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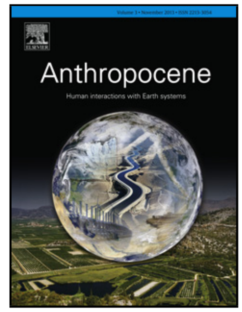


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Authors: Kristie L. Ebi, Howard Frumkin, Jeremy J. Hess

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# Protecting and promoting population health in the context of climate and other global environmental changes

Kristie L. Ebi, Ph.D., MPH, Howard Frumkin, M.D., DrPH, Jeremy J Hess, M.D., MPH

Kristie L. Ebi, PhD, MPH (corresponding author)

Rohm and Haas Endowed Professor of Public Health Sciences

Director, Center for Health and the Global Environment

University of Washington

krisebi@uw.edu

Jeremy Hess, MD, MPH

Associate Professor. Departments of Medicine, Global Health, and Environmental and Occupational Health Sciences

Co-Director, Center for Health and the Global Environment

University of Washington

jjhess@uw.edu

Howard Frumkin, MD, DrPH

Professor, Department of Environmental and Occupational Health Sciences

University of Washington

frumkin@uw.edu

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Abstract

The past 150 years have seen substantial public health advances globally. However, the intensive exploitation of energy and resources, the associated disruption of earth systems, and the resulting decline in some ecosystem services, threaten these advances. The risks are driven by global climate change, biodiversity loss, land use alterations, depletion of soil and water, and altered biogeochemical cycles; of these, the best studied with respect to human health is climate change. The human capacity to adapt to these changes is not fully understood. Adaptation to protect health must occur within the health sector, by strengthening public health and clinical care systems, and through collaboration with other sectors. This paper reviews known health threats, with an emphasis on climate change, then proposes a framework for prioritizing adaptation options based on: a) the probability of adverse health impacts; b) the effectiveness of protective interventions; and c) the magnitude of the public health impact. The framework can also be used to inform adaptation implementation, focusing on options that protect particularly vulnerable populations from climate change and other global environmental changes over coming decades.

Keywords: climate change, global environmental change, planetary health, health risks, adaptation, Anthropocene

## 1.0 Introduction

Ongoing and projected global changes affect human health in diverse ways, positively and negatively, with the risks expected to increase across this century. These complex changes include population growth and aging, urbanization, globalization of ideas, goods, services, and human movement, increases in the human exploitation of energy and resources, and growing anthropogenic impacts on earth system processes: climate change, biodiversity loss, land use changes, altered nitrogen and phosphorus cycling, fisheries declines, and environmental loading of toxic chemicals and air pollutants (Rockstrom, Steffen et al. 2009). Each of these changes can adversely affect human health, often through indirect pathways with multiple, interacting drivers (Whitmee, Haines et al. 2015). Health systems are beginning to adjust to these new challenges, moving from a reductionist, top-down framework to a systems-based perspective. In systems-based approaches, health professionals actively and purposefully collaborate with other sectors, assessing local vulnerabilities and capabilities and co-designing policies and programs accordingly (Ebi, Semenza et al. 2016). Addressing looming health challenges requires not only understanding health risks, working across siloes and embracing iterative risk management approaches, but also recognizing the potential health co-benefits of taking action.

We synthesize the health risks of global environmental changes, then focus on climate change because it is the best studied global environmental with respect to health risks, discussing the status of adaptation and mitigation efforts in health systems in reducing the risks of climate change, including the health co-benefits of mitigation; outline a framework for prioritizing adaptation efforts that links risks and responses; outline research needs; and provide concluding remarks.

## 2.0 Context: advances in health over the last 150 years, expectations for future population health, and the health risks of climate change

Substantial advances in human health occurred over the last century and a half. Infant mortality declined, life expectancy increased, malnutrition became less widespread, and the burden of infectious diseases declined. Much of this gain came from public works such as potable water and sewage systems (McKinlay and McKinlay 1977), from improved housing, and from improved nutrition (McKeown 1976)—interventions that often depended on intensive use of resources and energy. Additional health gains came from advances in health care. However, health gains were constrained in at least three ways relevant to the potential for furthering population health: maldistribution, plateauing, and emerging health problems.

With respect to maldistribution, the health improvements over the last century were concentrated in the world's wealthier nations—those that, not coincidentally, marshaled the greatest supplies of energy and resources—and in wealthier individuals within nations. Over recent decades, with economic development, many low- and middle-income countries have experienced considerable improvements in health as well. Since the Industrial Revolution, health statistics have consistently demonstrated an association between poverty and ill health (Marmot 2015), and between social inequality and ill health (Wilkinson 1996). The extent to which poverty and inequity are reduced will affect health gains over coming decades.

With respect to plateauing, greater use of energy and resources is associated with health improvements—but only up to a point (Mazur 2011). In Figure 1, each circle represents a country, with the size proportional to the country's population. Infant mortality (in the upper panel) and life expectancy (in the lower panel) improve up to a level of energy utilization of roughly 2500 kg petroleum equivalent per capita per year, with little improvement beyond that (Wilkinson, Smith et al. 2007). This suggests a limit to improvements in human well-being from the accelerating use of energy and resources in high and some middle-income countries.

Third, overall progress in population health was accompanied by emerging health problems. A half century ago, these were recognized in the context of the epidemiologic transition (Omran 1971)—the shift from an era of high birth rates, high death rates, and early mortality, much of it from infectious disease and hunger, to an era of noncommunicable diseases (NCDs) such as heart disease, cancer, and stroke, together with anxiety, depression, and other mental health issues, and injuries from such causes as industrial hazards and motor vehicle crashes—a shift known as the risk transition (Smith and Ezzati 2005). An additional feature of the NCD landscape has been the apparent rise of immune-related conditions such as allergy, asthma, and auto-immune diseases (Zuckerman, Harper et al. 2014); this may relate to changes in human exposure to environmental microbes (as proposed by the hygiene hypothesis) (Rook 2013, Rook, Lowry et al. 2015), and/or to changes in the internal human microbiome (de Vos and de Vos 2012, West, Renz et al. 2015). Emerging health problems will extend beyond those usually identified with the epidemiologic transition, for example an increase in emerging infectious diseases once thought controlled in high-income regions (Whitmee, Haines et al. 2015).

The health effects of climate change have been inventoried and reviewed, by the Intergovernmental Panel on Climate Change (Smith, Woodward et al. 2014), by national governments (Luber, Knowlton et al. 2014, Crimmins, Balbus et al. 2016), in academic journals (McMichael 2013, Patz, Frumkin et al. 2014, Semenza 2014), and in books (Butler 2014, Levy and Patz 2015, Luber and Lemery 2015). Considerable uncertainty remains about the current and projected magnitude and pattern of health risks at finer spatial scales. McMichael (McMichael 2013) provided a conceptual model of processes and pathways through which climate change can affect human health (Figure 2).

Among the most-studied health risks of climate change are heightened risks of temperature-related morbidity and mortality, infectious diseases, nutritional impacts, and degraded air quality. Other effects likely to impose large population health burdens include displacement of populations and civil conflict due to such phenomena as sea level rise and water scarcity, and mental health impacts. For each, drivers in addition to climate change also will contribute to future disease burdens.

**Temperature-related effects**: Excessive heat—both during severe heat waves and as a long-term condition—threatens health and well-being in numerous ways. Medical consequences range from relatively minor, self-limited conditions such as heat rash and cramping to severe outcomes such as heat stroke and death. More consequentially, mortality rates rise during periods of heat, mostly due to increases in cardiovascular deaths. For example, 70,000 excess deaths were estimated for the 2003 European heat wave (Robine, Cheung et al. 2008) and

11,000 for the 2010 Russian heat wave (Shaposhnikov, Revich et al. 2014). Those most vulnerable include the very young and very old, those with underlying medical conditions, the poor, and the socially isolated (Bouchama, Dehbi et al. 2007). In addition to these dramatic effects, heat is associated with a range of other impacts, from increased risk of kidney stones (Brikowski, Lotan et al. 2008, Tasian, Pulido et al. 2014) to impaired sleep (Obradovich, Migliorini et al. 2017), from increased violence (Gamble and Hess 2012, Mares and Moffett 2015) to substantial reductions in work capacity (Dunne, Stouffer et al. 2013, Kjellstrom, Briggs et al. 2016). Concomitant trends affect the risk posed by heat. For example, urbanization concentrates more people in places especially prone to extreme heat, due to the urban heat island effect (Kalnay and Cai 2003, Koomen and Diogo 2017), and this may in turn influence climate on a regional scale (Zhou, Dickinson et al. 2004). Similarly, heat not only creates its own risks, but also reduces air quality by driving ozone formation (Avise, Abraham et al. 2012). Some acclimatization to heat is possible, both physiologically and socially (through such means as air conditioning), but there are limits to adaptability.

**Infectious diseases**: Climate change, together with urbanization, land use changes, and biodiversity loss, may increase the risk of infectious diseases (Altizer, Ostfeld et al. 2013), such as changes in the geographic ranges of Lyme disease in Canada and *Vibrio parahaemolyticus* in the Baltic (Ebi et al. 2017). Of particular concern are vectorborne diseases, including those transmitted by mosquitoes (such as dengue fever (Morin, Comrie et al. 2013) and malaria (Ermert, Fink et al. 2012)), and ticks (Lyme disease (Tran and Waller 2013, Ostfeld and Brunner 2015)). The risk of vectorborne diseases may increase due to biodiversity loss, another global environmental change (Pongsiri, Roman et al. 2009, Keesing, Belden et al. 2010), as well as to changes in vector biology, habitat, and other factors. A second important category of infectious disease is those transmitted by water and food, such as cholera (Vezzulli, Colwell et al. 2013) and other diarrheal diseases (Semenza, Herbst et al. 2012). The risk of these conditions may increase due to changes in hydrology, pathogen biology, and other factors. Other factors, such as undernutrition (discussed below), may amplify the risks.

**Nutrition**: Climate change threatens agricultural productivity in many low- and middle-income countries through complex pathways, including the effects of heatwaves, storms, droughts, and flooding; pests and weeds; rising ozone levels; and reduced work capacity among farmers (Dunne, Stouffer et al. 2013, Tai, Martin et al. 2014, Paini, Sheppard et al. 2016, Springmann, Mason-D'Croz et al. 2016). In addition, the protein and nutrient content of some cereal crops declines with rising atmospheric concentrations of $CO_2$ (Myers, Kloog et al. 2014). Fish represents a substantial source of dietary protein for many populations, but global fisheries are threatened both by overfishing and by climate change (Brander 2010, Pauly and Zeller 2016). With growing populations, and with rising demand for meat-based diets, these trends may portend reversals of recent advances in global nutrition, and aggravated malnutrition in some regions (Dawson, Perryman et al. 2014, Phalkey, Aranda-Jan et al. 2015).

**Air quality**: Climate and other environmental changes are affecting the air that people breathe in diverse ways. The best known pathway is through air pollution resulting from combustion—not a new phenomenon in human history, as biomass combustion was a feature of human life since the time people first "conquered" fire, perhaps 300,000 years ago (Roebroeks and Villa

2011). However, the industrial revolution intensified human exposure to fossil fuel combustion products in ambient air and indoors (Brimblecombe 1987). Air pollutants, including particulate matter, ozone, oxides of sulfur and nitrogen, and others, increase the risk of cardiovascular disease, respiratory disease, cancer, and other illnesses (Bell and Samet 2016). Climate change affects air quality through additional pathways (Fiore, Naik et al. 2015). First, as noted above, warmer temperatures drive the formation of ozone, a respiratory toxin. Second, wildfires resulting from drier weather and degraded forests release large amounts of smoke, a cardiopulmonary risk for those downwind (Harvey 2016). Intentional fires used for land clearing and agriculture yield similar exposures, especially in parts of South America and the Pacific region (Johnston, Henderson et al. 2012, Marlier, DeFries et al. 2015). Third, some trees and other plants may increase their production and release of allergenic particles such as pollen in the setting of climate change (Ziska and Beggs 2012). These and other air quality-related processes pose a considerable threat to cardiorespiratory health (Rice, Thurston et al. 2014).

**Population displacement**: Human habitation has extended to nearly every part of the world, reaching high density in areas such as coasts and along rivers. Some populations may be displaced with climate change, specifically such drivers as drought, sea level rise, and severe weather events, with resulting place-specific shortages of food, water, and habitable land (McAdam 2010, McLeman 2014). This may occur relatively acutely, such as after a major disaster, or more deliberately and over a longer time frame, through the process of managed retreat (Abel, Gorddard et al. 2011, Koslov 2016). Key health risks among displaced populations can result from infectious diseases, nutrition, reproductive health, and mental health and psychosocial stressors (McMichael 2010, McMichael, Barnett et al. 2012).

**Civil conflict**: Increasingly scarce resources, displaced populations, and other destabilizing forces may represent risk factors for civil conflict (Hsiang, Burke et al. 2013, Bollfrass and Shaver 2015, Schleussner, Donges et al. 2016). Changing weather patterns due to climate change may have contributed to the Darfur conflict in the first decade of the present century (UNEP 2007), and to the uprisings in Syria and Egypt in the following decade (Werrell, Femia et al. 2015). At a more granular scale, warming temperatures may be associated with higher levels of interpersonal violence (Anderson 2001, Mares and Moffett 2015), resulting in injuries and fatalities, lasting psychological damage, and other harms (Levy and Sidel 2008).

**Mental health impacts**: Climate change and environmental degradation may threaten mental health in several ways. Disasters, such as floods and hurricanes, often trigger large population burdens of depression, anxiety, and other manifestations of post-traumatic stress (Goldmann and Galea 2014). The ongoing interruption of place attachment, the loss of accustomed weather patterns, biodiversity and other environmental assets, and the insecurity that comes with an uncertain future, may trigger grief, distress, anxiety, and other mental disorders (Albrecht, Sartore et al. 2007, Clayton, Manning et al. 2014). Individuals with mental health issues also may be more susceptible to climate-related exposures, such as to high ambient temperatures because of the side effects of certain medications, inappropriate behavioral responses, and/or abnormal physiological homeostatic mechanisms (Bulbena, Sperry et al. 2006).

**Timing of impacts:** As Whitmee and colleagues (Whitmee, Haines et al. 2015) noted, there is a seeming disconnect between ecosystem degradation and natural resource depletion and anticipated health impacts. They speculated that, while this may represent a true uncoupling, it more likely represents a delay related to system complexities and possibly blunted by increased (but time-limited) food productivity (Whitmee, Haines et al. 2015). However, as populations grow, the climate continues to change, and ecosystems continue to degrade, population health impacts associated with heat, infectious diseases, reduced food and water availability and quality, and diminished air quality, are expected to be increasingly manifest even in high-resource settings (Melillo, Richmond et al. 2014, Woodward, Smith et al. 2014). The timing has not been comprehensively projected, but climate change projections capture many of the risks as well as some threshold and feedback dynamics, with global average temperatures likely to cross the 1.5°C threshold between 2035 and 2050 depending on emissions (Intergovernmental Panel on Climate Change (IPCC) (2013). Other global environmental and socioeconomic changes will interact with the risks of climate change. For instance, urban land cover is projected to increase by 1.2 million $km^2$ by 2030, threatening vegetative carbon and biodiversity losses (Seto, Güneralp et al. 2012) and potentially accelerating adverse health impacts. Climate change has already significantly undermined agricultural productivity and increased the likelihood of conflict, with even more dramatic impacts projected by 2030 (Carleton and Hsiang 2016); has increased the geographic range and intensity of transmission of Lyme disease and *Vibrio parahaemolyticus*; and has increased heat-related mortality (Ebi et al. 2017). Projections of health risks suggest that climate change will have a significant impact on child health, primarily mediated by undernutrition, by 2030 (Hales, Kovats et al. 2014). Overall, projections suggest significant risks within the next two decades, with progressive worsening thereafter, although there is uncertainty regarding the magnitude, geographic pattern, and timing of risks later in the century. The extent to which impacts will arise will depend on interactions between worsening hazards, development, and health and on implementation of proactive and effective adaptation and mitigation policies and measures. There are growing examples of actions to increase climate resiliency, such as the U.S. program Building Resilience Against Climate Effects (Marinucci et al. 2014), and health facility climate resiliency toolkits (Paterson, Berry et al. 2014; Bouley, Roschnik et al. 2017).

Other global changes will also have health impacts. Biodiversity loss is an example. Biodiverse environments support human health in diverse ways, many of them mediated through mental health (Lovell, Wheeler et al. 2014). The loss of particular species or categories of species, such as pollinators, threatens serious nutritional losses (Nicole 2015, Smith, Singh et al. 2015), while the advent of invasive species on a regional basis can threaten agricultural productivity (Paini, Sheppard et al. 2016), promote infectious disease spread (Juliano and Lounibos 2005, Pyšek and Richardson 2010, Chown, Hodgins et al. 2015), and diminish subjective well-being (Jones 2017).

### 3.0 Status of health sector mitigation and adaptation efforts

The health sector will need to address the increasing challenges of global environmental change, particularly safeguarding population health without further unsustainable exploitation of natural systems. Health systems will also be faced with redistributing future health gains more equitably, within and across populations, and with developing strategies to protect and advance population health in periods of lower economic growth; protecting health from the adverse consequences of globalization; detecting and addressing emerging health threats associated with global environmental change; and redirecting research activities to embrace a different set of knowledge and implementation needs. These challenges are within the context that the world's populations enjoy unprecedented levels of good health, according to most metrics, (Whitmee, Haines et al. 2015), and that global development assistance for health is declining (Dieleman, Schneider et al. 2016).

The challenge of proactively reducing further global environmental change is perhaps best exemplified by climate change mitigation. While prominent health voices have increasingly mobilized around mitigation, highlighting the health co-benefits of a range of climate change mitigation activities (Haines, Smith et al. 2007, McMichael, Powles et al. 2007, Bell, Davis et al. 2008, Kinney 2008, Younger, Morrow-Almeida et al. 2008, Rissel 2009, World Health Organization 2009), actual progress toward articulating and achieving mitigation goals within the health sector itself has been relatively slow (Pencheon, Rissel et al. 2009, World Health Organization 2009, Primozic 2010). While there are estimates of health sector carbon footprints (Chung and Meltzer 2009), there is, for instance, no comprehensive estimate of health sector energy use and associated health effects. This highlights the sector's narrow conception of its own activities, how harms associated with health sector activities are accounted for, and implications for population health. Recent work has advanced the agenda of sustainability in health care (Connor and O'Donoghue 2012, McGain and Naylor 2014), operationalizing resiliency in health care facilities (Bouley, Roschnik et al. 2017), and mainstreaming carbon management in health care systems (Pollard, Taylor et al. 2013), and there are several life-cycle assessments of specific health sector activities (Brown, Buettner et al. 2012, Grimmond and Reiner 2012, McGain, Story et al. 2012, Campion, Thiel et al. 2015), but major progress in this area will require a broader scope and greater ambition for realizing sustainability imperatives in the health sector.

Adaptation encompasses a broad range of pursuits, from passive shifts in response to changing weather conditions to intentional activities including conducting vulnerability and adaptation assessments and developing health adaptation plans to increase population resilience. Adaptation activities also incorporate policies (Hess, Schramm et al. 2014) and programming (Hess, Marinucci et al. 2013). Adaptation efforts are progressing (Lesnikowski, Ford et al. 2011, Paterson, Ford et al. 2012, Lesnikowski, Ford et al. 2013, Austin, Biesbroek et al. 2016), albeit more slowly than needed and of insufficient extent. Progress also is being made in addressing potential barriers and constraints (Huang, Vaneckova et al. 2011). The peer-reviewed literature suggests a substantial gap between adaptation needs and adaptation activities (Dupuis and Biesbroek 2013).

This is not necessarily cause for immediate alarm given the anticipated timing of impacts and the fact that some adaptation will occur passively from continued economic development and from public health advances resulting from improved infrastructure, changes in energy production, and improvements in health care (Deaton 2013). With projected economic growth and the demographic transition, some health concerns that are particularly prevalent in low and middle income countries, e.g. diarrheal disease, are projected to continue to decline over the balance of the 21st century even in a changing climate (Hales, Kovats et al. 2014). Importantly, however, even as gains continue to accrue, climate change and other environmental trends will undermine the marginal public health benefits associated with economic development (Hodges, Belle et al. 2014).

Other challenges posed by global environmental change, such as biodiversity loss, are likely to slow or in some cases reverse progress in global health, particularly after 2030. One of the central challenges of adaptation will be developing strategies for anticipating, detecting, and responding to such threats, a challenge given their complex dynamics. Evidence of state shifts – fundamental changes in stable system states, such as desertification – with potentially profound health impacts related to loss of ecosystem services is accumulating (Barnosky, Hadly et al. 2012). The associated health impacts are understood to be manifold but have not been fully catalogued (Butler 2016). Those related to climate change are perhaps most fully elaborated and best understood (Haines and Patz 2004, McMichael and Woodruff 2004, Coote 2006, Haines, Kovats et al. 2006, McMichael, Woodruff et al. 2006, Frumkin, Hess et al. 2008) and can serve as a proxy for other global environmental shifts threatening human health.

To address adaptation and mitigation challenges more fully, the health sector will need to make fundamental shifts in its conceptualization of problems, partnerships, and practice in strengthening health systems (World Health Organization 2015b). The literature on climate change mitigation in the health sector serves as an example. Much of the relatively small body of work focuses on life-cycle analyses of small subsets of health care delivery. This focus on internal processes highlights a conceptual failure (Whitmee, Haines et al. 2015) to frame the problem at the appropriate scale, highlighting the central difficulty that many of the drivers of greatest relevance to population health are not under direct health sector control. Even in settings with relatively high central government involvement in health sector activities, where incentives to limit exposures with substantial health costs would be expected to be in strongest alignment with policy, there is relatively little emphasis placed on reducing greenhouse gas emissions and benchmarking the benefits of doing so for current and future population health. Health systems will need to quickly build consensus around indicators to track, evidence to assemble, and partnerships to enact the transformative change needed. Systemic changes are needed to advance sustainability and environmental stewardship in health systems as central concerns with immediate relevance to population health (Connor and O'Donoghue 2012, McGain, Story et al. 2012, McGain and Naylor 2014).

Metrics are essential, both to clarify the scope of the problems and to monitor progress. There has been some progress in identifying indicators of climate change health impacts, for instance (English, Sinclair et al. 2009, Hambling, Weinstein et al. 2011, Centers for Disease Control and Prevention. 2012, Cheng and Berry 2013, Houghton 2013). Recently a framework for developing indicators of health impacts and health system preparedness was advanced by the *Lancet* Commission, with a focus on health impacts of climate hazards, health resilience and adaptation, health co-benefits of climate change mitigation, economics and finance, and political and broader engagement (Watts, Adger et al. 2016). Additional efforts to merge these tracking activities with Global Burden of Disease assessments and forecasting, building on previous comparative risk assessment frameworks used to project climate change disease burdens (Campbell-Lendrum and Woodruff 2006), would also be important contributions.

The mitigation and adaptation challenges covered focused on climate change. Broadening the scope to include other challenges is necessary for multiple reasons, including the fact that some impacts (e.g. those related to biodiversity and biogeochemical flows) will be felt in coming decades, and because there are synergistic changes that result from interacting system shifts. Further, there is a danger that rapid advances in climate change adaptation and mitigation could, if not designed and implemented taking all sectoral risks into account, worsen the other planetary boundaries that are being crossed (e.g. biodiversity loss, water scarcity). The challenge is ultimately not scoping adaptation and mitigation activities appropriately; it is emphasizing the fundamental role of learning in the health sector's engagement of the challenges of global environmental and socioeconomic changes.

## 4.0 Research needs

McMichael outlined a research agenda for the health risks of climate change more than a decade ago (McMichael, Campbell-Lendrum et al. 2003). The Rockefeller Foundation – *Lancet* Commission on planetary health updated that agenda to include other global environmental changes and such drivers as population growth, consumption, and technology as drivers of environmental change (Whitmee, Haines et al. 2015). The Commission identified five major categories of needed research:

- *Better understanding of the mechanisms through which environmental change affects human health;*
- *Assessment of strategies to reduce environmental damage and harmful emissions including assessment of co-benefits (and co-harms);*
- *Assessment of the effectiveness of strategies and technologies to promote resilience and support adaptation to environmental change;*
- *Research to develop and implement more robust indicators of human welfare and the integrity of underpinning natural systems than exist at present and explore how these measures should be weighted across time (discount rates); and*
- *Translational research and implementation science to address the on-the-ground realities of what is feasible and relevant in the settings facing the greatest threats.*

There are several other pressing research needs. As noted, the nature, extent, and timing of past associations between insults to planetary health and adverse impacts on population health need to be quantified. Counterfactuals related to planetary health and ecosystem depletion need to be developed and used to generate short-term predictions relating planetary and population health and predictions need to be evaluated prospectively. There also is a need to understand the residual risks that health systems will have to manage after implementation of adaptation and mitigation policies and programs. Across all of these categories of research, there is a need to apply an equity lens, identifying disproportionate health burdens on particular at-risk populations, and devising strategies that engage those populations and rectify inequities.

Specific research needs are typically articulated from the perspective of health outcomes over a particular time frame (e.g. short-, medium-, and longer-term). For example, one set of research needs focuses on better understanding the health risks of heat-related morbidity and mortality, including risks in specific geographic locations, at particular temporal scales, and across locations and populations. Related research needs focus on a range of adaptation options, from heatwave early warning systems to reduce exposure to high ambient temperatures, to changes in the built environment to reduce urban heat islands. However, risks interact at local scales, with higher ambient temperatures contributing not just to heat-related morbidity and mortality, but also to potentially higher concentrations of ground level ozone, the replication of pathogens that can cause waterborne disease, and the creation of new suitable habitat for vectors of such diseases as dengue fever and Zika virus. Further, because higher ambient temperatures are associated with heavier precipitation events, some locations are at increased risk for flooding events. Better understanding is needed of how health risks of global change could interact in a location, how these risks interact with underlying disease burdens, how those risks could evolve over time in the context of ongoing global and socioeconomic change, the degree to which potential solutions can address a range of risks, and how responses can be designed to maximize response options and to address new and potentially additional challenges. Research is also needed on the implications of global change for health systems themselves.

## 5.0 Framework for categorizing and prioritizing adaptation efforts

### 5.1 Moving beyond enumerating health risks and adaptation responses

The climate change and health literature contains many lists of current and projected future risks organized by health outcomes, including projections of how risks could change over coming decades (reviews cited above). There also are multiple publications listing possible options to prepare for and manage current and projected risks, particularly for climate-sensitive health risks such as heatwaves or malaria changing their geographic range and incidence in response to a changing climate e.g. (Hess, McDowell et al. 2012)(Ebi 2009). These lists seldom take a holistic, all hazards approach to adaptation, considering what sets of interventions and recovery resources will be needed at the scale of individuals, communities, and nations, over short and longer temporal scales, and without considering how efforts will likely need to evolve as exposures continue to change. Proposed adaptation options infrequently identify thresholds at which the magnitude of climate change-related hazards could overwhelm coping capacity.

The focus of health adaptation to date has been on strengthening health systems (e.g. public health and health care policies, measures, and institutions) to better manage the changes that already are evident and to increase preparedness for projected risks. As discussed above, this incremental approach is unlikely to be sufficient in the face of accelerating challenges with global environmental changes. Designing programs to manage each hazard separately may lead to inadequate preparation of health systems to manage multiple and synergistic exposures. Further, to be effective in protecting population health, adaptation should incorporate strategies to manage the upstream drivers of adverse health outcomes. For example, the upstream drivers of emerging infectious disease threats that occurred in Europe over the period 2008-2013 were outside traditional health system policies and programs, including travel, trade, tourism, and climate and other environmental changes (Semenza, Lindgren et al. 2016). Multi-sector governance should include developing collaborative relationships with departments, ministries, non-governmental organizations, and others with responsibilities for regulating and managing these upstream drivers (Bowen and Ebi 2015).

Recent vulnerability and adaptation assessments and national health adaptation planning are taking systems-based approaches that incorporate planning, implementation, and evaluation processes, uncertainty, and unpredictability into analyses about the magnitude and rate of global environmental change, the response of human and natural systems to the changes, the effectiveness of interventions, and a strong component of learning (Woodruff 2016); (Ebi, Ziska et al. 2016); (World Health Organization 2015a); (Ebi and Otmani del Barrio 2017). They also are beginning to consider what sets of health adaptations are needed across scales to effectively manage risks, and how these adaptations might need to be modified over time.

5.2 How much could adaptation reduce the health risks of global change?

There have been limited efforts to consider how much climate change and other global changes could be adapted to, at particular temporal scales and geographic locations, i.e. how much the coping range of the health sector in a particular location can be moved and how quickly. Two notable efforts are Smith et al. (Smith, Woodward et al. 2014) and the UK Climate Change Risk Assessment 2017 Evidence Report (United Kingdom Committee on Climate Change 2017).

Smith et al. (Smith, Woodward et al. 2014) conducted a comprehensive literature review and used expert judgment to estimate the extent to which proactive and effective adaptation could reduce projected health risks of climate change, concluding the most effective measures to increase resilience in the near-term are supporting and improving current health system measures, such as provision of safe water and improved sanitation, and increasing access to basic health care and vaccination. In the short-term (e.g. until mid-century), risks were expected to increase for heat-related morbidity and mortality, undernutrition, food- and water-borne infections, vectorborne diseases, occupational health, and extreme weather and climate events. By the end of the century, risks would rise significantly as will the need for adaptation. The extent to which adaptation could limit the magnitude and pattern of risks would vary by health outcome. The underlying status of health systems and local vulnerabilities also would be determinants of the potential success of adaptation. This assessment, however, did not identify which specific sets of adaptations could be most effective at reducing future risks.

The UK Climate Change Risk Assessment 2017 Evidence Report (United Kingdom Committee on Climate Change 2017) categorized the risks of climate change based on understanding of the risks and the effectiveness of adaptation responses into: sustain current action; more action needed; research priority; or "watching brief. "Sustain current action" was invoked where there was sufficient understanding of the risks and there were adaptation responses that would likely be sufficient to protect population health and well-being, such as risks to health from poor water quality. Where there was sufficient information on the risks, but current adaptation responses were insufficient, the authors concluded that more action was needed, such as additional interventions to manage the risks to population health and well-being from high ambient temperatures, or the risks to people and communities from flooding. A research priority was noted where knowledge of the risks and responses was inadequate, such as risks to health from changing air quality. A "watching brief" was called for when evidence should be kept under review with long-term monitoring, such as risks of foodborne disease cases and outbreaks. The UK assessment also considered how risks could change with additional climate change, identifying areas where more action was needed to prevent increasing risks over the century.

### 5.3 Identifying baskets of adaptation options

Related to the question of how much aggressive adaptation may reduce climate change risks to health is the question of what aggressive adaptation entails in relation to a particular context, magnitude, and pattern of climate change (e.g. warming of 2°C) (e.g. Astrom, Oudin Astrom, et al. 2017). Policy- and decision-makers need insights into these baskets of adaptation options and the costs of their implementation, including addressing constraints and barriers (e.g., regulations, research on behavioral change). These baskets of adaptation options should include actions by individuals, communities, and health systems over short and longer temporal scales, considering local preferences and context, and how the effectiveness of the options could vary as climate change continues.

The complexities can be illustrated with preventing mortality during heatwaves, a relatively direct effect of climate change on health. There is growing evidence that adaptation is occurring e.g. (Sheridan and Dixon 2016) and projections of health risks in future decades are lower when assumptions about further adaptation are incorporated (e.g., (Hales, Kovats et al. 2014)). Adapting to increases in the frequency, intensity, and duration of heatwaves requires individual and community actions, and longer-term changes to the built environment. When a heatwave occurs, susceptible individuals can reduce their risk through such measures as accessing cooling centers, wearing lighter clothing, and drinking more water. Communities can implement early warning and response systems, which prevent some of the excess mortality that could occur (McGregor, Bessemoulin et al. 2015). Decreasing heat in the built environment through retrofitting, such as white roofs, and building redesign can reduce the urban heat island. Changes in labor practices might also be needed in response to heat-related work limitations (Dunne, Stouffer et al. 2013). The effectiveness of these options needs to be assessed collectively to inform which combinations would be particularly effective in a geographic location. Further, what is effective under today's climate may no longer be optimal under future temperatures. Increases in the frequency and intensity of heatwaves will motivate individuals and health systems to prepare for and adjust to higher temperatures, with deep uncertainty about how much and how quickly.

Choosing optimal or preferred baskets of adaptation options is complex because the local context will influence their effectiveness, with the degree of complexity varying across health outcomes. For example, projected increases in the burden of dengue fever could theoretically be controlled if a vaccine were available. However, not all individuals can or are willing to be vaccinated. There also is a need for improved and sustained community-based dengue surveillance and outbreak response; for locally appropriate vector control interventions; and early warning and response systems where they can be developed (Ebi and Nealon 2016).

Effectively designing, implementing, and monitoring adaptation options requires public health and health care leadership, institutional readiness, and human and financial resources.

5.4 Framework for categorizing and prioritizing adaptation efforts

Breaking adaptation challenges into several broadly applicable categories can help define baskets of adaptation options and improve estimation of associated costs. The Cynefin framework posits that the level of adaptation effort will vary depending on whether the situation is simple, complicated, complex, or chaotic (Snowden and Boone 2007). Cynefin is a Welsh word, often translated into English as "habitat" or "place," that describes the evolutionary nature of complex systems, including their inherent uncertainty. In this framework, the degree of complexity is shaped by the degree of certainty in defining the problem and its potential solutions (x axis) and the degree of agreement among stakeholders on how the problem and potential solutions should be approached (y-axis) (Figure 3). The x-axis also can be thought of as the certainty of the likelihood of impact from exposure to a particular hazard, and the y-axis as the certainty of the effectiveness of a basket of interventions. Time frame also is important, with greater uncertainty about the problem and solutions further into the future. Although these axes are not entirely independent, the framing can be useful for categorizing and prioritizing sets of risk management interventions and for identifying where to focus research and development.

Based on the relationship between the x and y axes, an adaptation situation can be simple, complicated, complex, or chaotic, with the following implications about the cause-and-effect of actions or interventions and their relationship to a health outcome:

- Simple: There is high certainty about the likelihood of impact given exposure to a hazard and adaptation options are generally agreed to be effective. Exposure-outcome associations are well-studied and generally continuous, though not always linear. Although further understanding is always needed, a wide range of health outcomes that could be affected by climate change, such as endemic dengue and heat-related mortality, fall into this category.
- Complicated: The multiple, interacting drivers of the health outcome means there is medium certainty about the likelihood of impact give exposure to a hazard, and there is some understanding of effective adaptation options. Undernutrition is an example of a complicated system, where changes in temperature, precipitation, and extreme weather events can interact with underlying population vulnerability, including rates of diarrheal disease, to affect the level of food security.
- Complex: System dynamics are characterized by nonlinearity, delays, feedbacks, and thresholds. The relationship between changing weather patterns and health outcomes is typically discovered in retrospect because of non-linear feedbacks, though prior experience with similar dynamics can be applied by analogy. Often there is less agreement on effective adaptation options, particularly in settings where significant system shifts have not yet occurred. Adverse health outcomes resulting from, for example, teleconnections (e.g. causal connections between environmental phenomena that occur over a long distance) fall into this category, such as the increases in food

prices resulting from a Russian heatwave that reduced wheat yields (Welton 2011). Other complex risks include interactions between multiple large-scale systems, such as ongoing drought, decreases in food security, migration, and conflict. Complex risks can be more successfully managed when a shift in dynamics can be anticipated and monitored (Lenton 2013, Marvin, Kleter et al. 2013) and there is the possibility of consensus regarding management options among system managers.

- Chaotic: Chaotic systems are highly sensitive to small stimuli. Depending on the information available and the timescale, no cause and effect relationships may be generally perceivable. These are rare in health systems.

These categories can be used to inform the design and implementation of baskets of adaptation options (John Colvin, personal communication).

For example, in simple situations, use of "best practices" is appropriate, with an emphasis on translation and implementation. For complicated situations, where cause-and-effect relationships are discoverable but may not all be known in a given context, there is a strong emphasis on research and analysis to determine and then implement good practice. Managing complicated situations often relies on analysis and expert knowledge. Complex situations require more experimentation and, often, modeling to support iterative cycles of learning to identify emergent solutions. These efforts typically rely on large-scale collaborations and networked knowledge production. Multiple responses may be designed, each with different groups of stakeholders. Chaotic situations call for strong and decisive leadership based on expert judgment; these situations contain unknown unknowns.

The UK Climate Change Risk Assessment (United Kingdom Committee on Climate Change 2017) and the Cynefin frameworks are complementary. Many health adaptations over the short-term could be categorized as simple because they are evidence-based and typically focus on improving health systems. In the framing of the UK Climate Change Risk Assessment, most of these adaptations could be categorized as either "sustain current action" or "more action needed." The added value of the Cynefin framework is that it focuses on knowledge and uncertainty for management, presenting a more complete picture of the challenges facing individuals, communities, and health systems.

Over the medium to longer-term, most health adaptations are complicated, with multiple drivers within and outside the health sector. There are many opportunities for health adaptation, such as limiting the geographic range and intensity of transmission of waterborne diseases by considering not just climate drivers, but also other environmental drivers, the institutional context within which adaptation will be implemented, and the social and behavioral context for adaptation. Such adaptations require more time and resources to develop and implement, ensuring key drivers are incorporated. Identifying where climate change could be expected to lead to the emergence of vectorborne diseases, for example, requires investments in data collection on the presence (and absence) of the vector; monitoring, surveillance, and analysis of cases; modeling of health risks; weather and climate data at temporal and spatial scales of relevance for disease modeling; and other factors. Such investments were made in Canada to monitor the emergence and spread of Lyme disease, and project future changes in its geographic range, providing critical information for decision-makers to manage current and future risks (McPherson, García-García et al. 2016). In the framing of the UK Climate Change Risk Assessment, most of these adaptations could be categorized as either more action needed or research priority based on the detailed understanding of the health outcome.

Some adaptation situations will be complex, such as sudden changes in the geographic range of infectious diseases. However, increasing investment in health systems could move some adaptation situations from complex to complicated, which would enhance opportunities for preparedness. In the framing of the UK Climate Change Risk Assessment, most of these adaptations could be categorized as research priority or watching brief.

Adding a third dimension to this framework, the magnitude of the impact, would be helpful for prioritizing levels of adaptation efforts. This allows further categorization of simple, complicated, and complex adaptation situations into those where the magnitude of impacts ranges from limited to high consequences for population health (e.g. Lindgren, Andersson et al. 2012). This addition can be used to categorize adaptation efforts across health outcomes, providing a snapshot of where gains would be relatively easy or more challenging, and what could be the relative benefit of adaptation efforts. For example, the multiple drivers of undernutrition, the uncertainty around the future quality and quantity of major cereal crops, and the high burden of disease mean adaptation will be complex and highly important. Scaling up of current interventions is needed, along with research and development to increase understanding of future risks. Within a health outcome, the framework can be used to categorize and prioritize a range of options. For example, for heat-related morbidity and mortality, heatwave early warning systems falling into the category of a simple adaptation because the associations between high ambient temperature and mortality is well described and because heatwave early warning systems have been shown to be effective. Modifying the built environment would be complex because changes to a complex system can have unexpected consequences. The framework can help visualize where overcoming barriers and constraints to adaptation will likely have large benefits in terms of protecting particularly vulnerable populations.

Another dimension that could be added to the framework is magnitude of the potential impact. Methods such as *robust decision-making* can be used in an analytic framework for evaluating the sufficiency of a set of adaptation options given a climate change scenario (Groves and Lempert 2007), in addition to the criteria used by health systems to manage risk (e.g., efficiency, effectiveness, consistency, cost-benefit analysis, feasibility, public perception, co-benefits). Robust decision-making was developed to address situations that feature deep uncertainty about climate change risks over short and longer time frames; it is a process to identify adaptation strategies that will perform well under a range of scenarios. The process includes (1) an iterative and participatory dialogue with stakeholders and decision-makers; (2) identifying a wide range of uncertainties and plausible futures that consider more than just climate change; (3) projections of how climate change could affect critical variables affecting a system, such as the shift from snowpack to precipitation for water utilities; (4) identifying the extent to which changes in weather patterns and in other variables could affect vulnerability to future climate change; and (5) identifying adaptation options that would be robust to a range of possible futures. Robust decision-making is being used to provide insights into, for example, whether specific decisions on protecting health care facilities in coastal regions would likely be sufficient under a range of projections of storm surge due to climate change.

## 6.0 Conclusions

Climate and other global environmental changes will challenge the ability of health systems to continue to improve population health. Past gains in population health were at least partially based on intensive use of energy and resources that will continue to constrain future improvements. Ongoing challenges will include inequities arising from maldistribution of resources, a plateau in the relationship between use of energy and resources and health in upper income settings, and health threats arising from unsustainable development choices. Incremental improvements in strengthening health systems are important first steps to transitioning to systems-based approaches that can more effectively manage the multiple, simultaneous challenges that individuals, communities, and health systems will experience over coming decades. But these improvements will likely be insufficient in the face of significant social and environmental changes (e.g. (Smith, Woodward et al. 2014); (Whitmee, Haines et al. 2015)).

Better understanding is needed of how much climate change could be adapted to. Taking a holistic perspective on the possibilities for moving a health system's coping level and levels of effort needed for effective adaptation, the proposed framework can be used to catalyze systems-based approaches to public health, moving beyond disease-focused silos (Ebi, Ziska et al. 2016). A paradigm shift is needed in health to achieve the sustainable development goals, including (1) ensuring leadership for intersectoral coherence and coordination; (2) shifting the focus of health systems from treatment to prevention through locally-led approaches; (3) identifying effective means to address the commercial determinants of adverse health outcomes; (4) taking a rights-based approach; and (5) enhancing civil engagement and ensuring accountability (Buse and Hawkes 2015).

These are valuable approaches for managing the health risks of global environment change, with efforts underway for each. For example, WHO guidance on national health adaptation plans and guidance on developing climate resilient health systems discuss the opportunities of taking advantage of environmental information to prepare for and prevent adverse health outcomes, and the needs for intersectoral coordination, incorporating inequities into assessment and planning, and enhancing civil engagement (World Health Organization 2015a); (World Health Organization 2015b). Lateral public health is a strategy to enhance community resilience by building on existing social capital (Semenza 2011). Community-based adaptation is a powerful approach to advancing resilience (Ebi and Semenza 2008), but will not be successful alone; developing early warning and response systems and projecting health risks over coming decades requires more engagement by higher levels of governance, along with better understanding of upstream drivers of health outcomes. Further efforts are needed to structure health systems so they can more effectively manage current and projected health risks under a range of climate and development scenarios. Doing so would support efforts to promote climate resilient health systems.

Climate and other global environmental changes are presenting significant risks to human health and well-being --- and significant opportunities to transform health systems to protect and promote population health in the face of significant social and environmental change over coming decades.

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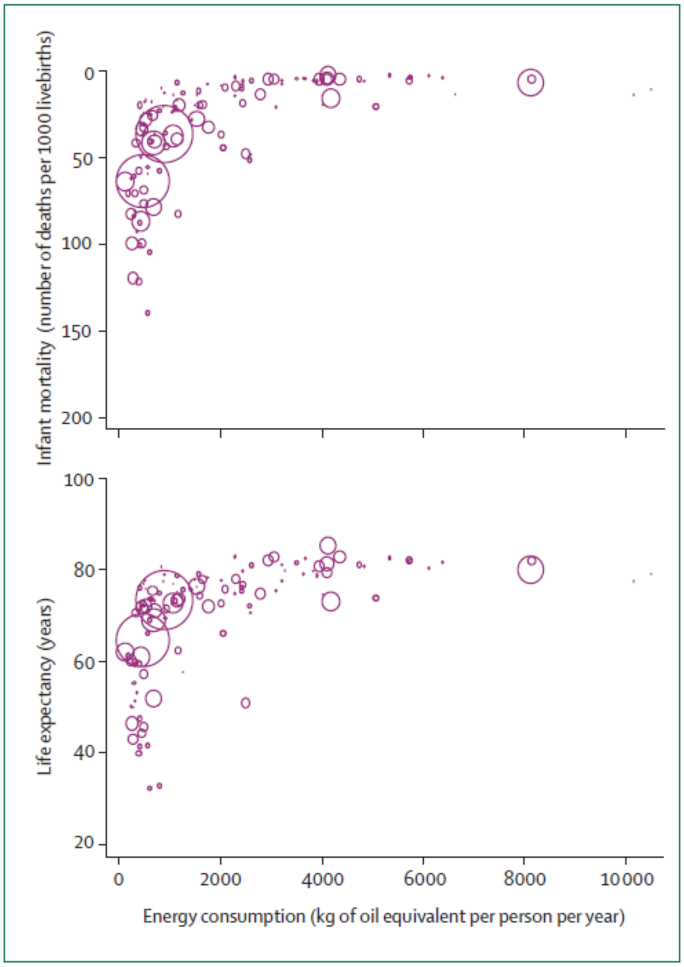
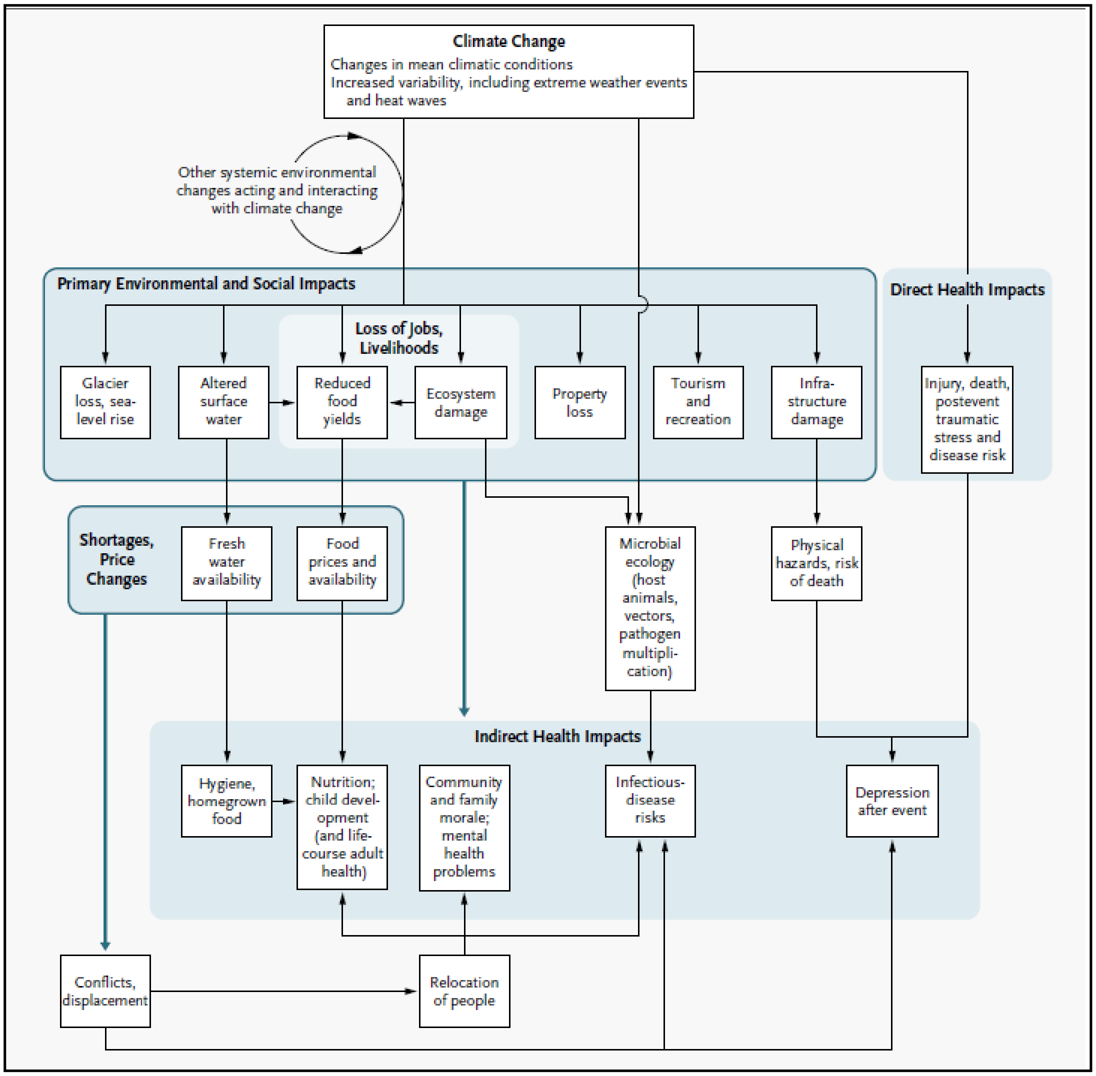
Figure 1: Infant mortality and life expectancy by level of energy utilization



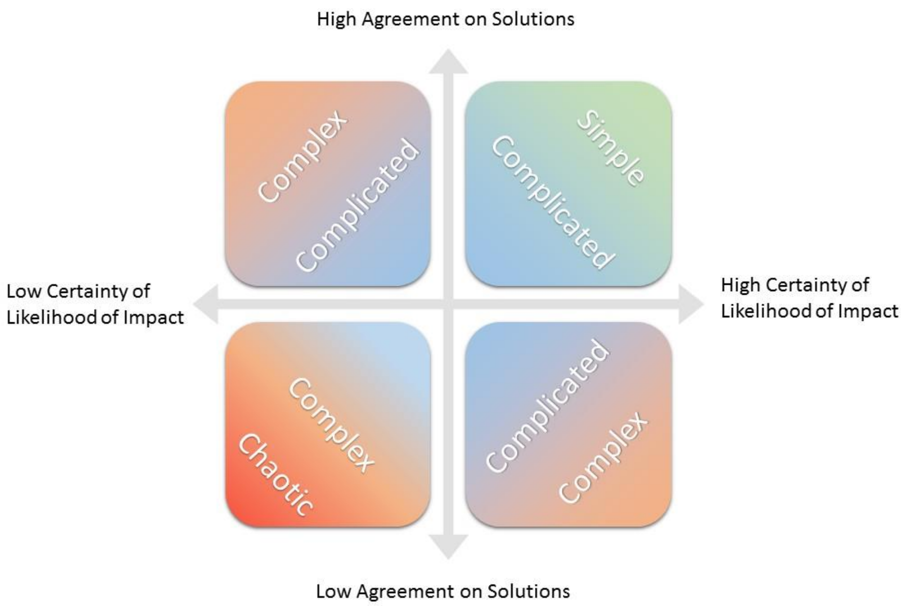

Source: Wilkinson et al. 2007

Figure 2: Conceptual model of processes and pathways through which climate change affects human health




Source: McMichael 2013

***Figure 3: Cynefin framework***




Source: based on John Colvin (personal communication)

***Figure 4: Cynefin framework and impacts***