Environmental and Human Health: Research Priorities

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PREPARED BY:

THE PUBLIC HEALTH AND ENVIRONMENTAL RESEARCH AND EDUCATION SUBCOMMITTEE

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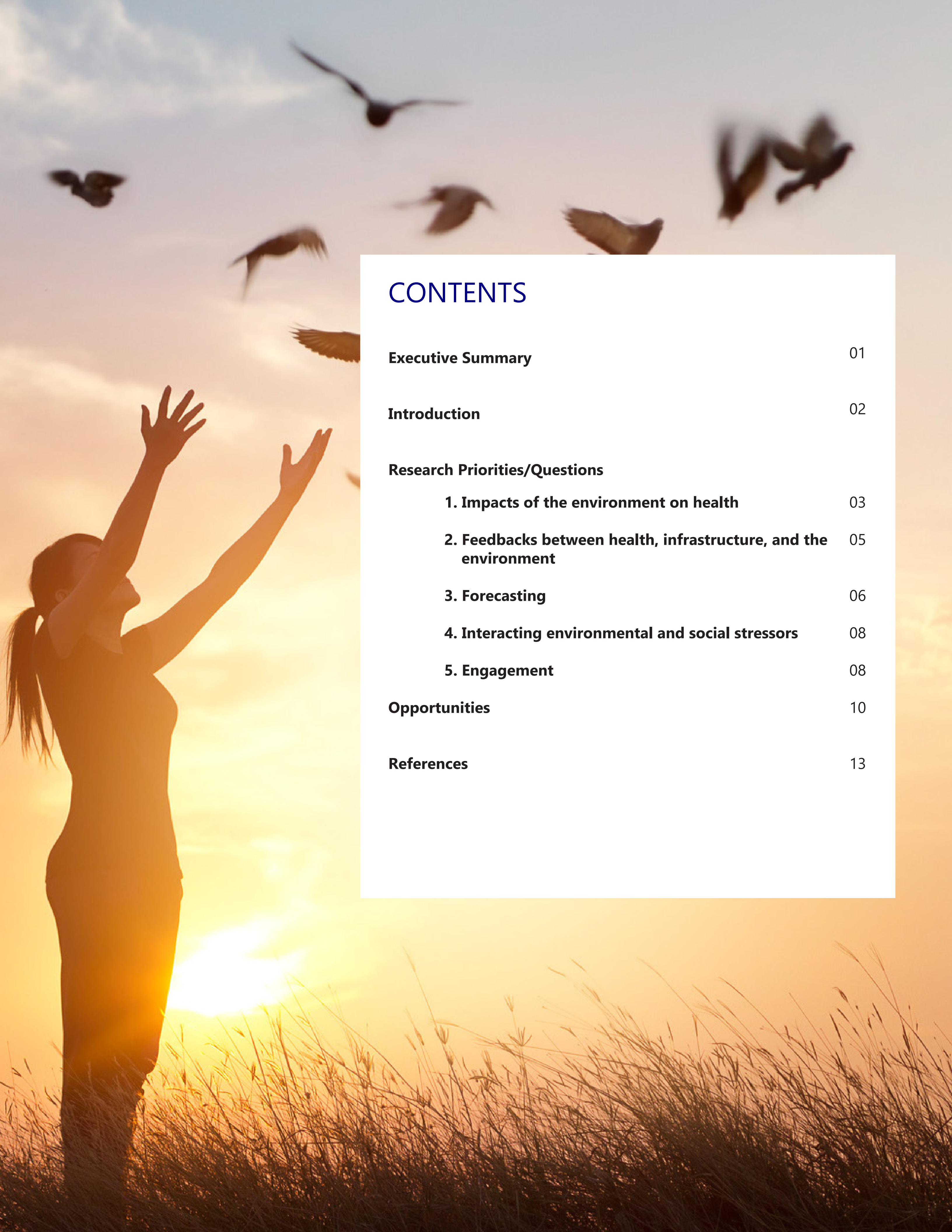

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Environmental and Human Health Research Priorities

Executive Summary

The novel coronavirus of 2019 (COVID-19) pandemic has highlighted the many different ways in which science, the environment, and society are interrelated. Central among these is the way human disruption of Earth's natural systems can lead to significant human health impacts, and conversely, how societal disruptions caused by the pandemic impacted the environment at various scales. The unprecedented speed of vaccine development and other COVID-19 related scientific endeavors has given the world an opportunity to reduce the ultimate toll of the pandemic. Nevertheless, evaluations of preparedness and response suggest strongly that better connections among biophysical, ecological, social, behavioral, health and data sciences, would have improved the odds of better outcomes, including the possible aversion of a global pandemic. These ongoing events are reminders that the most serious crises of our time will likely result from multiple and interconnected stressors that can only be tackled successfully in integrated and convergent ways. And while a global pandemic captures our attention, a quieter but equally if not, more important global health crisis is unfolding as Earth's natural systems degrade—a crisis we are ill-prepared to address. Both crises highlight how trust, communication, and politicization of science are critical factors that must be recognized as integral to effective risk and crisis responses.

The report was prepared by a subcommittee of the NSF Advisory Committee on Environmental Research and Education (AC-ERE). For over two decades the AC-ERE has emphasized the need to advance our basic scientific understanding of complex socioenvironmental systems and their many non-linearities, feedbacks, and teleconnections. In the months following the beginning of COVID-19 lockdowns, the AC-ERE organized an online symposium to explore some of the research gaps that the pandemic has revealed. The resulting conversation was much broader than COVID-19 and its intersections with the environment. It included discussions of spillover events more generally, planetary health, and strengths and weaknesses in NSF's ability to rapidly respond to urgent health and environmental crises. The discussion concluded that even though there are strong connections between environmental change and human health (e.g., spillover of viruses driven by land use change, the impacts of rising atmospheric CO_2 concentrations on the nutritional value of food crops, and relationships between the built environment, urban walkability, and obesity) and conversely, health impacts on environmental change (e.g., the effect of lockdowns on greenhouse gas and pollutant emissions), funding for programs to explore these connections has been historically lacking.

Therefore, this report seeks to articulate key priorities for future research into the ways in which human and environmental health intersect, as well as how to best respond to these impacts as a scientific community. These priorities should serve to inform researchers, programs within NSF, and interagency programs that bring together the key disciplines needed to answer urgent questions at the health-environment nexus. The report concludes by identifying new collaborations and scientific advances that are needed to anticipate and respond to future crises. Improving national capacity for anticipating future hazards and promoting human and environmental health will require investments in these opportunities by NSF, other federal agencies and actors, and the private sector.

Emerging Research Questions, organized thematically, at the Interface of Environmental and Human Health

1. **Impacts of environmental change on health:**
   1.1. *How are accelerating anthropogenic changes to the Earth's natural systems—biodiversity loss, climate change, land use change, pollution of air, water, and soil, scarcity of resources, and altered biogeochemical cycles—threatening human health?*
   1.2. *What is the scale of these threats? Which populations are at greatest risk and/or most vulnerable, and which dimensions of health are most impacted?*
   1.3. *How do inequities in environmental threats lead to inequities in human health?*
2. **Feedbacks between health, infrastructure, and the environment:**
   2.1. *How does human health, including inequities in health metrics, consequences of poverty, and societal impacts of disease outbreaks, feedback to affect air and water quality, resource use, and biodiversity?*
   2.2. *What are the drivers and mechanisms underlying positive nature-human health relationships?*
   2.3. *How can advances in understanding the health-environment nexus lead to innovations in engineering, design, and policy solutions?*
3. ***Forecasting**:*
   3.1. *How do we improve capabilities for understanding and forecasting connections between environmental change and human health?*
   3.2. *How can we develop better warning systems and anticipate blind spots?*
   3.3. *How can we prioritize investments that anticipate and prevent adverse health impacts among the most vulnerable populations?*
4. ***Interacting environmental and social stressors**:*
   4.1. *What is the relative role of specific resources and capacities—such as education, wealth, social capital, and knowledge—in building resilience to multiple and compounding socioenvironmental and health stressors?*
   4.2. *How can we integrate responses to multiple stressors in a way that is sustainable and equitable?*
   4.3. *How do changing inequities in environmental conditions interact with health disparities?*
5. ***Engagement**:*
   5.1. *How does public understanding of complex socioenvironmental systems intersect with health?*
   5.2. *Are there existing or new models of engagement that show potential for helping to solve environmental and health crises?*
   5.3. *Which actors, communities, and stakeholders have been excluded from participation in environmental and human health research and decision-making, and how can these barriers be overcome?*

Introduction

The evidence of rapid environmental change with implications for human health is all around us. Over the past few years, intense hurricanes devastated the Caribbean; wildfires raged in the American West, Australia, Siberia, the Amazon, and the Brazilian Pantanal; droughts and civil strife exacerbated famine in the Sahel; and the worst locust outbreak in 70 years destroyed crops in East Africa. Each of these events has had enormous costs in lives and livelihoods and has underscored the relationship between changing biophysical conditions and human health. COVID-19 in particular is remarkable in that it has precipitated a shared global crisis that has multiplied the difficulties of responding to environmental hazards like hurricanes and wildfires.

Yet rapid environmental change threatens a range of human health impacts that go far beyond infectious diseases to include nutrition, noncommunicable diseases, mental health, and displacement. As noted in the parallel AC-ERE report on Environmental Change and Human Security, environmental degradation also leads to conflict that further intersects with health. Considering the spillover events that contribute to novel viruses, we often see common underlying patterns in which habitat destruction for urbanization or farming puts stress on wild virus hosts, resulting in their interaction with domesticated and farmed animals, which then pass the virus on to humans (Plowright et al. 2021). Rising concentrations of atmospheric CO_2 lower the amount of iron, zinc, and protein in staple food crops, putting hundreds of millions of people at risk for nutrient deficiencies (Smith and Myers 2018). Dams on West African rivers put millions of people at risk for schistosomiasis (Sokolow et al. 2017), and biomass burning in Indonesia leads to an average of 36,000 excess deaths annually from cardiorespiratory disease (Marlier et al. 2019). In vulnerable communities, natural hazards like forest fires and hurricanes exact large social and mental health tolls in the form of joblessness, anxiety, depression, and suicidality (Galea et al. 2007). These effects, which are accelerating, tend to be durable for years after the event (Goldmann and Galea 2014). Consequently, there is an urgent need to shift from responding to these events after the fact to anticipating likely thresholds and tipping points in the health-environment nexus through data, monitoring and warning systems, improved models and metrics, the integration of engineering with natural, social, and biomedical sciences, and associated theoretical advances that require fully functioning multi-, inter- and transdisciplinary teams.

Over the past several years, research communities have coalesced to consider the global health threats associated with accelerating environmental change (Myers and Frumkin 2020) and the potential to advance environmental restoration and design in ways that promote health (Ford et al. 2015, van den Bosch and Ode Sang 2017, Aerts et al. 2018). One Health, Conservation Medicine, and Planetary Health are examples of fields that have emerged to promote work at the intersection of human health, animal health, and environmental health. These fields have been supported by the publication of the Rockefeller Lancet Commission report: Safeguarding human health in the Anthropocene in 2015 (Whitmee et al. 2015) and by the creation of several new journals including Lancet Planetary Health, GeoHealth, Nature Sustainability, One Health, and others. New degree programs in planetary health, one health, and conservation medicine have been established, courses designed, and professorships created. Even formerly non-health related environmental fields such as ecological restoration have expanded to consider the critical linkages between ecological restoration and health (McDonald et al. 2016). Yet in spite of this momentum, in the United States and other countries a workable approach to supporting research on human and environmental health has yet to emerge. The scientific questions and methods needed to understand the intersection of earth system processes, technology, environmental degradation, restoration, economics, behavior, and health cross numerous disciplines and funding agencies.

In addition to the inherent intellectual challenges associated with studying the impacts of global environmental change on human health, and how society can respond, there are gaps in the ways that programs are structured at NSF and across federal agencies that make supporting this research extremely challenging. The National Institutes of Health (NIH) is the primary federal agency directing health-related research, yet there are many gaps at the interface between the environment and health that are not currently addressed by the National Institute of Environmental Health Sciences (NIEHS) or other NIH institutes. Similarly, EPA, USDA, and NASA have had, at various times, relevant programs in environmental toxicology, nutrition, and earth monitoring systems, but these are not comprehensive enough to advance a systems-level understanding of the environment and human health nexus. NSF has important programs in risk management, cyberinfrastructure, and the ecology and evolution of infectious disease that are highly relevant for studying the nexus of environment and human health, yet these areas represent only a small subset of the range of scientific uncertainties that hamper our ability to understand, anticipate, and respond to health crises precipitated by environmental degradation. The events of 2020 have laid bare the profound ways in which these interrelations can impact our nation's health, economy, and national security. The goal of this report is to highlight emerging research questions and pathways for the research community to respond and build new collaborations and convergent approaches to tackle these challenges moving forward. In so doing, the report highlights strategies NSF can adopt to address critical gaps at the nexus of environment and human health.

Research Priorities/Questions

1. Impacts of the environment on health

NSF is uniquely poised to address complex phenomena at the interface between health and the environment, such as 1) the role of global environmental change in public health (Myers and Frumkin 2020), 2) the spillover of pathogens from wildlife to humans (Lloyd-Smith et al. 2009, Plowright et al. 2017), and 3) the impacts of environmental degradation, catastrophic events, and climate change on mental health (Goldmann and Galea 2014, Cunsolo and Ellis 2018).

<u>Global environmental change and public health</u> - The last fifty years have seen dramatic improvements in human health, wealth, and education globally. However, they have also seen rising inequities (e.g. Colmer et al. 2020) as well as rapid human population growth and increases in resource use and land use change which, in combination, are responsible for an extraordinary ballooning of humanity's total ecological footprint (Myers and Frumkin 2020). Human activities are driving fundamental biophysical change at rates that are much steeper than at any time in recorded history. These biophysical changes are taking place across multiple dimensions and consequently impact many aspects of human health and wellbeing (Figure 1).

Examples highlight the pervasiveness of these biophysical changes: Declines in pollinating insects reduce yields of pollinator-dependent crops that play a key role in protecting us from non-communicable diseases (Smith et al. 2015). Ocean warming is reducing the size of fisheries and moving their distributions away from the tropics and toward the poles (Cheung et al. 2013). In addition, the risk of infectious disease has long been understood to be shaped by biophysical conditions. Malaria incidence is increasing in the East African highlands as warming temperatures allow mosquitoes to thrive at higher elevations (Pascual et al. 2006) while urbanization and agricultural land use patterns drive mosquito insecticide resistance (Nkya et al. 2014).

Non-communicable diseases (NCDs)—principally cardiovascular diseases, cancers, chronic respiratory diseases, and diabetes, together with neurologic, endocrine, gastrointestinal, renal, allergic and autoimmune disorders—now account for the majority of deaths and suffering in both wealthy and poor countries. Global environmental change is exacting a growing toll from NCD, with global pollution of air, water and soil responsible for an estimated nine million excess deaths annually, most from cardiorespiratory disease, stroke, and some cancers (Landrigan et al. 2018). These are all critical uncertainties in the future of human and public health at local to global scales that are not well addressed by current NSF and other agency funding programs.

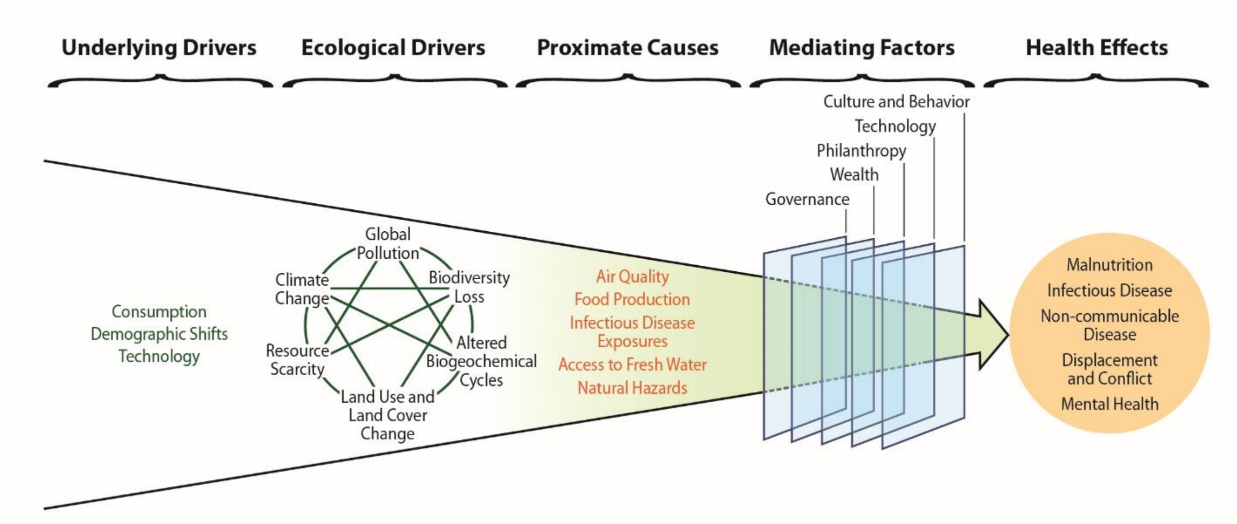

Figure 1 - Schematic of global environmental change driving health burden. Adapted from Myers, Samuel S. Planetary Health: Protecting Human Health on a Rapidly Changing Planet. 2017 *The Lancet* 390, no. 10114 (2017): 2860-68.

<u>*Spillover events*</u> - The risk of spillover of zoonotic pathogens from animals to humans depends on the distribution and intensity of pathogen infections in reservoir hosts, the interaction of humans with those hosts, and the compatibility of the novel pathogens with humans (Plowright et al. 2017). Therefore, spillover requires the alignment of ecological, epidemiological, behavioral, economic, and biological factors, with processes occurring across scales that span cells to landscapes. Each of these factors are well-studied within disciplinary silos but rarely studied from an integrated perspective (Plowright et al. 2017). The circumstances that trigger spillover often occur within a landscape context, and land use change and other disruptions to ecological integrity are considered critical drivers (Jones et al. 2008, Gottdenker et al. 2014, Plowright et al. 2021). For example the spillover of Hendra virus, Nipah virus, Ebola virus, Hantavirus, Rabies virus, Lyme Borreliosis, zoonotic malaria, plague, and many other pathogens has been associated with land use change (Reaser et al. 2021b). However, our knowledge of these processes is based almost entirely on correlational and observational evidence (Gettdenker et al. 2014) and studies that offer mechanistic insights are rare (Plowright et al. 2008). Therefore, there is no overarching conceptual framework for managing landscapes to reduce the risk of zoonotic spillover, and a lack of data to support such a framework (Plowright et al. 2021).

Hence there is an urgent need to fill critical knowledge gaps to understand the drivers of pathogen spillover at the landscape scale. In particular, investment is needed in large-scale studies that characterize the relationships between land use, environmental conditions, wildlife health *in situ*, and infection dynamics in reservoir hosts (Becker et al. 2019, Plowright et al. 2021)—topics that often fall through the cracks at NIH (not human-focused) and NSF (too disease-focused). Like the calls for a Global Immunology Observatory for humans (Mina et al. 2020), the study of wildlife reservoirs of zoonotic pathogens should be an international priority that leads to mechanistic understanding of zoonotic spillover (Plowright et al. 2021). Another key factor driving spread of pathogens from wildlife to humans is the dynamics of human-wildlife proximity. The mechanisms by which zoonotic pathogens come into contact with people are far more complex than human-animal contact within wildlife markets and food and fur farms. Transdisciplinary research is needed to understand how environmental and social change affect human-wildlife contact patterns—for example, through animals feeding on human-provisioned resources, the bushmeat trade, and general intrusions through habitat fragmentation. Once mechanisms that determine the distribution of pathogen on the landscape, and contact between humans and wildlife are understood, ecological countermeasures that mitigate or prevent spillover can be explored (Sokolow et al. 2017, Reaser et al. 2021a). Transdisciplinary studies are needed to develop decision support systems that guide management of ecosystems to prevent zoonotic spillover and resulting harm to human health.

Environmental degradation, conflict, and mental health - Mental health impacts from changing biophysical conditions are also a growing research frontier. Environmental disasters, including tropical storms, forest fires, floods and droughts, have been shown to have large impacts on mental health. Joblessness anxiety, depression, and suicidality are associated with such disasters and often last many years after the event (Goldmann and Galea 2014). Hotter temperatures are associated with increasing violence in many settings, from violent crime and conflict to professional sports. Hotter temperatures are also associated with increased rates of suicide (Cane et al. 2014). More recently, there is some evidence of eco-anxiety or ecological grief with potentially large global burdens of disease associated with knowledge that global environmental conditions are rapidly declining (Cunsolo and Ellis 2018). Many interdisciplinary questions in this area remain to be explored. What, for example, is the mental health toll associated with recent stories that human activity has pushed two thirds of the world's mammals, birds, reptiles, amphibians, and fishes to extinction (Cunsolo and Ellis 2018)? What is the burden associated with the loss of cherished places and ways of life, or the knowledge that our children may live in a world which no longer includes flourishing coral reefs or elephants? And perhaps most importantly, what information, understanding, and social conditions are and are not conducive to collective actions to reduce and reverse, where possible, the root causes of environmental catastrophes (Stern et al. 2006, Newell et al. 2014, Almeida 2019)? Notably, changing biophysical conditions have historically contributed to population displacement and even the collapse of civilizations (Medina-Elizalde and Rohling 2012, Kaniewski et al. 2013). As environmental change leads to more extreme storms, sea level rise, and loss of coastal barrier systems like coral reefs, mangrove forests, and wetlands, quality of life is already impacted in low-lying areas, some of which may become uninhabitable. Will increasing climate shocks, reduced capacity for outdoor physical labor, and drier conditions make certain regions no longer viable for food production? As poorly resourced populations are forced to move, will we see increases in disease outbreaks as well as a greater potential for violent conflict? These questions are important from both humanitarian and national security perspectives and require convergent research across multiple NSF-supported disciplines.

2. **Feedbacks between health, infrastructure, and the environment**

People both intentionally and inadvertently modify the environment to impact health, and these modifications may have feedbacks and cascading effects on complex socioenvironmental systems. Many modern infrastructure systems common in cities and settlements, such as stormwater conveyances, were engineered to mitigate disease transmission, but have since had unintended effects on water quality and aquatic ecosystems. While some of these relationships were studied prior to the pandemic, COVID-19 lockdowns have illustrated additional, previously poorly understood interrelationships between public health and the environment. NSF-supported research at this interface could have significant intellectual and broader impacts for designing new technology, infrastructure, and socioenvironmental systems that better support public health and equitable health outcomes.

The impacts of disease on cities and settlements - Infectious disease has shaped modern cities in significant ways. In the late 19th and early 20th centuries, outbreaks of cholera, typhoid, and other water-borne diseases led to a transformation of modern cities, not only in terms of water and wastewater infrastructure, but also with respect to the new class of urban planning and engineering professionals tasked with integrating scientific and technical expertise into urban governance (Melosi 2008, Pincetl 2010). These relationships between disease, technological development, urban form, and governance still strongly influence complex urban systems and their broader impacts on human and environmental systems, sometimes leading to unanticipated and undesirable outcomes such as high pollutant loads, reduced physical activity, and obesity. Currently, the COVID-19 pandemic appears to be disrupting human settlements and human-environment relationships once again, as some populations are leaving dense urban settings, increasing fears of severe and lasting impacts to the economy and livelihoods of both urban and rural dwellers (Nicola et al. 2020, Bonaccorsi et al. 2020). Such impacts are far from equitable. There are growing concerns about many intersections between demographic inequities and pandemic impacts, including redistributions of urban vs. rural populations and the potential for a depopulation of urban areas that disproportionately affects some demographic groups more than others. Such inequities are likely to intersect with displacement of vulnerable populations by wildfire, flooding, severe storms, and other climate change-related hazards.

Post-pandemic dynamics and the future of work - Population redistributions, changing travel patterns, and stay-at-home policies have significant implications for resource use and local-to-global scale environmental impacts (Figure 2). Reductions in traffic and atmospheric pollutant concentrations, shifts in wildlife behavior, and other environmental and ecological impacts were widely reported early in the pandemic (Diffenbaugh et al. 2020, Rutz et al. 2020). There may be other redistributions of environmental impacts, such as shifts in resource use, waste, and pollution from offices to residences. Changing patterns of tourism and recreation as well as breakdowns in global food trade may impact local biodiversity through poaching and other impacts on local ecosystems. It remains to be seen whether the human imprint on the earth system will return to pre-pandemic patterns, or whether cascading effects on the economy, poverty, global trade, mobility, and remote work will result in long-term changes to socioenvironmental systems exacerbated by climate change (Liu et al. 2020). Even for short-term effects, the pandemic-induced "anthropause" has highlighted poorly understood relationships between ecology, health, technology, social dynamics, and the environment (Diffenbaugh et al. 2020, Rutz et al. 2020). It will be essential to capture these dynamics with the necessary data and monitoring systems while we have the opportunity, as these relationships may give researchers unique insight into how the future of work will affect the environment.

Engineering, design, and ecological restoration for health - An improved understanding of how environmental and human health are interrelated can help us better shape the environment to meet human needs. While there is broad support in the literature for positive impacts of natural spaces on human health, the results from individual studies of nature-health interactions have been very mixed and sometimes contradictory with respect to impacts of nature and greenspaces on physical, mental, cognitive, and social health (Nesbitt et al. 2017, van den Bosch and Ode Sang 2017, Kondo et al. 2018, Houlden et al. 2018). This is due, in part, to a lack of controlled and randomized studies that bring together health scientists, social scientists, and ecologists (Browning et al. 2020, Pataki et al. 2021). Consequently, we lack the mechanistic understanding of human-nature interactions that is needed to design therapeutic and restorative spaces. In addition, recreational uses of some types of outdoor space changed during the pandemic, with implications for how these spaces should be designed and managed in the future (Slater 2020, Venter et al. 2020). Outdoor recreation, urban and neighborhood walkability, and transportation networks have been shown to influence metrics of physical health (Garfinkel-Castro et al. 2017). For example, most people generally understand that biking to work is healthier and more sustainable than driving, but road networks in most of the U.S. are not typically safe or convenient for bikers. Similarly, residents in many urban and rural parts of the U.S. do not have access to healthy food options, instead living in so-called 'food deserts,' with documented impacts on health (Fong et al. 2020). Increasingly there is a growing recognition that urban infrastructure systems can have a profound and widespread impact on mental health (Gong et al. 2016). Finally, the delivery and affordability of critical services such as clean air and water, heating and air conditioning, and electricity intersect with public health. Designing places that will result in better health outcomes requires convergent science at the interface of environmental science, public health, engineering, and design (Diez Roux et al. 2020).

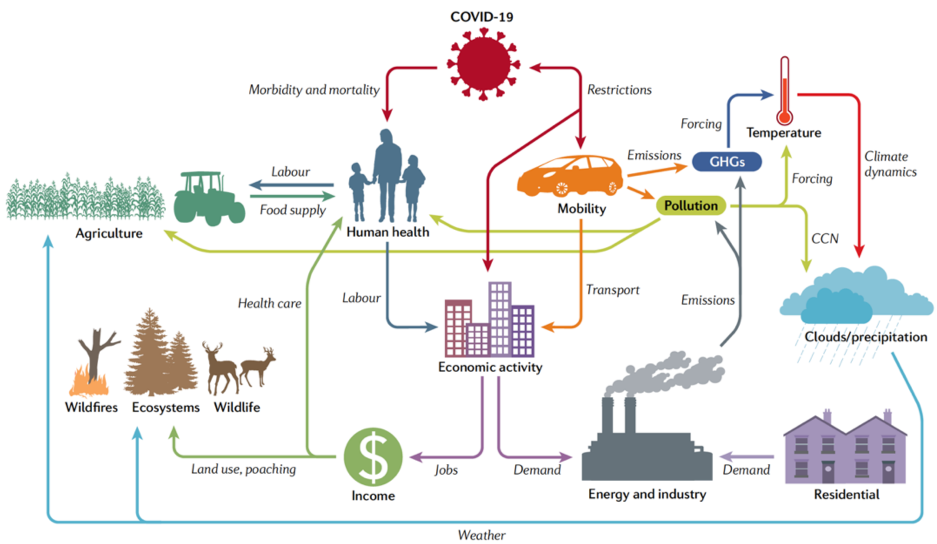

Figure 2 - Hypothesized effects of the COVID-19 pandemic on socioenvironmental processes at local to regional and global scales. From Diffenbaugh et al. (2020) Nature Reviews 1(9): 470-481.

3. **Forecasting**

Modeling of spillover infections has improved, but more development is needed - Recent advances in modeling of zoonotic spillover (e.g. Plowright et al. 2017) and disease emergence (Tebbens and Thompson 2018), as well as assessments of the status of biogeography, pathogeography, and related modeling efforts (Cortinas et al. 2002, Morse et al. 2012, Allen et al. 2017, Murray et al. 2018, Bird and Mazet 2018, White and Razgour 2020) highlight numerous challenges in anticipating environmental and health hazards. Integrated systems modeling (Tebbens and Thompson 2018) has incorporated biogeography into infectious disease modeling (i.e. pathogeography; Murray et al. 2018), and integrated risk assessments of the hierarchical ecological, epidemiological, and behavioral determinants of zoonotic spillover infections (Plowright et al. 2017) are currently under development. But many of the modeling efforts that explore the links between environmental change and infectious disease are still theoretical. For example, Faust et al. (2018) examined the consequences of land conversion on pathogen spillover in theoretical systems. Plowright et al. (2017) established a modeling framework for integrating data across scales to measure pathogen spillover risk. However, while these models generate new hypotheses and explore potential mechanisms, they can't make specific predictions. In order to advance predictive modeling, there is a need for linked, long-term data at multiple spatial and temporal scales to support assessments of functionality within and across ecological and human behavioral systems, and over time. These data must be collected by researchers across many disciplines, representing major transdisciplinary efforts (e.g., Figure 3). Yet disciplinary and institutional gaps between human and animal datasets and monitoring is a common problem, and underreporting of zoonoses remains a challenge (e.g., Christaki 2015). Where data do exist, hierarchical models may be very useful, but can also become computationally intensive and challenging to use (e.g., Cross et al. 2019). Further, models often assume that ecological and other processes are stationary, which may not be true as both climate and societal factors continue to change (e.g., Milly et al. 2008).

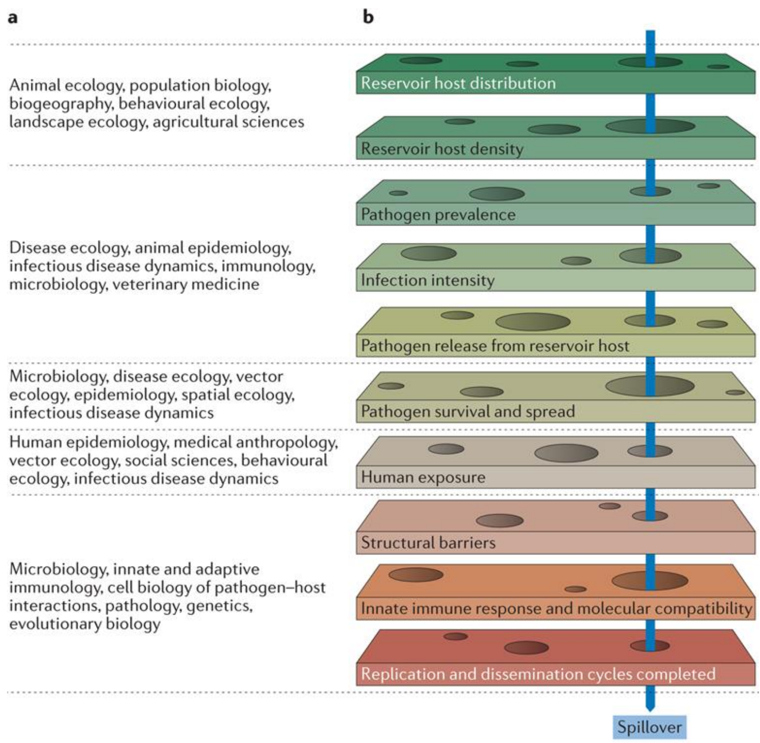

Figure 3 - The determinants of zoonotic pathogen spillover (a) and the the many disciplines involved in understanding the spillover process (b). A pathogen must overcome a series of barriers to transmit from one species to another. Most of these barriers are studied in isolation by specialized disciplines. To predict pathogen spillover, these disciplines need to work together to integrate data across many spatial and temporal scales. Adapted from Plowright et al. 2017 Nature Reviews Microbiology.

<u>*Advances in forecasting and informatics must be expanded to better anticipate health hazards*</u> - Extreme weather events and climate change exemplify newer developments in creating robust forecasting systems. Ensemble modeling is generally expected and machine learning increasingly incorporated into forecasting systems, with concomitant explainability, model validation, and reliability challenges. In the context of extreme weather, data assimilation in coupled ocean-atmosphere models promises important advances (e.g., Zhang et al. 2020) that could be applied more broadly to environmental and human health modeling. However, forecast improvements are commonly measured in terms of improving averages (e.g., the NOAA Hurricane Forecast Improvement program), potentially obscuring critical extreme events that impact health. Furthermore, forecasting health hazards requires the aggregation of disparate sources of data with varying spatial and temporal resolutions.

Consequently, advancing basic research on forecasting and early warning systems for health hazards associated with environmental drivers will require new collaborations between environmental scientists, biomedical researchers, and computational sciences, including earth observational systems, cyberinfrastructure, informatics, and the weather and ecological forecasting community. Recently, ecological forecasting has become a priority in the environmental sciences for forecasting near-term ecological processes (Dietze et al. 2018). These advances, and the necessary datasets for near-term forecasting, should be integrated into new or currently disparate computational approaches for environmental health warning systems, such as Agent-Based Modeling. These efforts must include research on the ability of people and communities to respond to early warning systems, as well as methods and solutions for integrating uncertainty and non-linearity in decision-making, similar to advances in climate change research. Advances in the social sciences will also be critical for incorporating complex human behavior and other cascading feedbacks into epidemiological modeling.

4. **Interacting environmental and social stressors**

Health and environmental hazards are increasingly confounded - Multiple and overlapping crises expose not only the inadequacy of our understanding of compounding and cascading health, environmental and social risk, but also the urgency of understanding what capacities and resources is needed to prevent, respond, and adapt to these crises equitably and sustainably. In the U.S., forest fires in California and hurricanes and flooding in the Gulf region during the COVID-19 pandemic mobilized and taxed city-level and state resources in ways that are very likely unprecedented. They have also revealed how existing socioeconomic inequalities and injustices can both expose already vulnerable groups to more harm and fewer choices, and further redistribute wealth and resources. In the case of COVID-19, for example, historical disparities have deepened prevailing vulnerabilities to environmental hazards as demonstrated in the differential health and economic impacts on disadvantaged communities (Gaynor and Wilson 2020, Montenovo et al. 2020, Karaye and Horney 2020). In the case of fires in California, research on the outcomes of public safety power shutoffs to mitigate the risk of wildfires showed that concerns about shutoffs were associated with poorer physical and mental health, made worse by self-reported trauma from previous wildfire experiences, especially among the most vulnerable (Wong-Parodi 2020). In the long-term there is also a great need to better understand the link between climate adaptation behaviors and specific health-related outcomes (e.g., does home weatherization enhance indoor air quality? Does that lead to improved respiratory health?). Causal climate impacts on health remains one of the most uncertain, but critical, dimensions of climate change assessments. For example, many studies identify associations between health impacts from climate events such as hurricanes and people's attitudes and intentions. However, we know far less about whether a particular climate event actually caused specific behaviors and subsequent health outcomes (Thompson et al. 2017, Wong-Parodi and Feygina 2018, Carman and Zint 2020).

Science to support decision-making about multiple and confounding hazards is greatly needed - Governments, agencies, communities, and households tasked with making decisions to prevent, respond and adapt to these complex systems crises need not only to better understand these feedbacks, but also how to build capacity in a sustainable and equitable way. While there have been growing calls to better respond to multiple and compounding hazards (Zscheischler et al. 2018), a systematic review of the literature and methods funded by the UK's National Environmental Research Council (NERC) found that studies focused on understanding, assessing, and responding to multiple hazards have been limited, mostly utilizing simulations rather than real geographies, and predominantly focused on two hazards rather than the complex multitude of stressors that simultaneously affect socioenvironmental systems (Ciurean et al. 2018). The report also highlights the rapid emergence of qualitative and quantitative methods, including multicriteria analysis, spatial mapping systems, and probabilistic models. In this context, geospatial land change models (LCM) that describe, explain, and project complex spatiotemporal dynamics of urban change (Van Berkel and Verburg 2012) can be useful for exploring overlapping stressors spatially through simulation of future scenarios. Such tools and scenarios can, for example, help decision-makers better understand what capacities are needed to prepare for the future (Vervoort et al. 2014). These models' flexible parameterization based on site specific development can also be particularly useful for engaged research where stakeholders can both assess and voice how they are affected by multiple stressors and what responses are more desirable than others (Voinov et al. 2016). Through participatory processes, these models can also encourage buy-in and knowledge use, and broaden participation if issues of equity, power, and justice are carefully considered (Mach et al. 2020).

5. **Engagement**

There is increasing belief from societal actors, researchers, and funders that public engagement increases understanding, legitimacy, and usability of knowledge (Lubchenco 1998, Cash et al. 2003, National Academies of Sciences 2016, Lemos et al. 2018, Arnott et al. 2020, Norström et al. 2020). Here we focus on three dimensions of how engagement with the public, communities, individuals, and socio-political systems (e.g., governments, policy-making systems, multilateral agencies and organizations) can support action towards preparing and responding to socioenvironmental interactions with health. We particularly focus on: 1) communicating science to address politicization and inaction; 2) co-production of actionable knowledge to increase knowledge use in support of preparing for and responding to socio-environmental crises, and 3) broadening participation and participatory modeling to envision plausible futures in support of behavioral change and action.

Communicating science. The role that doubt about scientific findings has played in the way different decision-makers at different scales (e.g., governments, agencies, individuals) responded to both the COVID-19 pandemic and to environmental crises has exposed how miscommunication about science can have dire and immediate consequences. Political polarization can stem from strategic disagreements on regulation and mitigation (Fisher et al 2013). Further, political polarization on scientific topics can be greater among the elite and those with most knowledge (Drummond and Fischhoff 2017), and polarization among the elite can lead to greater public polarization (Green et al. 2020). Despite this, consensus on climate change, for example, has increased, and empirical research suggests that presenting facts, rebutting fallacies, and countering misleading rhetoric can have positive effects (Schmid and Betsch 2019, Lewandowsky et al. 2020). The varying interpretations of COVID-19 modeling brought to the fore the need a concerted effort to better communicate uncertainty to maintain public support and inform individual response and science-based policies as "scientific consensus shifts over time" (Kreps and Kriner 2020). Research focusing on the role of science in informing policy has long suggested the need for science that engages with society ('an extended community of peers'), especially in cases where uncertainty and risk are high (Funtowicz and Ravetz 1993). Incentivizing such engagement is critical to increase not only the public's understanding of problems but also of the risks involved and what can be done to manage and mitigate them (National Academies of Sciences 2016).

Co-production of science and action. The COVID-19 crisis also highlighted the importance of understanding how engagement with society can critically increase the relevance, legitimacy, and credibility of science-based information (Cash et al. 2003) and its use (e.g., co-production of actionable knowledge that is available and accessible equitably). Recent scholarship on engaged and participatory research, especially focusing on the co-production of knowledge and decision-making, has highlighted how interacting with individuals, communities and governments early and often can increase usability of scientific knowledge (Mach et al. 2020). Co-production defined as the "iterative and collaborative processes involving diverse types of expertise, knowledge and actors to produce context specific knowledge and pathways towards a sustainable future" (Norström et al. 2020) — increases usability through mutual understanding and production of usable knowledge. Co-production also increases the fit of information to decision-making at different scales through customization, tailoring of knowledge to different contexts and by adding value to scientific knowledge to support decision-making (Lemos et al. 2012). The principles of co-produced knowledge — (1) context-based; (2) pluralistic; (3) goal-oriented; and (4) interactive (Norström et al. 2020) — suggest that it can be instrumental in making scientific knowledge more relevant, accessible and actionable. Yet the disproportionate ways socioenvironmental crises affect the health of minorities and low income communities lay bare the need to address issues of justice, power and equity at the root of these problems. For example, the Flint water crisis exposed how failing infrastructure, socioeconomic downturn, racism, social inequality and politics can profoundly shape negative health outcomes (Mohai 2018). It also unveiled how scientists' engagement with the public through Twitter expanded the scope of mobilization (Jahng and Lee 2018) and how residents engaging in 'popular epidemiology' by collecting data and mapping contamination were crucial to bringing the problem to the fore (Pauli 2020). These examples show how relationships between scientists and citizens in Flint were instrumental to push officials to respond (Pauli 2020). Hence, engagement can be instrumental in adding to the plurality of voices and knowledges that should inform effective action; carefully uncovering and addressing issues of justice, equity and participation in the process of engagement itself is essential (Mach et al. 2020).

Understanding complexity and broadening participation. Confronting many of the challenges explored in this report — from the need to address the complexity of multiple, overlapping and compounding stressors at the intersection of health and the environment, to the need to forecast the future and change behavior critical to prevent and respond to crises — may require an increasing commitment to broadening participation in environmental and health research. As explored in a parallel AC-ERE report on environmental education, cognitive frameworks and models matter for making sense of complex problems in health and the environment. Anthropocentricism is a predominant cognitive framework in western industrialized nations, leading to reasoning that places humans apart from the natural world. This may limit complex systems reasoning and decision-making about health-environment relationships. Yet there are other cultural models and conceptualizations of relationships between health and the environment. Indeed, broadening participation means both increasing the number of people engaged in knowledge production as well as the diversity and plurality of voices and ideas, especially those of traditionally marginalized and underserved communities.

Participatory models of research (e.g., participatory modelling in environmental science and community-based research methods in public health) can contribute to better research outcomes by capturing knowledge of local processes and issues and by increasing disruptive thinking about solutions not yet considered (Israel et al. 2005, Voinov and Bousquet 2010, 2010, Blumenthal et al. 2013). Participatory methods can also incentivize social learning, better reflect diversity and plurality of knowledge, and increase the relevance and fit of knowledge to decision-making (Hare 2011). Similarly, participatory scenario building can be instrumental in increasing understanding and uncovering participants' preferences and desirable visions for the future. For example, empirical evidence from fields such as sustainability science and adaptive management show that participatory scenario building can be effective in uncovering potential future conflicts, synergies, and opportunities. It can also build common understanding, foster learning, and support planning of future socioenvironmental systems (Oteros-Rozas et al. 2015). Yet the costs of stakeholder participation can be high and the ability of participatory research methods to include large numbers of people relatively low, making scaling up a challenge (Hare 2011). In contrast, the emergence of new approaches in data mining and collection through the use of social media data, crowdsourcing, and other large datasets has the potential to broaden participation to critically support planning, behavioral, and global health research (Litman et al. 2017, Wazny 2017). For example, using social media data can amplify our understanding of the landscape values of large portions of the population, thereby potentially increasing our understanding of their preferences at the intersection of socioenvironmental systems (Zanten et al. 2016). It can also unveil the critical role that changing social media can play in disseminating both accurate and misleading information about infectious diseases (Sharma et al. 2017).

Opportunities

1. The Research Community

Environmental and public health research should be an integral component of convergent research and institutions should foster the kinds of teams that can perform this work.

In the white paper *An AC-ERE Perspective on Convergence* released in December 2016, the AC-ERE identified several specific research initiatives that exemplified the potential for convergent research. Convergence work is seminal in creating early warning systems, because these systems require simultaneous knowledge of how systems work and are connected, what the tipping points or incipient state changes will be, and how society can retroactively or proactively respond at, or before, state change. The report highlighted how understanding human disease outbreaks and transmission lies at the intersection of climate science and modeling, ecological modeling and systems analysis, epidemiology, evolutionary biology, and human behavior. The COVID-19 pandemic has made it even clearer that convergence must include social, behavioral, and economic sciences, as well as biomedical research that falls at the intersection of NSF and other agencies. While the science of understanding complex systems undergoing a pandemic is itself a challenge, the results of the research must be understandable by and meaningful to a wide range of stakeholders. Warnings and mediation have impact only when the guidance is heeded, which is why their effectiveness depends on understanding how and why people process information (Mayhorn and Wogalter 2017).

Great progress has been made within the NSF in fostering interdisciplinary collaboration. But for convergence, the central problem is not necessarily finding excellence in each individual component of an interdisciplinary proposal—it is finding the value of the collaboration itself and overcoming the community-building challenges. Innovation in research in this area is often not strictly within the respective disciplines, but lies in stitching together several disciplines to shed light on connections between environmental change and human health. For example, agricultural ecologists have shown through an extensive network of farm plots across four continents that about one quarter of the yield gaps on farms growing pollinator-dependent crops is due to inadequate wild pollinators. Other researchers have quantified global crop yields and yield gaps for all crops worldwide. Unrelated public health research documents the global burden of disease from inadequate intake of fruits, vegetables, and nuts and seeds. Separately, ecologists have generated a comprehensive list of the pollinator dependence of every food crop globally. A different group has modeled per capita availability of 225 foods for the populations of 152 countries and yet another group has built the IMPACT model which estimates global food trade with elasticities for food prices and can model how increases or reductions in particular foods might alter global trade. By stitching together the work of these different groups in collaboration, it becomes possible to quantify the global health burden experienced today from inadequate wild pollinators, and to project how that burden may rise as the global population increases while pollinating insects continue to decline. By adding the work of an additional group that has been quantifying the effectiveness of a suite of “pollinator-friendly” practices, it is possible to generate policy recommendations for increasing wild pollinator populations and to quantify the health benefits of instating such policies.

Beyond the challenge of building complex, interdisciplinary research teams, there are structural challenges to performing such work. One such challenge, at the university level, is that training of young scientists tends to be focused within disciplines and there are few incentives for scientists to work across health and environmental disciplines. While this is a long-standing problem, it is exacerbated by significant training and other disciplinary gaps between the biomedical sciences and more academic disciplines. That funding agencies (both private and public) tend to also map along these disciplinary lines makes conducting such research more problematic. University administrators must give pause in hiring faculty with strong interests in working across the environment and health disciplines for fear that they are unlikely to obtain grant support. The result is a system that trains, rewards, and funds scientists to undertake either curiosity-driven research funded by NSF or mission-driven research funded by other agencies (particularly NIH with respect to health sciences), but does not support working across disciplines to address urgent questions at the nexus of health and the environment.

2. The National Science Foundation

Interagency collaboration is essential for facilitating and supporting environmental and public health research.

In this report we have identified critical research questions and topics that are difficult to address within existing programs at NSF or other agencies:

- The human health dimensions of complex socioenvironmental systems
- Health impacts of global environmental degradation and earth system change
- The interacting socioeconomic, ecological, and environmental factors that determine zoonotic spillover
- The impacts of health-related decision-making, land use, and infrastructure systems on the environment
- Modeling and forecasting of health hazards
- Interacting and compounded environmental and health hazards
- The relationship between environmental and health disparities
- Engagement and communication models for public understanding of how health and the environment are interrelated

Research in these areas would benefit from greater clarity in the research community about the role of NSF in health-related research. While there is often a perception that most research on human health is funded by the NIH, many, if not most, uncertainties at the intersection of the environment and health are somewhat outside the domain of the NIH and the other mission agencies. NSF, with its unique mission to advance basic sciences in the public interest, has a unique and critical role to play in supporting the national portfolio of research in the environment and health. Defining this role will require more information from and communications between the federal agencies regarding the domains of each agency and program with interests in the environment and human health, overcoming siloes within NSF and between NSF and other agencies, and a cross-agency commitment to supporting scientific advances in this area.

Our committee noted that for researchers in the biomedical sciences and public health, NSF programs and policies can be challenging to navigate and this may hamper in progress in research at the health-environment nexus. Faculty in schools of public health and medicine are usually expected to raise all, or most, of their salaries from research grants. As a result, schools of public health are reluctant to hire junior scholars interested in pursuing research careers in areas in which salary support is limited and programs are under-funded. NSF's long-standing policy that limits researchers to two months of salary support, except by explicit justification for an exemption, promotes the notion that NSF's programs are intended primarily for non-health sciences faculty who hold 9 or 12-month funded appointments. This is one reason why schools of public health and health sciences researchers do not look to NSF, inhibiting collaboration between health scientists and researchers from other disciplines in both research and education. By explicitly addressing public health and its disciplinary needs, NSF has an opportunity to facilitate the development of urgently needed inter-, multi-, and transdisciplinary teams and training programs across the natural, social, engineering, computing, education, and health sciences.

To make human and environmental health societal and scientific priorities in the coming decade, we recommend that NSF consider adding health priorities to existing programs, and/or creating specific programs that support collaborative approaches to solving complex problems at this interface, through interagency partnerships if necessary. Our committee interviewed program officers and staff from NSF as well as other federal agencies that fund research on the environment and health. Most agreed that there are significant gaps between the agencies in their ability to fund urgent research questions at this interface. Notably, staff of other agencies expressed great enthusiasm at the prospect of collaborating with NSF through existing and new interagency partnerships to address these gaps. We have gathered that there are sometimes unique constraints at particular agencies that make interagency partnerships difficult. Nevertheless, NSF has successfully established collaborative programs, such as the NSF-NIH programs in the Ecology and Evolution of Infectious Diseases (EEID) and Smart and Connected Health (SCH). The potential for accelerating advances at the interface between health, the environment, the economy, and national security is enormous if such efforts could be leveraged and expanded. For example, some researchers have called for a new NIH Institute of Climate Change and Health (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2253589/). An effort of this magnitude is greatly needed, but it is unlikely to succeed without a strong foundation in NSF-supported sciences, including but not limited to climate science, social and behavioral sciences, computational science and informatics, ecology, evolutionary biology, mathematics, and education.

In addition, a continuous dialogue among agencies is needed to adapt program scope as the domains of each agency change. Both NSF and EPA staff noted that important research in environmental health remains unsupported in the United States, because NSF's current scope excludes topics that are no longer funded by the EPA or any federal agency (e.g., many types of research in ecotoxicology). Recognizing that different agencies have varying resources, we highlight that even relatively low cost mechanisms for fostering interagency collaboration, such as fellowships and visiting appointments for NSF-supported scientists at other agencies, may be very impactful at the health-environment interface. The NSF-NIST program (11-066) is an example of such a collaboration that might greatly advance environmental health research if it was emulated with NIH, CDC, EPA, DOE, USDA, or other agencies.

We recommend that NSF explore expanding such partnerships and building new ones, recognizing that the NIH and CDC have extensive resources and expertise in the biomedical sciences that must be more strongly coupled to basic sciences research; USDA has important programs and expertise in food and nutrition; DoD has many programs and interests in the environment-health nexus as it relates to national security; DOE supports health research related to chemical and nuclear waste; and EPA has critical regulatory responsibilities in both community and environmental health. In addition, the U.S. National Academies are actively studying and advancing inter- and transdisciplinary environmental and health research. Collaboration through existing or new working groups and partnerships among these institutions will be instrumental to advance progress in the environment and health, and to maintain U.S. leadership in health and environmental sciences.

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- Serve as a forum for consideration of interdisciplinary environmental topics as well as environmental activities in a wide range of disciplines.
- Provide broad input into long-range plans and partnership opportunities.
- Perform oversight of program management, overall program balance, and other aspects of program performance for environmental research and education activities.

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