences, which have developed data and metadata structures and data infrastructure somewhat separately–for example, in aligning geospatial data. Progress on GeoHealth will also depend on extensive, rich, longitudinal environmental and health data, where collection efforts likely span many individual grants. These needs also fit well with the mission of the new Technology Directorate within NSF. It is also closely related to the recommendation provided in the climate change solutions reports provided earlier to NSF for broad environmental monitoring and enabling FAIR data. Some examples where NSF is already engaged in extensive data collection efforts include around wildfires and air and water pollution. Promoting and incentivizing interoperability will bring scientific communities together.

There are many current challenges with respect to enabling FAIR data and software, and much work needs to be done across the community. One key step that NSF could make to greatly incentivize and complement these efforts is to elevate the importance of data management plans by including them in the "intellectual merits" section of proposals, so they are considered as such by reviewers, rather than the last section of a grant. One approach might be to expand the "intellectual merits" to an outcomes approach that includes, for example, "…explaining how the outcomes of this work—including new data, software, materials, samples, and products—will have scientific and societal value and impact and be curated following leading practices." Adding such a direction would help elevate the importance of these outputs.

A larger challenge is supporting the infrastructure needed to support these data and make them interoperable. A leading solution is the many domain repositories in the Earth and environmental sciences, many of which were started with NSF support. Challenging and incentivizing federal institutions and especially universities including internationally to work with these repositories as a leading practice would be both cost effective and support quality curation (versus poorly curated and disorganized institutional repositories).

Another challenge is incentivizing the use of these data. For example, the costs of natural hazards are mostly reported based on loss of or damage to infrastructure; the human and environmental costs, including from increased acute and chronic disease and pollution burdens, mental health, and loss of ecosystem services, are usually not included, likely because they are not collected or regularly assigned to the triggering event. Thus these "GeoHealth" effects, which likely exceed the infrastructure costs in many cases, are mostly not known, but are needed to inform how to build resilience or direct responses most effectively, or to build predictive approaches and models.

These GeoHealth effects are particularly challenging for data integration initiatives because use and distribution of health data is often restricted in order to protect privacy. In elevating the importance of data innovation in GeoHealth, NSF can accelerate development of privacy-protecting data solutions that enable integration and analysis of data across disciplines. Achieving these data solutions and workflows would dramatically accelerate the pace of collaboration and innovation to address environmentally mediated health risks.

2. Leverage Existing Programs and Networks

NSF (and other funders) needs to signal clearly to the community that convergent research in GeoHealth is welcome and take clear steps in the proposal process to reinforce that message. The perception of many investigators, based on experience, is that it is difficult to get GeoHealth-related grants within existing disciplinary funding calls, both because of the interdisciplinary nature of GeoHealth and because reviewers of NSF proposals may not look favorably on health research that they feel falls within the NIH mandate. For this reason, researchers are intentionally leaving health out of their NSF proposals. Many Earth and environmental science programs at NSF are core to advancing GeoHealth and should welcome such proposals. Peer review guidelines and practices would need to be adjusted in support, for example by intentionally broadening the reviewer and panel pools and indicating in review panel instructions that GeoHealth aspects are encouraged or required (e.g. by including a health component or collaboration with stakeholders in government or community organizations).

There are numerous opportunities to do this, since GeoHealth touches practically every core program at NSF. Thus programs and funding approaches that extend across NSF are particularly relevant for GeoHealth, including RCN's and Convergent accelerator programs. RAPID grants can also be used. NSF funds several existing "centers" which already include interdisciplinary teams and for which their mandate could be extended to include GeoHealth specifically, for example in addressing environmental and health impacts of disasters. There are examples of other federal funding programs that could provide models, for example, NASA's applied science program, NOAA's Climate Test Bed, or other agency partnership programs.

3. Expand Collaborations and Encourage Joint GeoHealth Funding Opportunities with Other Agencies

NSF already has some collaborative grant programs with NIH that can be expanded around GeoHealth. Other relevant agencies include EPA, NOAA, USGS, DOE, DOD, CDC, and NASA. This may be a longer process for actual funding programs, but starting the intentional conversation with agencies, and educating and seeking support from the NSB, OSTP (including USGCRP), and Congress is important in breaking the large institutional barriers we have around GeoHealth. This may be necessary to ensure that GeoHealth programs and solicitations, which are by nature highly interdisciplinary, are viewed favorably and potentially even collaboratively across agencies with different disciplinary foci.

Federal appropriations for Agencies that could appropriately fund GeoHealth research are scattered across multiple Congressional Committees and sub-Committees. It would be helpful for NSF to work with other agencies to explore joint funding initiatives that are specifically designed to encourage work among these agencies. AGU and other professional societies can help promote to Congress the benefits of such joint funding initiatives. At a more basic level, these stakeholders could help with a broader census of existing programs that might streamline alignment and expansion.

One additional idea is to leverage, or encourage proposers to leverage, Federal Executive Boards in major metropolitan areas at the local level as these are often already working across various agencies. This approach might be powerful in some of the specific "Center" models below.

4. Incentivize the Broader Impacts Related to GeoHealth

Many areas of GeoHealth research are connected to local and regional public health and ecosystems health issues and challenges. Many communities with the greatest GeoHealth challenges are also those with systemic challenges around environmental justice and are facing the greatest harmful impacts from climate change, disasters, and environmental degradation. Expanded research support for GeoHealth is thus an excellent opportunity for NSF to better incentivize the "broader impacts" of science and showcase the societal benefits. This potential was a consistent input from the stakeholder communities. This can be leveraged in several ways.

First, we recommend that environmental justice and equity be embedded explicitly in any GeoHealth (or indeed NSF) funding program.

Second, several recommendations put forward on climate change solutions (https://doi.org/10.1002/essoar.10507256.2 and see sections starting on p. 7 and 12) can be easily extended or adopted for GeoHealth. These include allowing, or indeed encouraging, support for stakeholder engagement in grants. In this case, "stakeholders" could be representatives of community groups, governmental agencies, non-governmental organizations, or any other organization that is in a position to apply the research and its outcomes to improve a decision-making context. Providing direct grant support for the "Broader Impacts" work in grants would also help improve the recognition of this work, and value of it, in the science reward and promotion systems.

Third, NSF should consider how to support training and awareness of good community science practices among funded researchers and students. Such training would improve outcomes research, and through effective community work, engender trust in science.

5. Support Efforts to Build and Develop a GeoHealth Community

Developing a significant GeoHealth research program rapidly requires considerably more effort to connect disparate communities. There are currently few meetings, conferences, and workshops that allow for this. Funding workshops or conferences where such collaboration is required and intentional could catalyze these connections, for example, with multiple societies across disciplines, or regionally around a Center. It is important also that the social science and engineering communities be engaged as well as community stakeholders (see idea 4 above). This may also be an opportunity for collaboration with other federal agencies, e.g., NIH and NIEHS, HHS, NOAA, NASA, etc., or even internationally.

6. Signal Clearly that GeoHealth is a Critical Interdisciplinary/Convergent Research Field and Viable Career for Students

Many of the above steps would help, especially collectively, signal that GeoHealth is a viable and important area of convergent research, as it should be. The future of the field requires that we build research capacity quickly, and especially among early career researchers. Thus, in addition, NSF could target or set aside support for early career graduate students and post-doctoral researchers, especially ones that are trying, or wanting to, bridge or learn about other disciplines, for example by leveraging or expanding programs like CAREER around GeoHealth: https://beta.nsf.gov/funding/opportunities/faculty-early-career-development-program-career. Other ideas, e.g., related to GeoHealth Centers are outlined below.

Specific GeoHealth Challenges and Roadmaps for Growing NSF Support

The survey responses provided a wide range of specific, impactful ideas and challenges that NSF could support. The full range of ideas is included in the appendix. Of these, the community identified and developed roadmaps for six major challenges; four of these are provided below as leading examples that cover, and are organized with, a range of broad GeoHealth challenges. Topics on education and communication are covered separately. In many cases the roadmaps could be applied to other questions or challenges. Most also leverage or build off the key steps above and have several common themes around promoting convergent engagement, capacity building, environmental justice, and more. These also illustrate the unique convergent challenges, and needs, related to GeoHealth research.

In order to capture the diverse ideas raised by workshop participants we include the proposed "roadmaps" in only lightly edited form. As these roadmaps were drafted during a limited-time participatory workshop exercise, they present a starting point for more detailed work on NSF program development.

An additional recommendation focusing on GeoHealth and Climate Change was called out in AGU's recommendations to NSF on Climate Change Solutions (https://doi.org/10.1002/essoar.10507256.2; see pp. 20).

Challenge 1: Environmental Change and Disease

How will human interaction with the environment (including climate change, urbanization, migration, ecological habitat destruction) impact diseases that affect humans? How can we prevent adverse outcomes? Who is at most risk? Diseases include infectious and non-communicable diseases (e.g. cardiovascular, respiratory, cancer, mental health outcomes). Much more work needs to be done to understand the potential health implications of exposures to complex mixtures of chemicals in the environment, and of chronic exposures to low levels of contaminants and contaminant mixtures.

There is a great need in understanding the geography of impacts and effects better. This plays directly to several strengths of the geoscience community, which has developed the tools (i.e., remote sensing, spatial analysis), assimilation of big data (coupled bio-geo-social datasets), the history of working with coupled models, and a deep conviction that geography (location) matters.

<u>Possible Approach:</u> Create and support a program to develop multi-institutional consortia of representatives from universities, government agencies at federal, state or local levels, NGOs, international organizations, and private sector to identify hotspots of environmental change (both climatic and land use) and identify what health outcomes are of particular concern in those areas and how big/diverse are the affected populations. For the most part these critical data and information are not well described at a level that is actionable.

<u>Potential Outcome:</u> In 2-3 years, it should be possible to have learned which global communities are under extensive threat for adverse health outcomes spurred by the confluence of multiple environmental hazards, which benefits society or enables further research by identifying most vulnerable populations and the specific health outcomes of concern. This work will also create the baseline assessment and a suite of datasets that can serve as the basis for developing longer-term strategies for GeoHealth development. It would also clarify how many people suffer with what kind of diseases and provide valuable information for where to direct public resources to undertake mitigation approaches and enhance community resilience.

<u>Implementation requirements and steps, and other ideas:</u>

- Build and incentivize community
- Starting from the geographic/GEO perspective, identify hot spots of environmental change that will influence risk factors connected with multiple health outcomes.
- Gather and organize environmental data from Earth observations and models.

- Add health data which can be crowdsourced or shared by public health agencies and through collaborations
- Partner with international organizations (WHO, WMO) NIH, NASA, NOAA and foster international author groups.
- Follow-up engagements with the communities where hotspots have been identified?
- Collaborate with public health agencies that facilitate data sharing in both directions. We would like to have more access to epidemiological surveillance data, and can give something back in return.
- May be able to approach regionally.
- Facilitate access to the data products for the general public as well as the scientific community.
- Direct outreach to and engagement with disadvantaged communities, particularly those in areas where hotspots have been identified.
- Generalize to other environments with similar processes (develop predictive science). Predict better health impacts of climate change and urbanization

Ways to Scale Further: We proposed to create a multi-stakeholder consortium that includes representatives from academia, government organizations at the local, state and federal levels, private sector and the NGO, with the changing memberships throughout the life-term of the project (new members joining at various stages) to enable a sustained concerted effort over time.

At the end of the initial three-year project, the goal will be to have assembled a harmonized baseline dataset and developed methods for identifying hot spots of environmental change along with criteria for identifying the specific health risks associated with each hotspot. This dataset will include characteristics of the physical environment including climate, land cover, and land use as well as the distribution and social characteristics of human populations. A unique characteristic of this assessment will be the capacity to look at the cumulative effects of multiple environmental health risks. For example, are megacities at increasing risk of heat-related illnesses also at risk of urban malaria? The projects will have developed a consortium of researchers and public health experts and communities focused on several of these hotspots that have been selected for more detailed assessment. The program will also foster a collaborative community that can work across disciplines, environmental media, diseases, and organizational roles to more rapidly research and identify solutions to health-damaging environmental changes in the future.

Scale-up in later phases of the effort will involve:

- Extending the baseline assessment with long-term projections of future change.
- Engagement with more scientific experts who can refine and improve the assessment of environmental risk factors.
- Finding projects focused on assessment of specific hotspots of interest.
- Identifying areas of concern outside the hotspots.
- Engagement with more hotspot communities for more detailed consideration of the environmental changes, associated health risks, and implications for communities.
- Incorporation of new sources of epidemiological data to test the underlying predictions of environmental health risks.

Challenge 2: Cumulative Impacts of Acute and Chronic Environmental Hazards

What are the cumulative health impacts of pollution in air, soil, and water? How will increasing or changing hazards exacerbate these impacts? Is there a tipping point in terms of human health? Ecological health? How does repeated exposure through time impact health outcomes? What are the positive feedback loops? How will climate change affect human exposure to and vulnerability to pollution? Who is most vulnerable to these cumulative impacts and how do we prioritize and work with those communities? These include both the acute and chronic health effects; the chronic effects have in particular been understudied and may be even more important.

Possible Approach: NSF will develop an integrated research program that intentionally calls for proposals that research the cumulative impacts of acute and chronic environmental hazards in GeoHealth (x, y, z, happening concurrently in a single community or region). Examples might include: (i) A hurricane during the height of mosquito season leading to an infectious disease outbreak in a low-income community that is still recovering from the previous hurricane season. (ii) A wildfire that happens during a heat wave and global pandemic. (iii) the distribution and health impacts of plastic pollution; (iv) the acute and chronic effects of mine pollution and drainage; (v) adverse health effects of urbanization (to help design urbanization better).

Potential Outcome: In 2-3 years, a new transdisciplinary research methodology will have been developed that considers hazards not in silos but together, and that accounts for and predicts the health impacts of disasters and climate change. This will have enabled communities to be better prepared for these events and has begun to justify a governmental structure as well as research structures to respond to cascading hazards.

Implementation requirements and steps, and other ideas:

- The research conceptualization starts with the broad premise and goal of achieving convergent research in GeoHealth—it is intentionally cross disciplinary.
- This effort brings together separate research, for example, conducted on wildfires, heatwaves, and pandemics–to explore how they interact together and what are the cumulative and cascading impacts, risks, and costs?
- Will need to conduct a risk assessment and potentially develop a research methodology
- NSF + USGS would need to open repositories to enable this more transdisciplinary research.
- Local communities, responders, and end users need to be at the research table at the beginning to ensure the research is actually responding to the user-needs.
- Facilitation across the salient science disciplines (including government agencies both research and response agencies) are necessary to work across silos and begin to remove assumptions or barriers to engagement.
- Need to draw focus to why research in cumulative impacts is beneficial both to a more holistic response, but also cultivates a more holistic/transdisciplinary research culture that is usable.
- There are major policy implications to when these concurrent events occur. It also has major economic implications to respond to these events. The research funding as well as response funding models would need to be adapted or more integrated. Federal, state and local levels of

government will need to be proactive and set-up to work together to respond to these sorts of crises.
- Ensuring community voices are included in the early conversations defining the research and the issues that are most impacting their ability to achieve well-being, which includes natural environmental conditions, human health and social justice.
- There could be a citizen science component to the research that would engage the community in the research project and provide them with more ownership and commitment to the research.
- Ensure Indigenous community members are included in early conversations defining the context of the issue, the research questions and being open to utilizing Indigenous knowledges or ways to approach this research and sharing it back with communities.
- For both the environmental justice and Indigenous community work, it is critical that neither are “tacked on” to the process, but fully integrated from the beginning of the project and remain engaged throughout.
- Have outcomes / resources materials available in the needed Indigenous languages or presented in a culturally appropriate manner.

<u>Ways to Scale Further:</u>
- Scaling – acquiring more case studies will help NSF build capacity and connections with other agencies to take on collective action and response. These case studies can also be used for University courses and training of regional and community officials.
- Start projects at the regional level, with the hope to get to state and local over time. There will be limitations in terms of cross-boundary impacts beyond the initial focus, but could expand overtime as learning progresses.
- Build a global community of practice with researchers, practitioners as well as salient stakeholders that design specialized workshops as well as broader forums to share insights, lessons learned, etc.
- Data sharing will be key in enabling this form of research and practice. Eventually be in an open data repository.
- After 2 years, 4 regional studies will have been commissioned and in progress or completed.
- By year 6, all US regions will have at least one study in progress/completed, with one international project underway.
- This will cultivate a positive feedback loop—where the intent is to bring positive impact to health and well-being, and through more integrated research, new insights will be learned that will inform health and well-being in each step of the way.

Challenge 3: Dynamics of Acute Environmental Hazards

This is related to Challenge #2, but with a focus on resilient infrastructure in the context of the following motivating environmental change questions: How will hazards change in the future and how will that impact human health, including the increased floods, heat stress, drought, and fires? How does repeated exposure to acute environmental hazards affect human health and the systems (ecological and social) that maintain human health?

Possible Approach: Building hazard-resilient and hazard-responsive essential infrastructure for everyone. This is accomplished by connecting the existing hazards and health research communities in a synthesis center starting through an RCN. Synthesis centers are think-tanks and serve as resources for communities who want to tackle the synthesis issue, convene people around the topic, produce tools for practitioners, engage in and study pilot projects, collect integrate and synthesize data that advances research and practice (including dealing with the real-world issues of data collection and integration), and engage with decision-makers.

Some specific questions that could be addressed by this approach include: What makes essential infrastructure systems, including health services delivery systems, resilient to hazards and able to respond to hazards? How does that vary regionally and across different demographics? What information do systems need to respond in the moment, and what are the most robust and user-friendly ways to deliver that information? What systems can be built to study real-world disasters and learn from them? What knowledge is needed to understand risk factors for adverse individual, family, and community outcomes and the effective interventions that can reduce adverse impacts and promote well-being. What specific measures can increase resiliency or adaptation?

Other thoughts include:

- Engage state Science Advisors to help manage crisis and coordinate disparate science related information streams
- Need to test, develop and apply AI to large, integrated data sets
- Build a network to create a forum for Geo and Health science (physical, mental, clinical) researchers to come together, to provide capacity with respect to early career, funding for disaster research, improved processes for harmonization between data streams, etc.
- Enabling federal agencies to share data easily (they can’t do it easily now, in part because of “weird” laws)
- Enabling Career Building by helping researchers (especially early-career researchers) to be able to meet people doing similar research but in fields that are different than the field they are in - facilitate connections between epidemiologists, toxicologists, social health researchers, infectious disease researchers, natural hazards researchers. This could happen with a convening (virtual or real) a staff position devoted to building the network, seeding projects, ecology of infectious diseases is an example, establishing new programs
- Build capacity in MSIs, leveraging the strengths they bring to the table (like, but not limited to community engagement)
- Specific investments utilizing the NSF Disaster Converge Network and Centers to create a structured forum advancing and harmonizing Geo and Health science (physical, mental, clinical) focusing on disasters and environmental hazards. An investment in resources for researchers to come together, to provide capacity with respect to early career, funding for disaster research, improved processes for harmonization between data streams, etc.

Potential Outcome: U.S. infrastructure systems are stressed by diverse and often compounding GeoHealth hazards, and this is a particular challenge for essential infrastructure such as healthcare systems. These systems are not built to respond quickly to these hazards when they occur, or to develop strategies to enhance resilience and response capabilities for future hazards. Doing so requires interdisciplinary and transdisciplinary synthesis to develop prediction-capable understanding of coupled natural-human systems across scales. Additionally, we need to link the geospatial community and data with the health community and their data in preparation of, in response to, and to support recovery from hazards and disasters. Central to this challenge are data sharing and harmonization to support the application of advanced analytics and collaborative decision tools. Investment in several disaster-specific RCNs (e.g. Converge Network) could be strengthened in the short term to include a wider array of transdisciplinary researchers (e.g., healthcare providing institutions, academic public health, disaster managers, and local and state government representatives). Specific investments utilizing the NSF Disaster Converge Network and Centers could create a structured forum for convening and advancing and harmonizing Geo and Health science (physical, mental, clinical) focusing on disasters and environmental hazards. An investment in resources for researchers to come together, to provide capacity with respect to early careers, funding for disaster research, improved processes for harmonization between data streams, etc. Through these investments strategies for future investments can be developed that identify system weaknesses and propose priorities for enhanced disaster resilience in essential infrastructure, including the health system. Through these efforts and findings a sustainable network of transdisciplinary researchers can be established along with an expanded network of centers and institutions including the establishment of a [Disaster Resilient Health Systems] synthesis center that will offer a durable convening platform for advancing research, transdisciplinary coordination, communication, capacity building, career growth, and training in partnership with at-risk community stakeholders.

<u>Implementation requirements and steps, and other ideas:</u>

- Integration of datasets needed that include Personally Identifiable Information, diffuse medical system data systems, and information that agencies are currently not allowed to share.
- Ability to access harmonized data records for analysis, while maintaining necessary privacy protections.
- Promotion of common data elements and set meta-data standards to allow for timely data integration.
- Partners might include local and state governments, Foundations, economists and financial investors; Diverse academic departments (public health, engineering, socio-behavioral, anthropology, communications, policy and political science, engineering, environment); Community members from disaster-affected or disaster-exposed communities; Public Health and Health Care system leaders and data managers; Emergency Management; NIH, CDC, and other Federal health agencies
- Workshops are a must. Participation requirements/criteria on proposals would also be valuable.
- How do we incentivize broader impacts?
- Focus the initiative around the capacity of MSIs, building on their strengths
- Expand approaches for measuring societal impacts in NSF funded grants
- Development of effective generalizable knowledge and solutions. Moving away from anecdotal and case-studies to well-designed transdisciplinary research protocols developed in advance of disasters and implemented systematically by the research community with community stakeholders.
- Platforms for and funding for innovative transdisciplinary science and career advancement for researchers and scientists to advance discovery and applied knowledge focusing on, and engaging with, vulnerable communities.

- Building on existing networks of community engagement and investing in gap areas to create a pre-established and sustainable hub of partnerships to develop and implement science focused on issues of concerns relevant to the health and well-being of communities most at-risk of hazards and disasters.
- How do we respect, learn from, and contribute to local and Indigenous knowledges and local and Indigenous communities?
- Solicit disaster-response/preparedness project goals and leaders from the local community
- Support Indigenous led and housed research-to-action programs.
- Workshops with indigenous communities to build relationships and further understanding about concerns and shared opportunities to advance research

Ways to Scale:

- Leverage and make targeted new investments to existing NSF Hazards Converge Network to incentivize the integration with the health community to collectively promote needed science, both basic and applied, to address hazards for vulnerable communities.
- Community investments to reduce the health risk of identified hazards
- Investments to examine and advance data integration between geospatial and health data streams
- Ensure that the concept is developed with inter-agency collaboration, so that there is shared ownership and thus shared commitment to sustained funding
- Establish cross-agency, synthesized record keeping of health impacts of disasters (both near and long term) impacting communities to prioritize funding both for recovery and preparing for future health impacts of disasters. Such a record could also aid future research endeavors.
- Create a convening/synthesis center for workshops, sharing of information and communications, promotion of exchanges of early career scientists, foster innovations, and promote best practices.
- Work to expand investments and a structured convening platform in this space in partnership with Federal Health Agencies (NIH, CDC, HRSA, SAMHSA, CMS, ACF) through active engagement, workshops, etc. along with Geospatiol agencies (NOAA, USGS, NASA, EPA)
- Connected network between NSF and NIH centers and the broader research community to address the evolving complex challenges of disasters and climate change
- Increasingly prepared transdisciplinary research workforce to be able to innovate basic, applied, and solutions based research to improve community health and well-being.
- Create a specific intentional and sustainable network of community partnerships representing diverse, at-risk for disasters, vulnerable stakeholders to link to/collaborate with the evolving academic center and network
- Use this infrastructure to foster the development of expertise and communications, trusted partnerships, between communities and researchers to develop and implement longer-term impactful research and interventions
- The Hazards Converge Network is, by design and practice, equitable, inclusive, and actively advances justice.

Challenge 4: Embedding and Addressing Environmental Justice throughout and with GeoHealth Programs

What are the current injustices associated with GeoHealth and how do we undo them? What strategies are most effective for remediating environmental injustice from, or that include, a GeoHealth perspective? What can research do to prevent or minimize emergent environmental injustice?

While the idea below is related to a specific GeoHealth environmental justice initiative, there was a strong sentiment that EJ needs to be addressed and supported explicitly and intentionally throughout the GeoHealth programs. Some ideas for each challenge are included in their implementation steps.

Please also see many parallel ideas in the Climate Change Solutions recommendations (ref, p. 7)

Possible Approach: Develop A CIVIC program initiative, possibly with interagency collaboration, on EJ and health that would be implemented through a few GeoHealth centers and direct support related to the "Broader Impacts" of NSF grants.

Potential Outcome: This program initiative, with interagency collaboration, on EJ and health would be based on two complementary efforts: (i) support several GeoHealth centers where community engagement would be intentionally incentivized; (ii) further incentivize and leverage the broader impacts statements with directed funding (5-10% of grant, for example) for engagement in community science. The centers would create or develop separate programs bringing geohealth solutions and engagement to communities, focused on the community needs. The GH centers would help develop a model for education or researchers and showcase GH careers and illustrate or develop leading practices for local impacts. This approach would help communication of science and ambitiously train scientists in community engagement. The grants must have a community partner or specifically indicate how the "broader impacts" support would benefit communities. Adding in such an incentive, with review, would help incentivize researchers to learn and apply leading practices for community engagement and environmental justice.

This could also incentivize engaging with regulatory/policy agencies is also a missing aspect in what's currently funded - the increasing focus on communities is not always inclusive of working with state/national governmental agencies, who often also have more capacity to use GeoHealth data and make decisions that affect health of a larger number of people.

Implementation requirements and steps, and other ideas:

- Put funding behind broader impacts statements and ask for specifics
- Community engagement required/included to be specified in grants
- Risk that this is still "small" scale so…invite community groups to review broader impact approaches - or even opening some of the funding to community groups to award to scientists/projects or initiate projects with scientists and researchers would help
- Support could or should be for communities not just researchers (e.g., equipment, training…)
- And developing a civic science GH initiative that would be the focus of grants.

- Include a few regional "centers" supporting GH translations work that would require interdisciplinary interactions and partner with HBCU and MSI (already beginning with culture change grant program at NSF)
- Collaboration would be needed across multiple stakeholders in the region (industry/business, community colleges, etc.; Multi-agency (NOAA, NASA, NIH, EPA, CDC, USDA/FS, Census, DoEd, DOE, DOD...). See suggestion above on working with regional federal centers.
- Would need to develop an agreed upon set of standards, curricula for community science training (or leverage existing best practices).
- Would need to support and develop inexpensive distributed sensors for community data collection and analysis
- Also need to support infrastructure for curating data
- Can scale internationally through partnering with e.g., USAID
- Many NSF projects are internationally focused already.
- For broader impact work, it will depend on the topic but community engagement is required.
- For the Center–required to have multiple stakeholders in the proposal.

Ways to Scale: Pilot with a few agencies (e.g., NSF, NOAA) then scale with other agencies potentially at the same center; can add other centers and expand internationally too, with international partnerships. See for example, NASA SEVERE program and USAID (with NASA and NOAA). E.g., famine early warning system. Future Earth networks. And engaging NGOs (Gates, Wellcome).

Education and Careers in GeoHealth

As noted above, developing education and career paths in GeoHealth is critical for development of this important discipline. Much of this will be incentivized by funding agencies, including NSF, clearly signaling that GeoHealth will be supported as an interdisciplinary and convergent discipline. The current challenge is that training, student development, funding, and conference are mostly within the disciplines covered by GeoHealth, and pulling together a coherent path is difficult or nearly impossible for students or faculty. Typically students (and faculty) must navigate multiple departments and schools to receive relevant training and develop mentors and colleagues. A large effort to catalyze education and careers should include:

- Signaling that GeoHealth is important and supported (see above). Indeed many of the initiatives above and also below (Moonshot Ideas) would begin to send such signals. Especially valuable would be interagency cooperation with significant funding.
- Supporting the development of a coherent community through:
    - Incentivizing relevant societies to work together
    - Developing and supporting conferences and workshops in GeoHeath or "GeoHealth" faculty interactions or hackathons, especially multiple conferences (this can also be interagency and intersociety).
- Directly supporting students navigating this path through graduate and postdoctoral fellowships

- Leverage existing programs like the NSF research fellowship traineeship program or the NSF CAREER program to focus on GeoHealth.
- Supporting HBCUs and MSIs especially
- Incentivizing community science around GeoHealth; Public Health students are often required to include direct community work or service as part of their education.
- Promoting visiting faculty, lectures, and sabbaticals that would encourage faculty to engage with other departments around GeoHealth
- Developing GeoHealth Centers
- Supporting curriculum development in GeoHealth (e.g, through SERC or other NSF funded efforts).

Many of these efforts could begin immediately, although significant impacts would probably take a few years.

Moonshot Ideas

We also envisioned a few larger ideas where the impacts would occur after ca. 10 years but for which the impacts would be significant. Many of these, as well as the ideas in the Climate Change Solutions Report (see https://www.essoar.org/pdfjs/10.1002/essoar.10507256.1 p. 20) emphasize interagency work. Most are aimed around the emergency of climate change. Several of these ideas go together and also require new technology and FAIR and especially interoperable data (also mentioned in the climate change solutions report; AGU is also cooperating with Optica (formally Optical Society) on their Global Environmental Measurement and Monitoring initiative (GEMMs) https://www.gemminitiative.org/en-us/. As such, these ideas would take longer for development and impact, but the needs are great.

1. Compound and cascading hazards

This builds off of and extended Challenge #2 above. Understanding, predicting and, ultimately, reducing risk associated with compound and cascading hazards under global change is a shared challenge for NSF and NIH. NSF topics are required to understand and predict hazards (e.g., the PREEVENTS program) and the role of coupled natural-human systems (e.g., the DISES program), as well as to assess vulnerability and resilience options of infrastructure (multiple programs). NIH topics are necessary for understanding impacts on human health and the health system, integrating health data to the analysis of these complex multi-hazard events, and connecting environmental and social exposures to health risks. At NSF this would coordinate across most or all of the directorates. This would include topics like heat and air quality but also pandemic and hurricane infrastructure resilience under multiple threats, human migrations, and behaviors in response to an environmental emergency/stress, etc. Recent examples include heat-related deaths from Hurricane Ida, COVID impacts on evacuation logistics (there are examples from the US, but India had some of the most compelling cases), 2017 cholera outbreak in East Africa related to drought and displacement, drought-wildfire-smoke exposure in the US in summer 2021, and many more.

Identifying the risk and vulnerability is critical here. Other societal issues play a role like systemic racism, inequity in healthcare access, transportation system resilience. There's a large mental health aspect to these as well, and it has not gotten the same degree of investment as other areas. Links between climate, environmental, and social drivers of mental health and approaches for prevention through systemic change have been neglected.

2. Mapping and predicting the exposome

the NIH has had programs on the exposome for some time. But when examined solely under the NIH purview one would expect these investigations to focus on the ultimate exposure pathway and health outcome. To map and predict exposures relevant to health, however, we also need to understand things like the provenance, mobilization, and bioaccumulation of toxins (mercury, for example), environmental chemistry and microbiology of toxins and pathogens in the open environment, environmental and climatic impacts on contacts between humans and their environment, etc. An integrated program could advance fundamental understanding and have applications for tracking and preventing exposures. This would loop in multiple agencies (NSF, CDC, NIEHS, EPA, NOAA…).

3. FAIR and integrated data and analysis tools for GeoHealth

This is a known challenge and central to the other topics, and builds off of the immediate steps above, but it's worth taking on with a coordinated NSF/NIH effort to support the needed infrastructure and culture. How do we leverage the full power of health data and environmental data to advance understanding and informed interventions? This requires data integration, innovation and design of data analysis systems that streamline the ability of researchers to work with integrated datasets while protecting PII, and support for data infrastructure. This would fit well with the new technology directorate and the GEMMs initiative above (involving societies and NIST also) and could add to any of these other initiatives.

4. GeoHealth and pandemic risk

Both NIH and NSF have launched pandemic research programs in response to COVID-19. While some of these could be applied to study GeoHealth dynamics, we didn't see any calls that specifically target integrated questions like *the role of deforestation and human-wildlife interactions in pandemic risk*, or *vector control under global change*, etc. We envision a pandemic-related NSF/NIH call that builds naturally from active programs and could be both targeted and high impact.

5. Urban heat effects

This is a growing health challenge tied directly to climate change. Addressing it would involve a multi-institutional attack on the problem of urban heating. Relevant agencies include EPA, Forest Service, NASA, together with universities to strategically identify heat zones in the top 20 cities using remote sensing, satellites etc., and develop integrated mitigation strategies involving urban planting, creative use of water and mist, and other cooling ideas.

GeoHealth Communication and Decision Strategies

As emphasized in the charge, a proactive communications strategy is needed around GeoHealth broadly and to multiple audiences: The research community, institutions, the public and policy makers worldwide, and societies and national academies. Indeed, it is surprising, and sobering, that the critical importance of this convergent science to global sustainability and numerous health and resource challenges are not widely appreciated yet. Much of this is a result of some of the key challenges identified in the survey regarding siloed funding, lack of an institutional identity, and lack of robust career paths. More nuanced communication is also needed related to understanding and conveying the health-related ripple effect and unintended consequences of environmental decisions, policies, and mitigation strategies and building consideration of GeoHealth into decision-making and action – at personal, community, and society levels (for example in responding to hazards).

This broad communication challenge needs several approaches. While the focus of this charge is for activities in the near-term, any solution must build capacity over longer time frames.

One immediate step is mentioned above (in the six actions steps) and involves a clear signal from NSF and other funding agencies to the research community of the importance of and need for GeoHealth research. Responding quickly to the ideas here, and from other societies, will help. Much communication also results from scholarly activities—meetings and publications—and incentivizing these, and public events related to them, will help. Engaging relevant societies and coordination with other funders, particularly NGO's that are engaged in GeoHealth related work, would also expand outreach. Including incentives for outreach in grants, including direct engagement with communities, as noted above, is also important.

GeoHealth also needs a clear and consistent definition (like how we started this report).

Boundary Spanners

For larger and sustained impact, GeoHealth needs to foster a community of boundary spanners (teams with multiple disciplines, and inclusive of academic and non-academic people) who cross disciplines to further accelerate research as well as action within communities. These boundary spanners would focus on areas in policy engagement, community engagement, financial/business/economic, media/public communications, etc. This benefits society by breaking down silos, facilitating evidence-based policy development, amplifies best practices for elevating community needs, and engages the private sector. Direct engagement with communities engenders trust in science.

In many ways this effort is helped by addressing some of the opportunities above, including around education and careers and incentivizing the “broader impacts” around GeoHealth proposals and/or the ideas around a GeoHealth center or component of other Centers.

Potential examples to learn from are these programs in other agencies: NASA HAQAST, NOAA RISA, NIH Research to Action, all of which require stakeholder engagement throughout the entire research process, from the proposal forward, and incentivize improved stakeholder applications as a main research outcome, in addition to the more traditional metrics of success (e.g. publications, conference presentations).

Other important considerations include:

- Stakeholder-driven science, including community needs, policy questions, business/economic incentives
- Link GeoHealth research with applications that improve environmental quality and public health
- Develop community of boundary spanners who can nimbly adjust to stakeholder needs and inform partners
- Create core curriculum and pedagogy for boundary spanners
- Awards could go to existing teams in order to allow participants with different education and credentials.
- These would also help make research data usable at the community scale
- NSF could leverage federally funded research centers like MIter, that identify ways to take research and data into product innovations for the private sector
- Stakeholders include governmental agencies (including local health departments), community groups, NGOs/think tanks, economists/business
- Many NSF programs could be leveraged: geoscience disciplines (atmospheric, biology, etc.) and social science (e.g. economics, sociology), education, etc.
- NSF fellowships such as a diversity fellowship or graduate fellowship would help. This and supporting broader impacts work would also provide institutions with incentives to support.
- Motivate communities through education and outreach
- Training Programs exist and can be leveraged and expanded.
- Incentivize academic institutional change - include policy engagement as part of grant success metrics, accept TEx projects or similar as ways that grants have societal impact
- Already have journals in place - e.g. *GeoHealth, Community Science* (e.g., https://communitysci.org) - NSF support would be helpful (e.g. offset open access costs). These are just AGU journals, there are others too.
- Support a workshop(s) with boundary spanners already working in this area and accelerate their work, statement about importance, each organization commits in their own way to accelerate
- Incorporate explicit training / curation of resources for best practices in engaging communities in identifying & addressing their concerns with science-based support from the GeoHealth community
- This is of key importance. A major role of the boundary spanner is to give voice to indigenous communities and their priorities.

- Develop trust with communities over a long time period

Ways to scale:
- Create new NSF structure that enables team of teams problem-oriented approach
- Recruit current boundary spanners, convene them, figure out training needs, recruit new people who want to become boundary spanners
- Create 10 year road map, akin to governmental agency roadmaps
- Fund alumni of the program to reconvene and continuously add to our understanding of how to do this well.
- Create new fellowship program

Conclusions

This report highlights the great importance of GeoHealth and several immediate opportunities to accelerate and invigorate convergent science. While the focus is on recommendations to NSF, in response to their charge, many of the ideas, inputs, and recommendations extend and apply to other stakeholders including other funding agencies, institutions, publishers, and societies, and to policy makers and government leaders worldwide. In addition, the challenges related to GeoHealth are illustrative of other convergent science challenges for which the science support systems and structures developed during particularly the 20th Century are not fully aligned. We thus hope that the ideas in this report are considered in this broader context as well.

AGU thanks all the participants and especially the steering committee and AGU GeoHealth Advisory Board for their time and input, and NSF for support. This work was supported by the National Science Foundation Grant ICER- 2222021 and by the American Geophysical Union.

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Appendix

The attached appendix includes the list of participants, the survey questions, selected survey results as graphs, and list of answers to the open-ended responses.

Acyonymn List

ACF - Administration for Children and Families
AGU - American Geophysical Union
AI - Artificial Intelligence
APHA - American Public Health Association
CAREER - Faculty Early Career Development Program
CDC - Centers for Disease Control and Prevention
CIVIC - Civic Innovation Challenge
CMS - Center for Medicare and Medicaid Services
DISES - Dynamics of Integrated Socio-Environmental Systems
DOD - United States Department of Defense
DOE - United States Department of Energy
DoEd - United States Department of Education
EJ - Environmental Justice
EPA - United States Environmental Protection Agency
FAIR - Findable, Accessible, Interoperable and Reusable
FASEB - Federation of American Societies for Experimental Biology
FS - United States Forest Service
GEMM - Global Environmental Measurement & Monitoring
GH - GeoHealth
HAQAST - Health and Air Quality Applied Sciences Team
HBCU - Historically black colleges and universities
HHS - United States Department of Health and Human Services
HRSA - Health Resources and Services Administration
MSI - Minority-serving institution
NASA - National Aeronautics and Space Administration
NIEHS - National Institute of Environmental Health Sciences
NIH - National Institutes of Health
NIST - National Institute of Standards and Technology
NOAA - National Oceanic and Atmospheric Administration
NSB - National Science Board

NSF - National Science Foundation
OSTP - White House Office of Science and Technology Policy
PREEVENTS - Prediction of and Resilience Against Extreme Events
RAPID - Rapid Response Research
RCN - Research Coordination Networks
RISA - Regional Integrated Sciences and Assessments
SAMHSA - Substance Abuse and Mental Health Services Administration
SERC - Smithsonian Environmental Research Center
SETAC - Society for Environmental Toxicology and Chemistry
TEx - Thriving Earth Exchange
USAID - United States Agency for International Development
USGCRP - United States Global Change Research Program
USGS - United States Geological Survey
WHO - World Health Organization
WMO - World Meteorological Organization