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Current and future threats to human health in the Anthropocene

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ABSTRACT

It has been widely recognised that the threats to human health from global environmental changes (GECs) are increasing in the Anthropocene epoch, and urgent actions are required to tackle these pressing challenges. A scoping review was conducted to provide an overview of the nine planetary boundaries and the threats to population health posed by human activities that are exceeding these boundaries in the Anthropocene. The research progress and key knowledge gaps were identified in this emerging field. Over the past three decades, there has been a great deal of research progress on health risks from climate change, land-use change and urbanisation, biodiversity loss and other GECs. However, several significant challenges remain, including the misperception of the relationship between human and nature; assessment of the compounding risks of GECs; strategies to reduce and prevent the potential health impacts of GECs; and uncertainties in fulfilling the commitments to the Paris Agreement. Confronting these challenges will require rigorous scientific research that is well-coordinated across different disciplines and various sectors. It is imperative for the international community to work together to develop informed policies to avert crises and ensure a safe and sustainable planet for the present and future generations.

1. Introduction

Homo sapiens have been in existence for only a tiny fraction of Earth's history, but human imprint has now become so large and active that it is the dominant cause of most contemporary environmental change (Steffen et al. 2011; IPCC 2021; Brondizio et al. 2019). Our climate is rapidly changing, and there has been over 1.2 °C of global warming relative to preindustrial temperature driven by human activity (WMO 2021). Ice sheets in Greenland and Antarctica are losing mass at an increasing rate, and sea-level rise is accelerating (Voosen 2020). Evidence suggests that current rates of extinction are about 100–1000 times the likely background rate (Pimm et al. 2014). Around 1 million species will face extinction unless action is taken to reduce the intensity of drivers of biodiversity loss such as climate change, urbanization and deforestation (Brondizio et al. 2019). Without such action, there will be a further increase in the global rate of species extinction, which may lead to the sixth mass extinction (Barnosky et al. 2011). Many emerging diseases, including the ongoing pandemic of coronavirus disease (COVID-19), stem from complex interactions among wildlife, domestic animals and humans, driven by anthropogenic changes in land-use, food production, and trading (Di Marco et al. 2020). More importantly, the impact of human activities on Earth has been intensifying rapidly in the past several decades, leading to disruption and transformation of most natural systems (Myers 2017). These disruptions in the atmosphere, oceans, and across the terrestrial land surface pose serious threats to human health and wellbeing. It is the first time that humanity faces a

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planetary emergency (The Club of Rome 2020). There are emerging threats to human health from global environmental changes (GECs), and urgent actions are required to tackle these pressing challenges (Haines and Scheelbeek 2020; Whitmee et al. 2015).

The overarching aim of this paper is to provide an overview of the nine planetary changes and the threats to human health posed by these changes. We searched relevant bibliographic databases for different topics. For example, in the area of climate and health, we searched PubMed, Web of Science and Scopus using a combination of medical subject headings (MeSH) and free-text terms for conditions of interest. We searched for studies published before Jan 31, 2021, with search terms related to climate ("climat*", "heat", "cold", "meteorolog*", and "weather") and health ("risk*", "effect*", "health", "consequenc*", "impact*", and "threat*"). Only major epidemiological studies published in English were included in this scoping review.

2. Definition and indices of the anthropocene

In the past 200 millennia (less than one ten-thousandth of Earth's lifespan), humanity has flourished from being hunter-gatherers (200,000 – 8000BP) to agriculturalists (8000BP – 20th Century), and then to today's predominantly high-tech, closely-interdependent, urban dwellers (McMichael 1993). The rapid expansion of humankind in numbers and per capita exploitation of Earth's resources has continued apace (Crutzen 2002). The human population has increased from 1 billion in 1800 to 7.8 billion today and is expected to reach 9.9 billion by 2050 (Population Reference Bureau 2020). Human activity is having a significant impact on Earth. We face the combined threats of climate change, biosphere degradation and human health crises (Steffen et al. 2015). In 2002, atmospheric chemist Paul Crutzen described the multiplicity of changes in the Earth's natural systems and suggested that Earth may have entered the "Anthropocene epoch," characterized by the dominance of humans over the global environment. The Anthropocene would terminate the Holocene epoch (meaning "recent whole"), a geological time interval of relative climatic stability lasting around 11,700 years (Crutzen 2002).

Human changes to the Earth System are multiple, complex, interacting, often exponential in rate and globally significant in magnitude (Lewis and Maslin 2015; Steffen et al. 2004; 2015; Brondizio et al. 2019; IPCC 2021; 2014). They affect every Earth System component – land, coastal zone, atmosphere and oceans. The magnitude, spatial scale, and pace of human-induced change are unprecedented (Lear et al. 2020). In terms of fundamental element cycles and some climatic parameters, human-driven changes are pushing the Earth System well outside of its normal operating range in the Holocene. In addition, the structures of the terrestrial and marine biospheres (including both abiotic (e.g. landform) and biotic traits (e.g. habitat-forming organisms)) have been significantly altered directly by human activities (Brondizio 2019). There is no evidence that the Earth System has previously experienced these types, scales, and rates of change; the Earth System is now in a no-analogue situation, increasingly referred to as a new epoch in the geological history of Earth, the Anthropocene (Steffen et al. 2004; Whitmee et al. 2015).

Although the Anthropocene epoch has been broadly and increasingly discussed in the literature, there has been vigorous debate about whether this warrants recognition as a new geologic time unit (Biermann and Kim 2020; Malm and Hornborg 2014; Ruddiman 2003). Anthropogenic markers of functional changes in the Earth System have been carefully reviewed through the stratigraphic record. The evidence shows that carbon, nitrogen, and phosphorus cycles have been substantially modified over the past century (Waters et al. 2016). Rates of sea-level rise and the extent of human perturbation of the climate system exceed late Holocene changes (IPCC 2021). Biotic changes include species invasions worldwide and accelerating rates of extinction (Brondizio 2019). These combined signals render the Anthropocene stratigraphically distinct from the Holocene and earlier epochs (Waters et al. 2016).

Humanity has constantly faced environmental constraints at local and regional levels in the past century. For example, wealthy countries often export their wastes to poor countries posing a serious threat to the health of local populations (McMichael 1993; Sthiannopkao and Wong 2013). These problems remain to some extent, and additionally, we face constraints at the planetary level due to rapidly growing human population and increasing use of natural resources (Haines and Scheelbeek 2020; Whitmee et al. 2015). Human societies can develop and thrive within nine planetary boundaries (PBs), viz., climate change, changes in biosphere integrity (earlier "biodiversity loss"), biogeochemical flows, land-system change, stratospheric ozone depletion, ocean acidification, freshwater use, atmospheric aerosol loading, and novel entities (Rockström et al. 2009). Maintaining critical Earth System processes, which regulate the interactions between oceans, land, atmosphere, and life, within these PBs would keep Earth in a relatively stable state. However, four of these PBs (climate change, biosphere integrity, land-system change and biogeochemical flows) have been exceeded and others are under pressure (Note: Different indicators are used for different planetary boundaries (Steffen et al. 2015)). Undoubtedly, these planetary changes pose grave risks to human health.

3. Health impacts of global environmental change

Planetary boundaries and imminent health risks are closely linked (major links shown in Table 1). It must be emphasized that these risks are just some examples for illustration, and are by no means comprehensive. Earth has undergone many periods of significant environmental change, and it can be generally divided into three phases over the past 12,000 years (Waters et al. 2016; Rockström et al. 2009; Steffen et al. 2018):

Humanity entered the Holocene epoch about 11,700 years ago, during which the planet's environment has been unusually stable, and human civilizations have arisen, developed and thrived (i.e., Phase 1). Since the Industrial Revolution, human actions have expanded dramatically and have become the main driver of local and regional environmental change (Phase 2). After the mid-20th century, a new epoch (i.e., the Anthropocene) has arisen, in which environmental change is occurring at a global scale. Human activities may have already pushed the Earth System outside the stable environmental state of the Holocene, with consequences that are detrimental or even catastrophic for human civilizations (Phase 3). Concerns have been raised that crossing the climatic threshold (i.e., a certain level of greenhouse gas emissions) would lead to a much higher global average temperature than any interglacial in the past 1.2 million years and to sea levels significantly higher than at any time in the Holocene, which may lead to continued warming on a "Hothouse Earth" pathway even as human emissions are reduced (Waters et al. 2016; Rockström et al. 2009; Steffen et al. 2018). Humanity has never experienced environmental change at such a pace and scale (Steffen et al. 2018). Therefore, such a Hothouse Earth pathway would be expected to create serious threats to ecosystems, social systems and human health and well-being.

3.1. Climate change and human health

The link between climate change and human health was first established by some eminent researchers including Alexander Leaf, Andy Haines and Tony McMichael in the late 1980s-early 1990s (Haines and Parry 1993; Leaf 1989; McMichael 1993). As a leading authority on the health risks of climate change, McMichael elegantly categorized climate impacts into direct and indirect mechanisms to produce health outcomes and render immediate and/or delayed health risks (McMichael 1993). This concept was further elaborated by Watts and colleagues: direct risks result from changes in weather extremes such as storms, flooding, wildfires, droughts, or heatwaves. Indirect risks are mediated through changes in the biosphere or broader environment (e.

Table 1
Links between planetary boundaries, and imminent health risks.

Planetary boundary	Parameters	Health risks
Climate change	Atmospheric carbon dioxide concentration and change in radiative forcing	Direct: Mortality, morbidity and injury linked with heat and extreme events (e.g. heatwaves, flooding, bushfires and storms) Indirect: Through ecosystem-mediated pathway: e.g. infectious disease, air pollution-related health burden Through Socioeconomic system-mediated pathway: e.g. drought-related mental illness, climate refuge crisis, health impacts of conflicts and wars linked with climate change
Land system change (e.g., Urbanization)	Percentage of global land cover converted to cities or cropland	Urbanization-related health risks (e.g. obesity, NCDs and mental disorders) and food/water insecurity
Biodiversity loss	Extinction rate	Reduced diversity of genes, species and ecosystems leading to fewer pharmaceuticals, nutrition deficiency, unbalanced microbiome and increased spillover of zoonotic infectious diseases
Biogeochemical flow changes (N, P)	Amount of nitrogen removed from the atmosphere for human use and quantity of phosphorous flowing into the oceans	Algal blooms and dead zones leading to fishery collapse and affecting health and wellbeing in coastal communities; unavailability of phosphorous fertilizer damaging agriculture leading to undernutrition
Aerosol loading	Overall particulate concentration in the atmosphere	Cardiorespiratory and cerebrovascular diseases, and lung cancer
Stratospheric ozone depletion	Concentration of ozone	Melanoma, cataracts and immune deficiency
Freshwater use	Consumption of freshwater by humans	Impacts on availability and quality of freshwater, agriculture, water/food security and water-borne disease
Chemical pollution	Concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof	Impacts on reproductive health, endocrine hormone system, neurodevelopment, and metabolic diseases
Ocean acidification	Global mean saturation state of aragonite in surface sea water	Impacts on marine biodiversity, coral reefs, fisheries, and aquaculture leading to undernutrition, malnutrition, and community collapse.

g., in the distribution of disease vectors, or changes in air quality or food availability), and others through social processes (leading, for instance, to migration and conflict) (Watts et al. 2015). These three pillars (i.e., direct risks, indirect risks through ecosystem changes, and indirect risks through disturbance of social processes) interact with one another, and with changes in land use, crop yield, and ecosystems that are being driven by global development and demographic processes.

3.1.1. *Direct risks*

Rising global temperatures from climate change have significant impacts on mortality, morbidity, and injury as well as labor productivity (Andrews et al. 2018; Gasparrini et al. 2017; Murray et al. 2020; Parks et al. 2020; Watts et al. 2021; Zilbermint 2020). The global average heat-related mortality per year in people older than 65 years has increased by 53.7% from 2000–04 to 2014–18, with a total of 296,000 deaths in 2018 (Watts et al. 2021). Recently, Parks and colleagues (2020) used the data on mortality and temperature over 38 years (1980–2017) in the contiguous USA and quantified how anomalous temperatures, defined as deviations of monthly temperature from the local average monthly temperature over the entire analysis period, affect deaths from injuries. They found that a 1.5 °C anomalously warm year, as envisioned under the Paris Agreement, would be associated with an estimated 1601 (95% confidence interval (95% CI): 1430–1776) additional injury-related deaths. Of these additional deaths, 84% would occur in males, mostly in adolescence to middle age. Moreover, deaths will also be influenced by location. The Multi-Country Multi-City study shows the worldwide mortality impacts of climate change that, under high greenhouse gas (GHG) emission scenarios, would disproportionately affect warmer and poorer regions of the world (Gasparrini et al. 2017).

The global incidence of extreme weather events (EWEs) has been increasing over the past 50 years (Keim 2020). From 1969 to 2018, 10,009 EWE disasters caused more than 2 million deaths and almost 4 million cases of disease. About 7.3 billion persons required immediate assistance. Eighty-nine per cent of EWE-related disaster mortality was caused by storms, droughts, and floods (Keim 2020). Heatwave-related excess mortality is expected to increase dramatically in the future, particularly in tropical and subtropical countries/regions (Guo et al. 2018). The higher the population growth and the greenhouse gas emissions, the higher the increase of heatwave-related excess mortality. The expected changes in 2031–2080 compared with 1971–2020 range from approximately 2000% in Colombia to 150% in Moldova under the highest emission scenario and high-variant population scenario, with an assumption of no adaptation (Guo et al. 2018). Another devastating EWE is wildfires, and an increasing number of large wildfires of unprecedented intensity, extent and duration has happened over recent years, including those in the western United States in 2018 and 2020, Australia in 2019 to 2020, and Amazon rainforest in Brazil in 2019 and 2020 (Xu et al. 2020). The health risks associated with wildfires include direct risks from exposure to fires and/or heat, as well as risks from wildfire smoke.

3.1.2. *Indirect risks through ecosystem changes*

Climate change can cause indirect effects through mediating natural and/or socioeconomic systems. Effects mediated through disturbances in ecosystems include the alteration in the patterns of air-, water-, food- and vector-borne diseases, as well as changes in fresh water availability and food security (Bakonyi and Haussig 2020; Ferguson 2018; Murray et al. 2020; Wu et al. 2016; Scheelbeek et al. 2018). For example, vector-borne diseases remain a major cause of morbidity and mortality, particularly in the tropical regions. Despite much progress in the control of malaria, malaria-associated morbidity remains high, whereas arboviruses—most notably dengue—are responsible for a rising burden of disease, even in middle-income countries (Ferguson 2018). Within the last decade, the geographical spread of West Nile virus (WNV) has been observed in Central Europe and in the Mediterranean region, and in 2020, the geographic expansion of WNV has continued in Europe (Bakonyi and Haussig 2020). For waterborne diseases caused by pathogenic Vibrio bacteria, strong increases in the percentage of coastal area suitable for transmission are observed at northern latitudes (40–70°N), in the Baltic Sea and along the north east coast of the United States (Murray et al. 2020). The number of days per year suitable for Vibrio in the Baltic reached 107 in 2018, double the early 1980s baseline.

Climate change can increase air pollution (McMichael 1993; Watts et al. 2021), and it is well established that air pollution (including both ambient and indoor) kills seven million people each year, mainly from cardiovascular and respiratory diseases and lung cancer (Landrigan et al. 2018). A modelling study estimated the climate and public health outcomes attributable to global fossil fuel use, indicating the potential benefits of a phaseout (Lelieveld et al. 2019). They show that the phaseout of fossil fuel use (i.e., stopping GHG emissions) can avoid an excess mortality of 3.61 (95% CI: 2.96–4.21) million per year from outdoor air pollution, alone, worldwide.

3.1.3. *Indirect risks through disturbance of social processes*

Effects mediated through socioeconomic processes include post-trauma (e.g., drought, flooding and cyclone) stress, and health impacts from climate-related migration, conflicts and wars. For example, farmers often experience significant stress about the effects of drought on themselves, their families, and their communities. Farmers who are younger, live and work on a farm, experience financial hardship, or are isolated are at particular risk of drought-related stress (Austin et al. 2018). Climate change is increasing sea levels and impacting extreme weather events, land degradation, food and water security, and air quality, which affect human migration, displacement, and relocation with significant health consequences (e.g., stress, psychosocial ill-health, communicable and non-communicable diseases) (Schwerdtle et al. 2017). Anthropogenic sea-level rise (SLR) is projected to impact, and, in many cases, displace, a large proportion of the population via inundation and heightened SLR-related hazards (Hauer et al. 2019). With the global coastal population projected to surpass one billion people this century, SLR might be among the most costly and irreversible consequences of climate change. Many low-lying nation states such as Maldives, Tuvalu, Kiribati and the Marshall Islands may lose an entire territory and have to displace their whole population (Hauer et al. 2019). This anticipated territorial loss encompasses legal concerns regarding statehood, national identity, refugee status, state responsibility and access to resources (Vidas et al. 2015). Evidence also suggests that climate has affected organized armed conflict within countries, and intensifying climate change is estimated to increase future risks of conflict (Mach et al. 2019).

3.2. *Urbanization and human health*

Land-use change is a process by which human activities transform the natural landscape, referring to how land has been used, usually emphasizing the functional role of land for economic activities. A megatrend of global land-use change (e.g., urbanization) can be observed in all parts of the world (Gerten et al. 2019). The human imprint on the planet has grown rapidly over the planet in recent decades (Gerten et al. 2019). Land use change affects fauna and flora, contributes to local, regional, and global climate change and is the primary source of soil, water and land degradation (Pielke 2005). Urbanization is the most obvious representation of land-use change and could have positive and negative health effects (Poel et al., 2012; Xu et al. 2008). By 2050, close to 70% of the global population will live in cities (Eurostat 2016). Compared with the past, the living conditions in cities are not likely to be squalid and unsanitary for the vast majority of urban dwellers (Leon 2008). Cities and urban living, compared with the countryside, can offer many more opportunities, including better employment, education, better quality of life, greater wealth and economic vitality, and access to better health care, all of which have important health advantages (Poel et al., 2012). On average, people in urban areas are in better health than those in rural areas (Poel et al., 2012).

However, there are many emerging threats to urban health, which are related to water pollution, degradation of environment, violence and injury, non-communicable diseases, unhealthy diets and physical inactivity, harmful use of alcohol as well as the risks associated with disease outbreaks (Chen et al. 2017). Rapid unplanned urban sprawl is often associated with dirty and/or unsanitary environments which can concentrate health risks and introduce new environmental hazards. For instance, densely populated cities are experiencing urban heat island effects and higher levels of air pollution (Tan et al. 2010; Zha et al. 2010). The artificial urban surfaces clearly differ from natural surfaces and processes (Zhang et al. 2012). In urban areas, additional heat generated by fuel combustion, transport, air conditioning and human activities, as well as the slowing down of wind speed due to roughness effects caused by building structures, may increase urban air temperatures and air pollution (Sabrin et al. 2020) and lead to what is often called the urban heat island effect. Strongest urban heat island effects and highest air particle concentrations usually appear during stable atmospheric conditions or in the transition from stable to neutral conditions (Li et al. 2020). Concentrations of ozone, particulate matter < 2.5 μm ($PM_{2.5}$) and particulate matter < 10 μm (PM_{10}) always increase under stagnant conditions, along with the urban heat island formation (Li et al. 2020). The urban heat island effects often lead to an increase in energy consumption by air conditioning during summertime, thus enhancing the emission of air pollutants as electricity is still predominantly generated by burning fossil fuels (Österreicher and Sattler, 2018). The urban heat island also accelerates the photochemical reactions and formation of ozone (Li et al. 2020; Sabrin et al. 2020). Highly reflective surfaces can increase peak ozone concentration due to a high intensity of outgoing shortwave radiation accelerating photochemical reactions (Li et al. 2020). Heat waves and air pollution have serious adverse effects on the health of urban dwellers (Tan et al. 2010).

Furthermore, urbanization brings social and economic changes that can threaten population health (Fotso 2007). City living and its increased pressures of mass marketing, availability of unhealthy food choices and accessibility to automation and transport all impact on lifestyles that directly affect health (Handy et al. 2002). It is associated with profound changes in diet and in exercise that in turn increase the prevalence of obesity, with attendant increases in risk of type II diabetes and cardiovascular disease (Mendez et al. 2005). Also, cities heighten social tension, increase conflicts and raise overall stress (Dannenberg et al. 2003). There is strong evidence that urban people are much more likely to report mental illness, depressive symptoms and behavioural problems (Dannenberg et al. 2003).

Health services and interventions that are more readily available to the urban population are effective in reducing morbidity and mortality (Stevenson et al. 2016). Urban planning for healthy behaviours and safety, improving urban living conditions, involving communities in local decision making, ensuring cities are accessible and age friendly, and making urban areas resilient to emergencies and disasters, etc. are useful interventions and benefit community health (Yuan et al. 2018). For example, well-planned cities using a compact city approach can result in reduced city-specific particulate emissions owing to reduced motor-vehicle emissions and incentivized walking, cycling, and public transport while reducing subsidies for private motor vehicle use. These approaches will increase the health and sustainability of growing cities (Stevenson et al. 2016). Properly-designed urbanization and improved access to basic services correlate with lower short-term morbidity such as fever, cough and diarrhea (Ahmad et al. 2017). Thus, energy-efficient, equitable and sustainable cities can address both public health and climate change challenges simultaneously.

3.3. *Biodiversity loss and human health*

Biodiversity loss is one manifestation of the suite of accelerating global environmental changes wrought by humans. A biodiverse ecosystem is one which is complex, healthy, and stable, and biologically diverse, i.e. replete with multiple species, and maintained by the interactions between those species (Morton and Hill 2014). Biodiversity loss is driven both *deliberately*, such as by industrial-scale agricultural practices (in particular mono-cropping), and also *inadvertently*, through, for example, climate change where the climate parameters that determine where a particular species can thrive may shift seasonally or geographically, or through the introduction of an invasive species that interrupts existing relationships among native species. Biodiversity loss can also be the result of 'collateral damage' arising from human practices, such as the use of pesticides to protect a crop from a competitor (or predator) species, which also wipes out useful pollinator species.

The relationship between biodiversity and human health, and in particular the potential for negative impacts on human health of reduced biodiversity, has concerned epidemiologists since at least the mid-1990s (Marwick 1995). All land and sea systems are at risk from human activity, including grasslands, forests, rivers and lakes, coral reefs and marine systems (Chivian and Bernstein 2004).

Disrupted ecosystems and reduced biodiversity can alter the pattern of disease and facilitate emerging diseases (Malloy et al. 2019). Encroaching human settlement may introduce humans to an area as a new host, exposing them to zoonotic and vector-borne disease that previously circulated in wild animal populations, while diminishing numbers and types of non-human vertebrate host species can increase the disease risk for humans (Kilpatrick et al. 2017). For example, Lyme disease risk is lessened in areas with high diversity of vertebrate species as a number of these cannot pass on the bacteria once bitten by an infected tick, breaking the chains of transmission (Chivian and Bernstein 2004). Wild animals serve as a reservoir of emerging diseases, and economic activities that increase close contact between humans and wild animals, such as through animal trade, enable opportunities for new pathogens to cross over into humans (Cunningham et al. 2012). The effects of this can be devastating to population health, as was the case with the Severe Acute Respiratory Syndrome (SARS) outbreak in 2003 (Zhong et al. 2003), Middle East Respiratory Syndrome (MERS) in 2012 (Nassar et al. 2018), and likely too the more recent pandemic of coronavirus disease (COVID-19) (Petrosillo et al. 2020).

Ecosystems determine water quality with a key ecosystem service being water purification, while deforestation, which directly and deliberately removes plant species and consequentially reduces animal habitat, can contribute to flood risk, polluted water, and consequent water-borne disease (Nabi et al. 2019).

Food production for human consumption is another example of deliberate reduction of biodiversity, in this instance to serve human food needs, particularly and most obviously in the case of large-scale industrial agriculture and mono-cropping. The use of herbicides and pesticides in agricultural practices further inhibit species diversity (again, deliberately) and is driving the loss of keystone species – a species without which an ecosystem cannot function – such as pollinating bees (Powney et al. 2019). The loss of bees could ultimately have catastrophic consequences for human food systems that are dependent on the services of pollinating insects. Reliance on foods that are produced through mono-cropping can lead to nutrient deficiencies and excess energy consumption (Johns and Eyzaguirre 2006). It also risks failure – and subsequent hunger – should there be a 'bad season' for whatever reason that affects that one crop. In the context of food insecurity, greater local agricultural biodiversity, as nurtured through traditional food systems, for example, underpins adequate dietary diversity and reduces risk of malnutrition (Frison et al. 2006; Johns and Eyzaguirre 2006). Loss of biodiversity in marine ecosystems can not only diminish valuable human food sources, but also endanger cultural practices and livelihoods, adversely affecting health and wellbeing (Matthies-Wiesler and Fleming 2019). Overfishing, marine pollution and climate change continue to pose substantial threats to marine ecosystems.

Mere exposure to biodiversity is beneficial for human psychological and physical health, with engagement with 'green space' contributing to reduced cardiovascular risk factors and improved immune function (Roslund et al. 2020), and decreased psychological stress (Aerts et al. 2018; Rook 2013). The more complex an ecosystem, the greater the benefits to human health may be. Aerts and colleagues (2018) found that species diversity corresponded positively to psychological and physical wellbeing, but note that the number of studies is limited.

Traditional medical practices around the world have relied on the natural world for thousands of therapies (Alves and Rosa 2007), many of which have been successfully incorporated into modern Western (allopathic) medicine, such as aspirin (Montinari et al.2019) and quinine (Achan et al. 2011). Loss of species limits our potential to discover new compounds for the development of therapeutic drugs (Chivian and Bernstein 2004; Neergheen-Bhujun et al. 2017).

Humans have only described perhaps 10% of the Earth's species (Chivian and Bernstein 2004), and possibly only 0.001% of the subset of microbial species (Locey and Lennon 2016), and threats to biodiversity mean we are likely to be losing species before we even know them. Despite abundant wealth and technologies giving the illusion that we exist separate to the world we inhabit, humans remain ultimately dependent on the environment in which we live, the other species that inhabit it, and the quality of the interactions between species.

Fortunately, action that protects biodiversity is also good for our health, in particular increasing the biological diversity of our diet while ensuring more sustainable practices for land and marine systems, reducing our consumption and waste generation, and increasing our physical activity to limit greenhouse gas emissions that cause climate change (Campbell et al. 2011). The benefits of biodiversity for human health extend to the microbiome, the symbiotic microbiota that inhabit our bodies, the functions of this essential ecosystem service we are only just beginning to comprehend (Mills et al. 2019).

3.4. Biogeochemical flows and human health

The link between biogeochemical flows and human health has not been fully understood. Nitrogen (N) and phosphorus (P) are essential elements for life on the Earth. Both are the major components of global biogeochemical cycles. Nitrogen constitutes ~78% of the Earth's atmosphere with an estimated inventory of 4.0×10^{18} kg (Kopáček and Posch 2011). The continental crust, mantle, sedimentary rocks, and oceans are also bulk nitrogen reservoirs (2.4×10^{16}–1.7×10^{20}kg) (Kopáček and Posch 2011). Biological nitrogen fixation, the reduction of atmospheric dinitrogen gas (N_2) to bioavailable ammonium (NH_4^+), is a central pathway in the global nitrogen cycle (Demtroder et al. 2019). Ammonium is oxidized through nitrification to produce nitrite (NO_2^-) and nitrate (NO_3^-) assimilated into organic matter, or is reduced through denitrification to N_2 recycled into the atmosphere (Zerkle et al. 2017).

Increasingly growing food and energy production and consumption of humankind has perturbed the global nitrogen cycle by releasing substantial amounts of reactive nitrogen including nitrogen oxides (NO_x) and ammonia (NH_3) (Andersen et al. 2014; Flombaum et al. 2017). They are key atmospheric pollutants leading to acidification, eutrophication, and biodiversity change in terrestrial and aquatic ecosystems (Andersen et al. 2014; Flombaum et al. 2017; Jung et al. 2019). Emissions have increased sharply since the onset of the industrial revolution due to combustion of fossil fuels and use of synthetic N-fertilizers (Kopáček and Posch 2011; Shakoo et al. 2020; Shibata et al. 2015). Agriculture is the largest emitter of N_2O with an increase of around 1% annually (Shakoo et al. 2020). The anthropogenically-induced nitrogen emissions affect global biogeochemical cycles and ecosystem sustainability, and thus impact human health and well-being through influencing lung function and respiratory diseases as well as food production (Frumkin and Haines 2019; Greaver et al. 2016; Manisalidis et al. 2020; Shibata et al. 2015; Watts et al. 2015). High concentrations of nitrate in water can induce certain diseases, such as infant methemoglobinemia and cancer (Feng et al. 2020).

After its discovery in 1669, phosphorus was named "the miraculous bearer of light", arising from its chemoluminescence (Jarvie et al. 2019). The element plays a vital role in photosynthetic capture of solar light in terrestrial plants and ocean phytoplankton, which account for a large proportion of Earth's total biomass (Behrenfeld 2014; Pan et al. 2011). Natural phosphorus mobilization is slow, where it resides as pentavalent P in phosphate minerals and organic esters (Yuan et al. 2018). Given the rapid population growth and food demand increase, humankind has been perturbing the global phosphorus cycle by intensifying phosphorus releases from the lithosphere to ecosystems. For example, nearly half a billion tonnes of the element from phosphate rock have been mobilized into the hydrosphere over the past half century (Cordell et al. 2011). To dig for more phosphorus, there is the destruction of whole islands for phosphate mining (e.g., Nauru and Banaba islands) (Clifford et al. 2019). Not only is there global phosphorus limitation, the element which is available is often used inefficiently (such as phosphorus fertilizer). Losses of phosphorus from agricultural soil worldwide are estimated to be between 4 and 19 kg ha^{-1} yr^{-1} on average as erosion by water contributes over 50% of total phosphorus losses (Alewell et al. 2020).

Given the phosphate life cycle is currently predominantly linear, from production to waste, global society needs to resolve the dilemma through new sustainable policies on phosphate mining, and long-term management of biogeochemical phosphate cycles. Further research is also required to exploit renewable phosphate fertilizers, improve crop and livestock production and management, and develop new technology to increase sewage treatment and phosphorus recovery efficiencies, to ensure humanity can continue to feed itself into the future while protecting environmental and human health (van Dijk et al. 2016). Phosphorus, an essential nutrient, performs vital functions in skeletal and non-skeletal tissues and is pivotal for energy production (Bird and Eskin 2021). There is an important role of phosphorus and its polymers in the renal and cardiovascular system as well as in brain health.

3.5. *Aerosol and human health*

A strong increase of aerosols has been observed on local, regional, and global scales during the Anthropocene epoch (Tsigaridis et al. 2006). Aerosols are defined as solid or liquid particles suspended in air or other gaseous environment with typical sizes in the range of 0.001–10 μm (e.g., air particulate matter) (Shiraiwa et al. 2017). Aerosols are generated from a wide range of natural and anthropogenic sources. Increased concentrations of atmospheric aerosols can lead to modifications of Earth's energy balance and hence change climate.

There is a substantial variation in air pollution both between and within regions of the world. High levels of air pollution are observed in Asia, Africa, and the Middle East, while the 10 countries with the lowest pollution are mainly developed countries (HEI 2020). The long-term satellite-observed trend in aerosol optical depth (AOD) shows an increase of 2.2–2.3%/year during 2003–2017 (Jose et al. 2020). However, the global aerosol concentrations began to decline in the past several years with a significant variation between regions (Hammer et al. 2020). It is projected that, if there were a strong decrease in anthropogenic emissions, the total AOD would remarkably decline globally (Lamarque, et al. 2011).

Ambient aerosols can lead to both short-term and long-term impacts on human health (Brunekreef and Holgate 2002; Landrigan et al. 2018; Lee et al. 2020; Whitmee et al. 2015). Short-term exposure to aerosols has been related to increased risk in mortality, morbidity (e.g., cardiovascular and respiratory diseases) and adverse birth outcomes (Brunekreef and Holgate 2002; Dong 2017). Long-term exposure to aerosols has been associated with excess deaths and hospitalizations for cardiovascular diseases such as hypertension, heart attacks, and stroke; respiratory diseases such as COPD, lung cancer, and acute lower respiratory illness; chronic metabolic diseases; as well as other health issues such as adverse pregnant outcomes, psychological disorders, and neurological disorders (Brunekreef and Holgate 2002; Shiraiwa et al. 2017; Shi et al. 2020). Although the underlying mechanisms of air pollution affecting human health are not totally understood, exposure to air pollution could disrupt the airway epithelial barrier and cellular signalling pathways, destroy parenchyma, increase oxidative stress and inflammation, dysregulate cell immunity, lead to epigenetic modifications, and adversely affect human health(Amit et al 2013; Guan et al. 2016).

The health impacts of particulate matter are related to particle sizes, chemical constitutes or sources. Smaller particles are more hazardous than larger particles because they usually have higher surface area to mass ratio, carry more toxic chemicals, and penetrate deeply into the lungs (Shiraiwa et al. 2017). Recently, more attention has been paid to bioaerosols, which are a subset of atmospheric PM, and are emitted directly from the biosphere into the atmosphere (Shiraiwa et al. 2017). They comprise living and dead microorganisms, dispersal units, and further cellular materials from plants and animals (Matthias-Maser et al., 1995). Bioaerosols can be infectious, allergenic or toxic for living organisms, which may cause or aggravate human, animal and plant diseases in ecosystems (Reinmuth-Selzle et al. 2017). For example, emerging evidence indicates that the SARS-CoV-2 virus may be transmitted by faecal aerosol in buildings (Kang et al. 2020).

The global burden of disease study has estimated that about 6.7 million people died from air pollution in 2019, including 4.1 million caused by ambient particulate pollution, 2.3 million by household air pollution, and 0.37 million by ambient ozone pollution (GBD 2020). Air pollution has become the fourth leading cause of deaths globally. More than 70% of the air pollution-related deaths occur in Asia, and more than 50% in China and India alone. The World Health Organization (WHO) estimates that 92% of the world's population live in areas with annual mean $PM_{2.5}$ greater than 10 μg/m^3 (WHO guideline) (HEI 2019).

3.6. *Stratospheric ozone depletion and health impacts*

About 90% of ozone is in the stratosphere, which begins about 10–15 km (km) above Earth's surface and extends up to about 50 km altitude. The stratospheric region with the highest concentration of ozone, between about 15 and 35 km altitude, is commonly known as the "ozone layer". Scientific evidence clearly shows that stratospheric ozone depletion is driven by ozone-depleting substances (ODSs) such as chlorofluorocarbons, methyl chloride and bromide, emitted from human activities (Solomon 2021). These ODSs can release reactive chlorine in the stratosphere, which catalyses the destruction of ozone and leads to the "stratospheric ozone hole", which is predominantly over the southern high latitudes (Oram et al. 2017). The most pronounced ozone losses are associated with the Antarctic ozone hole, which occurs each year over Antarctica between August and December (ASOE 2011). During the 1980s–1990s, stratospheric ozone layer declined by about 2.5% in the global mean, and the upper stratospheric ozone declined by approximately 5–8% per decade (WMO 2014). Thanks to international cooperation like the Montreal Protocol on ODSs, stratospheric ozone levels have increased slowly over the past 20 years (WMO 2018).

The stratospheric ozone layer protects life on Earth from the harmful wavelengths of ultraviolet (UV) radiation from the sun, and the depletion of the ozone layer increases UV radiation which confers a great threat to human health (de Gruijl and van der Leun 2000). UV radiation can cause severe diseases in humans such as skin cancer, cataract and immune deficiency (Anwar et al. 2016; Lucas et al. 2015). For example, the melanoma mortality increases approximately 1–2% for every 1% decrease in stratospheric ozone layer (Lautenschlager et al. 2007). The WHO estimated that more than 1.5 million disease-adjusted life years are lost worldwide each year due to overexposure to UV radiation (Lucas et al. 2006).

3.7. *Fresh water and health*

Fresh water, a vital life resource for drinking, cooking, sanitation and personal hygiene, plays a crucial part for everyday life. A distinct human fingerprint on the global water cycle in the Anthropocene is that fresh water is disappearing in many of the world's irrigated agricultural regions (Rodell et al. 2018). The United Nations estimated that a total of 3.6 billion of the world's population live in areas which suffer potential water scarcity at least one month per year, and this number could grow to 4.8–5.7 billion by 2050 (UN-water 2018). Some regions such as Northern Africa have already encountered enormous pressure of limited fresh water, while other regions of intensive agriculture and dense settlement (e.g., USA, Europe, the Middle East, the Indian subcontinent and eastern China) have also shown an increasing concern on this matter (Vörösmarty et al. 2010). In addition, human-induced pollution, catchment disturbance, and climate change could also have considerable impacts on fresh water resources (UN-water 2018; Vörösmarty et al. 2010). It is reported that, in 2016, a total of 829,000 people died from water-related diarrheal diseases, and more than 1 billion people in 149 countries suffered from sanitation-related tropical diseases (such as guinea worm disease, helminth infections, trachoma, etc.) (WHO 2019). In addition, long-term exposure to high levels of chemicals (e.g., arsenic) in drinking water can lead to lesions, cancer, cardiovascular disease and diabetes (WHO 2018).

3.8. Chemical pollution and health

Many chemicals have an important role in modern life and more than 14 000 new chemicals have been synthesized since 1950 (Whitmee et al. 2015). Primary types of chemical pollution include persistent organic pollutants (POPs), heavy metals, plastics, and radioactive compounds, which result from industries, electronic waste recycling, mining and so on. The total quantity of chemicals released to the global environment is unknown, but in North America, 4.9 million metric tonnes of chemicals were released to the environment or disposed in 2009, of which nearly 1.5 million metric tonnes of chemicals are persistent, bioaccumulative and toxic; over 56,000 metric tonnes are known or suspected carcinogens, and nearly 667,000 metric tonnes are considered reproductive or developmental toxicants (UNEP 2013).

Chemical pollutants adversely influence human and ecosystem health by virtue of their persistence and ability to undergo long-range transport. For example, the burden of disease from selected chemicals was estimated at 1.6 million lives and 44.8 million disability-adjusted life years (DALYs) in 2016 and nearly 1 million workers died as a result of exposure to hazardous chemicals in 2015 (UNEP 2019). Releases of antimicrobials, heavy metals and disinfectants to the environment may also contribute to antimicrobial resistance (Diamond et al. 2015; UNEP 2017).

3.9. Ocean acidification and health

Oceans constitute the largest biome (1.37 billion cubic kms) on the planet covering 70.8% of Earth's surface with an average depth of about 3,700 m (Boeuf 2011). Ocean acidification refers to a series of chemical reactions that reduce seawater pH, carbonate ion concentration, and saturation states of calcium carbonate minerals (NOAA 2020). A reduction in the pH of the ocean is primarily caused by uptake of carbon dioxide (CO_2) from the atmosphere. The ocean absorbs more than 90% of the heat released into the Earth's environment and nearly one-third of CO_2 emissions (Gruber et al. 2019; NOAA 2020), providing a critical buffer to atmospheric fluxes of heat and CO_2. Since the Industrial Revolution, the acidity of oceans has increased about 26% (Whitmee et al. 2015).

Oceans support human fisheries and aquaculture, providing more than 4.5 billion people with at least 15% of their average per capita intake of animal protein (Falkenberg et al. 2020). Ocean acidification could pose a threat to human health due to malnutrition and poisoning via altered food quantity and quality (Béné et al. 2015; Falkenberg et al. 2020). The population of some marine species is at high risk of collapsing due to the adverse effects of increasing ocean acidity on reproduction and survival, which would remove the bottom of the food chain in marine ecosystems, threatening the survival of upper trophic levels and human food sources from marine environments (Kawaguchi et al. 2013). Increased acidity would also affect the health of some species (e.g., *Nephrops norvegicus*) that may be more susceptible to infections of bacteria (Hernroth et al. 2015), and enhance the uptake of toxic substances in some organisms (e.g., cadmium accumulation in marine bivalves, increased Benzo[a]pyrene accumulation in blood clams), suggesting a potential threat to seafood safety (Shi et al. 2016; Su et al. 2019). Moreover, ocean acidification could also disrupt pelagic food webs via the proliferation of toxic algal blooms, the proliferation of which may pose an emergent threat to coastal communities, aquaculture and fisheries (Riebesell et al. 2018). In addition, ocean acidification decreases opportunities to develop and obtain medical resources via the loss of biodiversity (Falkenberg et al. 2020). Unfortunately, ocean acidification will continue and nearly a doubling in acidity of seawater is projected by 2100 (Falkenberg et al. 2020).

3.10. Compound effects of multiple drivers

The impacts of GECs on human health are likely intertwined and we address this issue using asthma and allergic diseases as an example. The rise of allergic diseases has been one of the important changes to human health through the Anthropocene. Several epidemics of allergic disease have occurred due to the change in interactions between humans and the environment (Beggs and Bambrick 2005; Platts-Mills 2015). The impact of GECs (e.g., climate change, urbanisation and biodiversity loss) on aeroallergens such as pollen and fungal spores and allergic respiratory diseases such as allergic rhinitis and asthma is complex, involving interactions with multiple drivers.

There is now a large body of evidence that climate change impacts aeroallergens and allergic respiratory diseases (Beggs 2021). This is via the effects of both increasing atmospheric CO_2 concentration and temperature. Impacts include changes in airborne pollen concentrations, allergenicity, aeroallergen seasonality, and the spatial distribution of aeroallergens. Evidence indicates that temperature-related changes in pollen abundance and seasonality have occurred across the Northern Hemisphere (Ziska et al. 2019). Anderegg et al. have recently conducted a landmark detection and attribution study, quantifying the role of anthropogenic climate change in widespread advances and lengthening of pollen seasons and increases in pollen concentrations across North America from 1990 to 2018 (Anderegg et al. 2021). Experimental studies growing different plant species in past, current, and projected future CO_2 concentrations have shown that elevated CO_2 concentrations can increase the allergenicity of grass pollen (Albertine et al. 2014), ragweed pollen (El Kelish et al. 2014), and *Alternaria* fungal spores (Wolf et al. 2010).

Grass pollens are the major cause of pollinosis in many parts of the world. Climate change may lead to an expansion of tropical/subtropical C_4 grasses over typical temperate C_3 grass areas (Morgan et al. 2011). The change in the proportion of C_3 and C_4 grasses may, in turn, be a factor that alters the pattern of allergic disease (Davies et al., 2021).

Several studies on projected future impacts of climate change have also emerged. Building on previous work (Hamaoui-Laguel et al. 2015; Storkey et al. 2014), Lake et al (2017 and 2018) produced estimates of the potential impact of climate change on common ragweed (*Ambrosia artemisiifolia*) pollen allergy in Europe taking into account the change in ragweed's range (it is an invasive species currently spreading across Europe) and current and future ragweed pollen concentrations. Allergic sensitisation to ragweed will more than double in Europe, from 33 to 77 million people, by 2041–2060. Higher ragweed pollen concentrations and a longer ragweed pollen season may also increase the severity of allergy symptoms (Lake et al. 2017, 2018).

Changes in severe weather will also affect aeroallergens and allergic respiratory diseases. For example, increases in tropical cyclone (hurricane) frequency and intensity would result in increased flooding of homes and growth of indoor mould. Similar changes in thunderstorms would be cause for concern in regions prone to epidemic thunderstorm asthma (Thien et al. 2018). It has been shown that thunderstorms can increase the impact of allergens as, for example, they can cause pollen grains to break into smaller fragments, which can then reach further into the respiratory system (Bannister et al. 2021).

Compounding these impacts of climate change on aeroallergens and allergic respiratory diseases are the consequences of urbanisation and biodiversity loss. The concentration of human activities in urban areas can increase air pollution, and this can interact with aeroallergens in a variety of ways to increase allergic respiratory diseases in urban inhabitants (Lucas et al. 2019; Reinmuth-Selzle et al. 2017). Climate change may also drive increases in surface level ozone and airborne particulate matter (West et al. 2013). For example, climate change has been shown to increase ozone through increased photochemical reaction rates and biogenic emissions, and meteorological changes (West et al. 2013). The urban environment can include highly allergenic plant species that are not native to the area, either planted publicly or privately (e.g., birch), or introduced unintentionally (e.g., weeds such as *Parietaria* and *Plantago*) (Beggs 2010; D'Amato et al. 2007). There is potential for this issue to be exacerbated in attempts to mitigate climate change and the urban heat island through inappropriate plantings (Salmond et al. 2016).

As illustrated above, climate change and urbanisation are significant drivers of biodiversity loss. This is significant in light of recent hypotheses which suggest that contact with natural, biodiverse environments enriches the human microbiome, promotes immune balance and protects against allergy and inflammatory disorders (Haahtela 2019; Prescott 2020). Poorly designed urbanisation reduces the abundance and diversity of airborne microbes, contributing to urban-associated diseases through altered immune function (Flies et al. 2020a, 2020b).

Changes in biogeochemical cycling also impact aeroallergens and allergic respiratory diseases. For example, Paseka et al. (2019) point out that soil nitrogen and phosphorus, which have increased in many environments through human activity, contribute to pollen production rate and pollen grain size which may exacerbate pollen allergies.

The implications of changing aeroallergens may go well beyond changes in allergic respiratory diseases. Recent studies have shown that increasing pollen exposure can heighten vulnerability to respiratory

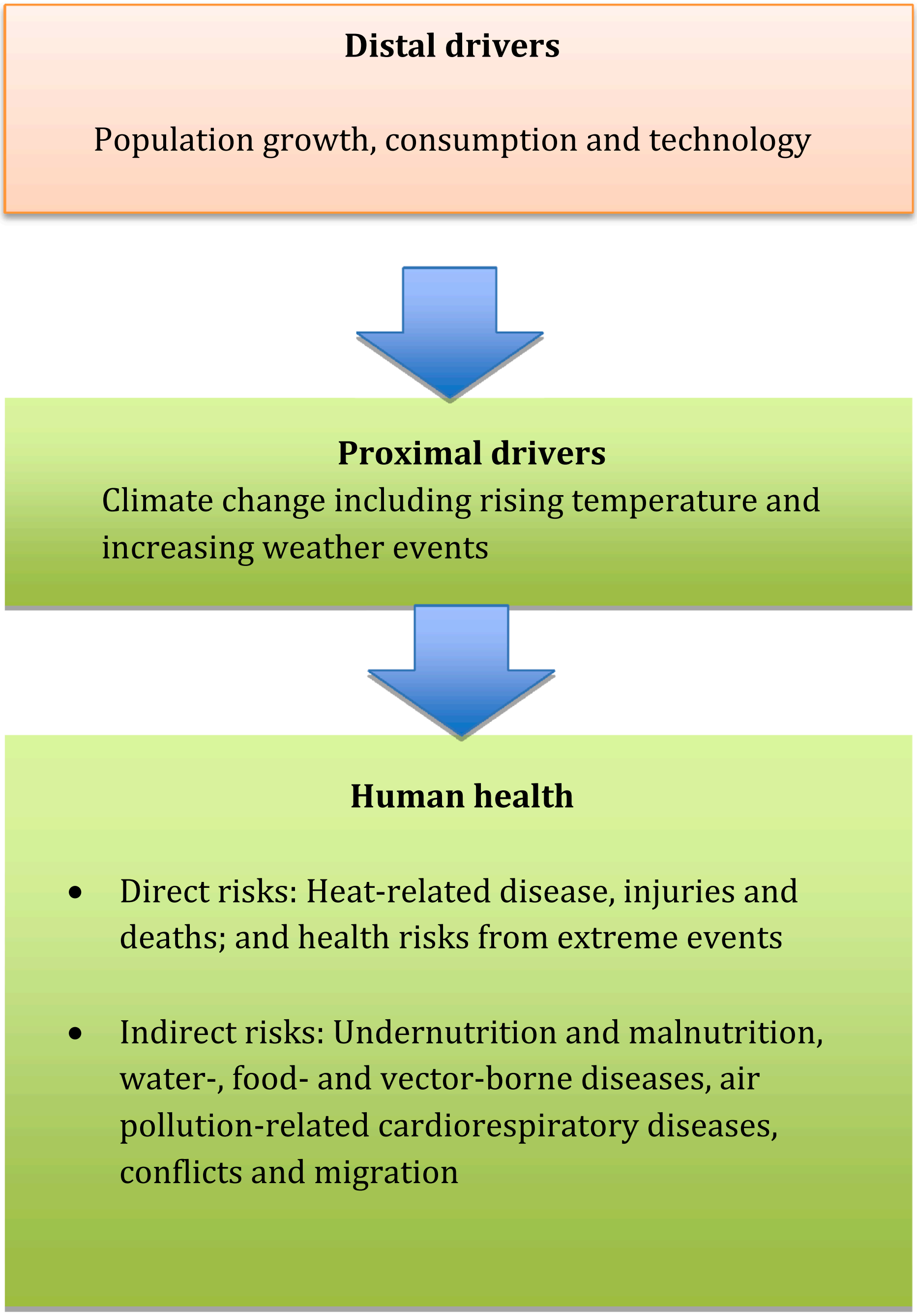

Fig. 1. Schematic diagram of the causes of climate change and emerging threats to human health.

viral infection, including SARS-CoV-2 (Damialis et al. 2021), and its role in the emergence of zoonotic viral diseases is worthy of further research (Wang and Crameri 2014).

4. Challenges and opportunities

Although, as reflected in the literature discussed above, the tremendous progress has been achieved in this field over the last three decades, there are still many challenges ahead, and meanwhile, opportunities abound. Fig. 1 reveals that, as an example, climate change – a major aspect of global environmental changes, is driven by multiple factors and affect population health directly and indirectly. It is also anticipated that, as climate change proceeds, future threats to human health will increase. For example, Watts and colleagues (2021) reported that, during the past 20 years, there has been a 53·7% increase in heat-related mortality in people older than 65 years, reaching 296 000 deaths in 2018 (categorised as a current and direct health risk). This risk is likely to increase as global warming continues and populations are ageing (a future and direct health risk). The climate suitability for infectious disease transmission has been growing since the 1950s, with a 15.0% increase for dengue (a current and indirect health risk) (Watts et al. 2021). The pandemic of COVID-19 is still sweeping across many parts of the world and the threat from infectious disease will rise in a rapidly changing world (a future and indirect health risk). We must escalate our efforts and fulfil the commitments made in the Paris Agreement.

GECs are typically entangled and should not be treated as isolated issues. Therefore, it is essential to quantify the compound effects of multiple drivers on population health through interdisciplinary and multi-sectoral collaboration. Such evidence will form the foundation for guiding government policy and public health practice.

It is vitally important to take pre-emptive action well ahead of problems becoming entrenched. Human health and natural systems are interdependent, and *Homo sapiens* cannot survive without properly protecting the Earth's natural "life support" systems (McMichael 2013; Steffen et al. 2015; Watts et al. 2021). Basic components of these systems such as air, water, arable land and biodiversity are all essential to human health and well-being.

At the early stage of the Anthropocene epoch, we must endeavor to return to the "safe operating space" within planetary boundaries. If we fail to do so, societal collapse could become the reality, because the crossing of planetary boundaries is likely to have serious and cascading effects. We must increase key ambitions (e.g., net zero carbon by 2040 or earlier) and scale up action. Global CO_2 emissions continue to rise, even though, 5 years ago, the Paris Agreement aimed to limit climate change to "well below 2 °C" relative to preindustrial levels by the end of this century (UNFCCC 2021). To achieve this goal will require a 7.6% reduction in CO_2 emissions every year, representing an increase in current levels of national government ambition of a factor of five (Watts et al. 2021). Stronger climate action can bring great improvements in population health. For instance, nine countries (i.e., Brazil, China, Germany, India, Indonesia, Nigeria, South Africa, the UK, and the USA) contribute over 70% of the world's greenhouse gas emissions (Hamilton et al. 2021). These countries could reduce 1.6 million air pollution-related deaths, 6.4 million diet-related deaths, and 2.1 million physical inactivity-related deaths annually by 2040, if they adopted commitments consistent with the Paris Agreement and placed health at the centre of their climate policies (Hamilton et al. 2021).

We must enhance the resilience of communities and increase the adaptive capacity to any changes that cannot be avoided (Haines and Scheelbeek 2020; Watts et al. 2021). Every country, city and community need to develop and implement mitigation and adaptation strategies such as climate-sensitive urban planning to encourage people to cycle and walk instead of driving to reduce our environmental footprint and increase physical activity (co-benefits); early warning systems for heatwaves, droughts, wildfires, floods, storms and disease outbreaks; and vulnerability mapping to reduce risks of coastal flooding and extreme events.

Scientists and policy-makers have a pivotal role to play in developing transformative, sustainable policies to reduce air pollution, enhance public transport systems, improve diets and life style behaviors, increase equality and fairness, and strengthen public health and medical services. Health should be a priority issue in all government policies for sustainable development and in international negotiations to protect planetary health. Without health, residents, both urban and rural, will suffer, the economy will suffer, and the whole society will suffer, which is clearly reflected in the on-going pandemic of COVID-19 (Tong et al. 2021).

5. The way forward

This review highlights how GECs associated with anthropogenic activity influence human health, and the strategies to prevent and minimize these health risks. Nonetheless, several significant gaps remain in measuring, modelling and policy development around the implications of GECs for human health, and future research should endeavor to fill these gaps.

First, Earth System processes are inherently dynamic and can change abruptly, with large uncertainties about systemic threshold values and their implications for the economy, society and planetary health (Biermann and Kim 2020). We may already be on a "Hothouse Earth" pathway so many unexpected events may appear sooner or later. Even though there have been robust discussions about the definition and start date of the Anthropocene (Zalasiewicz et al. 2019, 2021), there is now widespread consensus in both the geological and Earth System science communities that the Anthropocene began around the mid-20th century (around 1950) (Steffen et al. 2016; Zalasiewicz et al. 2015). Formalization of the Anthropocene in the Geologic Time Scale is now underway.

Second, although many effects of GECs have already been observed and more health hazards are still yet to manifest, the empirical linkages between GECs and human health are contentious to some extent. Since many GECs and social changes have been occurring at the same time, it is challenging to attribute any health consequences to a single, independent GEC. Research has only begun to turn to the underlying mechanisms that might drive the GEC-related health consequences, but it is abundantly clear that more research is critically needed to understand the causal relationship between GECs and human health. Critically, our understanding of thresholds and tipping points beyond which societal collapse becomes inevitable is limited.

Third, mitigation and prevention of the GEC-related health effects depend on many factors. For instance, international efforts to keep human activity within a "safe operating space" are so important that humanity is unlikely to thrive, develop, and even survive if we fail to do so. Therefore, it is critical to raise the awareness of this important issue among scientists, policy-makers and the general public, and chart our course towards sustainable development through international collaboration and innovation.

Fourth, adaptation to GEC-related health impacts has become essential because a certain number of irreversible GEC has already occurred. For example, GHG emissions have caused a 1.2 °C increase in global average surface temperature above the preindustrial levels (WMO 2021). Even though the pandemic of COVID-19 is temporarily reducing carbon emissions due to the lockdown in many countries, atmospheric levels of GHGs continue to rise (Le Qúeŕe et al. 2020; WMO 2021). If GHG emissions were stopped today, climate change will continue for at least a few decades, due to the inertial nature of the climate system (IPCC 2018). Thus, it is essential to develop adaptation plans to cope with the increasing threats to human health from climate change. Nevertheless, what are the most cost-effective adaptation measures remains to be determined at local, regional, national and global levels.

Finally, projections of future GEC-related health consequences are vitally important for formulating evidence-based government policies, but are confronting multiple uncertainties. For example, there is considerable debate over the thresholds and tipping points of GECs (Biermann and Kim 2020). Additionally, how useful advanced technologies (e.g., geoengineering) are in mitigating GECs remains to be evaluated and some may entail very high risks. Furthermore, many other factors can influence such projections, including sociodemographic changes, policy responses and adaptation. Little research, to date, has quantified public health implications of GECs using a global and programatic approach.

There are several limitations in this study. The broad areas of this topic preclude us to conduct a comprehensive and systematic review. As a multidisciplinary and cross-sectorial collaboration, some inconsistencies in the article may be inevitable.

6. Concluding remarks

A mounting body of evidence has demonstrated that humanity has entered a new geological epoch – the Anthropocene, which is stratigraphically different to the Holocene and earlier epochs (Steffen et al. 2016; Waters et al. 2016). Human activity has caused many global environmental changes and these GECs threaten both human health and planetary health. In the Anthropocene, all nations, rich or poor, must set aside their antagonisms and jointly confront the emerging threats facing the planet as Earth is the only planet we can live on. Rich countries have the moral duty to take a greater share of the cost of action, as they have benefitted most economically from the pillaging of the natural environment, and their wealth may also offer some protection against many of the consequences.

Rigorous scientific research on GECs and human health will require well-coordinated, multidisciplinary, and cross-sectoral collaboration. It is beyond any reasonable doubt that as GECs continue, we will face increasing and compounding health threats. Therefore, it is imperative for the international community to work together to develop informed policies to avert crises and ensure a safe and sustainable planet for the present and future generations.

CRediT authorship contribution statement

Shilu Tong: Conceptualization, Writing – original draft, Writing – review & editing, Visualization. **Hilary Bambrick:** Writing – original draft, Writing – review & editing. **Paul J. Beggs:** Writing – original draft, Writing – review & editing. **Lanming Chen:** Writing – original draft, Writing – review & editing. **Yabin Hu:** Writing – original draft, Writing – review & editing. **Wenjun Ma:** Writing – review & editing. **Will Steffen:** Writing – review & editing. **Jianguo Tan:** Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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