

# Planetary Health: Focusing on the Intersection of Human Health and the Earth System

Carlos A. Faerron Guzmán,<sup>1,2</sup> Nicole Redvers,<sup>3</sup>  
John S. Ji,<sup>4</sup> Oliver Lacey-Hall,<sup>5</sup> Jemilah Mahmood,<sup>5</sup>  
Oskar Masztalerz,<sup>6</sup> Alexandra L. Phelan,<sup>7,8</sup>  
Johan Rockström,<sup>6,9</sup> and Samuel S. Myers<sup>7</sup>

<sup>1</sup> Planetary Health Alliance, Johns Hopkins University, Baltimore, Maryland, USA;  
email: carlos.faerron@jhu.edu

<sup>2</sup> Graduate School, University of Maryland, Baltimore, Maryland, USA

<sup>3</sup> Schulich School of Medicine and Dentistry, University of Western Ontario, London, Ontario, Canada

<sup>4</sup> Vanke School of Public Health, Tsinghua University, Beijing, China

<sup>5</sup> Sunway Centre for Planetary Health, Sunway University, Kuala Lumpur, Malaysia

<sup>6</sup> Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany

<sup>7</sup> Johns Hopkins Bloomberg School of Public Health and Johns Hopkins Institute for Planetary Health, Baltimore, Maryland, USA

<sup>8</sup> Johns Hopkins Center for Health Security, Baltimore, Maryland, USA

<sup>9</sup> Institute of Environmental Science and Geography, University of Potsdam, Potsdam, Germany

**ANNUAL  
REVIEWS CONNECT**

[www.annualreviews.org](http://www.annualreviews.org)

- Download figures
- Navigate cited references
- Keyword search
- Explore related articles
- Share via email or social media

Annu. Rev. Environ. Resour. 2025. 50:303–37

First published as a Review in Advance on  
August 12, 2025

The *Annual Review of Environment and Resources* is  
online at [environ.annualreviews.org](http://environ.annualreviews.org)

<https://doi.org/10.1146/annurev-environ-111523-102309>

Copyright © 2025 by the author(s). This work is licensed under a Creative Commons Attribution 4.0 International License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See credit lines of images or other third-party material in this article for license information.



## Keywords

Planetary Health, Earth system, Planetary Boundaries, sustainable development, climate change, global health equity

## Abstract

The core insight of Planetary Health is that the Earth crisis is fueling a global health crisis. Planetary Health examines the links between human health and Earth's natural systems. This review outlines key drivers of environmental degradation and how they lead to global environmental change, which is marked by the transgression of six Planetary Boundaries and causes severe health impacts such as malnutrition and the spread of diseases, with increased risks for vulnerable populations. The concept of Earth system justice highlights the need for just solutions to address inequities within and between generations. The review discusses actions like sustainable food and energy systems, circular economies, governance changes, and collaboration across sectors. It also emphasizes the importance of Indigenous knowledges

and building resilience for vulnerable populations. Aligning human well-being with the health of natural systems is necessary to address current challenges and ensure a livable future for all.

## Contents

1. INTRODUCTION .....	304
1.1. Emergence of Planetary Health .....	306
2. EXAMINING THE DRIVERS OF LARGE-SCALE ENVIRONMENTAL CHANGES .....	307
2.1. Demographic Transitions .....	308
2.2. Technological Advances in Resource Extraction .....	308
2.3. Industrialization .....	308
2.4. Societal Values and Economic Priorities .....	309
2.5. Governance Failures .....	309
2.6. Rapid Urbanization .....	309
2.7. Agricultural Practices and Expansion .....	310
3. ANTHROPOGENIC EARTH SYSTEM CHANGES .....	310
3.1. Interactions Among Changes and Tipping Elements .....	314
4. DIRECT AND INDIRECT IMPACTS ON HUMAN HEALTH AND WELL-BEING .....	314
4.1. Nutrition .....	314
4.2. Infectious Diseases .....	316
4.3. Noncommunicable Diseases .....	316
4.4. Direct Injury and Displacement .....	317
4.5. Sexual and Reproductive Health .....	317
4.6. Mental Health .....	318
5. INEQUITY IN ENVIRONMENTAL HEALTH IMPACTS .....	318
5.1. Transforming Back to the Safe and Just Corridor Is Critical for Human Health .....	318
6. SOLUTIONS FOR RAPID TRANSFORMATIONAL CHANGE .....	319
6.1. Reimagining Energy Systems .....	320
6.2. Transforming Food Systems .....	321
6.3. Reinventing Transportation Systems and Built Environments .....	322
6.4. Transforming Economic Systems .....	322
6.5. Social, Behavioral, Narrative, and Value Change .....	323
6.6. Governance Reform .....	326
6.7. Strengthening Community Resilience and Local Collaboration .....	326
6.8. Achieving Earth System Justice and Social Equity .....	327
7. CONCLUSION .....	327

## 1. INTRODUCTION

Over the past 7 decades, we have witnessed unparalleled advances in human health and well-being (1). Driven primarily by poverty reduction, breakthroughs in public health initiatives, medical advances, and improvement in food systems, global average life expectancy has risen from 46 years in 1950 to 71 years in 2021 (2). Simultaneously, social innovations, such as expansion of human

rights frameworks and social safety nets, have lifted more than one billion people out of extreme poverty in the last 3 decades and have improved access to basic human needs such as health services and food security (3).

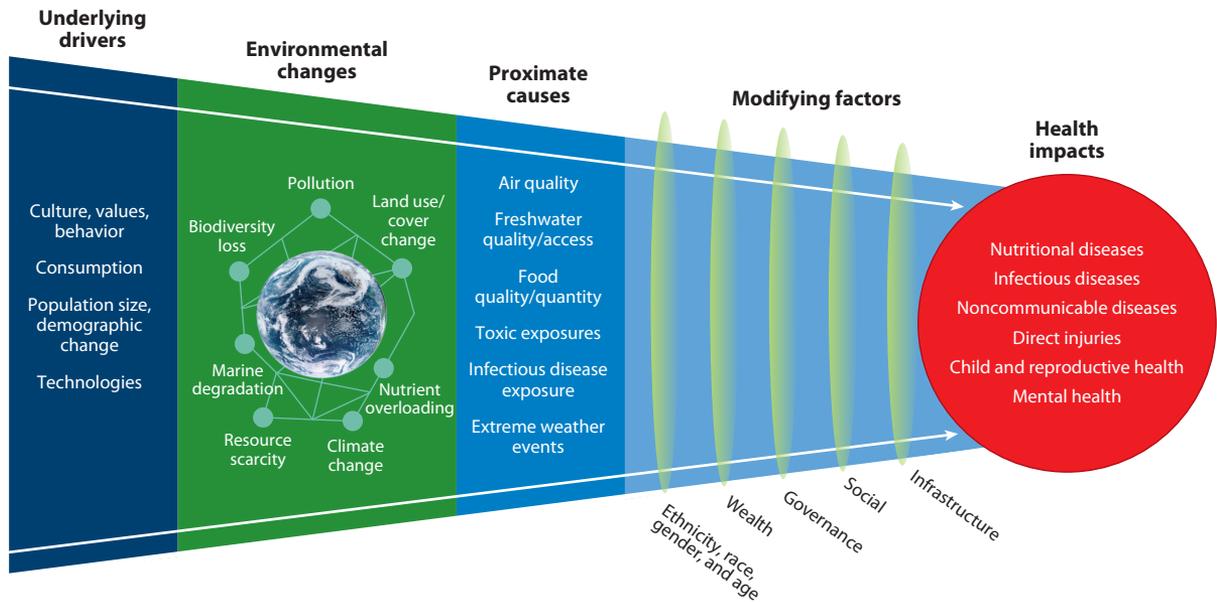
Despite global progress, disparities remain stark. For example, life expectancy ranges from 54 years in Nigeria to 86 years in Monaco, a gap exceeding the overall global improvement since 1950 (2). Significant hurdles also persist into the future: According to a recent United Nations report, only 17% of the Sustainable Development Goals (SDGs) targets are on track to be achieved by 2030 (4). The COVID-19 pandemic also highlighted and worsened these existing challenges by shedding light on the vulnerabilities in both global health systems and economies. For instance, it pushed 23 million additional individuals into extreme poverty and exacerbated food insecurity for more than 100 million people (4, 5).

Alongside the mixed advances and setbacks observed today, much of the progress to date has relied on the extensive exploitation of natural resources, resulting in widespread environmental degradation (1). The recent acceleration of human resource use has had profound and compounding consequences for Earth's natural systems, including the global climate system, the biosphere, and nutrient and water cycles (1). Six of the nine Planetary Boundaries (PBs) have been transgressed, pushing us beyond the safe operating space for humanity on Earth and leading to a high risk of large-scale disruptions to our climate and biosphere and of crossing irreversible tipping points with potentially devastating consequences (6) (see the sidebar titled *The Planetary Boundaries Framework: Defining the Safe Operating Space for Humanity*). Global environmental changes are placing past and future advances in human health and development at substantial risk, which will disproportionately affect vulnerable communities worldwide and worsen global health disparities (7).

In order to safeguard and improve human health and well-being, a threefold challenge needs to be addressed: first, adhering to safe environmental boundaries to ensure Earth's stability and resilience in order to maintain its capacity to buffer change; second, avoiding any harm from Earth system change to current and future generations; and third, allowing everyone minimum access to essential resources necessary to live healthy lives in dignity (7). These interconnected

## THE PLANETARY BOUNDARIES FRAMEWORK: DEFINING THE SAFE OPERATING SPACE FOR HUMANITY

The Planetary Boundaries (PBs) framework was used as a starting point for defining the field of Planetary Health in the first *Lancet* Commission report in 2015 (1). Widely recognized in Earth system science, this framework defines a so-called safe operating space for humanity on Earth by defining safe thresholds for nine critical processes that regulate the state and functioning of the Earth system: climate change, change in biosphere integrity, stratospheric ozone depletion, ocean acidification, alterations to biogeochemical flows (of phosphorus and nitrogen), land system change, freshwater change, atmospheric aerosol loading, and novel entities. These processes are measured by 13 indicators, including climate forcing (measured in watts per square meter) or extinction rate (species lost per million species years). Transgression of safe thresholds is associated with an increased risk of crossing irreversible tipping points and losing Earth system resilience, namely the capacity of our planet's natural systems to buffer (anthropogenic) change, which can result in permanent large-scale shifts in the Earth's biosphere, climate, and other subsystems (12). By contrast, transforming back into the safe operating space is associated with a high likelihood of keeping the Earth system in the same stable state that contemporary human societies have evolved in for the past 10,000 years. The PBs framework has evolved since 2009, and it was comprehensively assessed, with quantification of all nine PBs, for the first time in 2023. Annual assessments—the Planetary Health Checks—began in 2024 (6, 13).



**Figure 1**

Pathways from global environmental change to inequitable human health impacts. Anthropogenic activities are disrupting Earth's natural systems, driving interconnected large-scale environmental changes that affect human health and its determinants. These environmental changes, shaped by socioeconomic systems, cascade through modifying factors to generate diverse and inequitable health outcomes. Figure adapted with permission from <https://planetaryhealthalliance.org/planetary-health-schematic>, copyright 2025 Planetary Health Alliance, which was adapted from Reference 10, copyright 2017 Elsevier. Earth image reproduced from an Adobe Stock image by Gizem Geçim Kandal (<https://stock.adobe.com>; file number 489137253).

challenges underscore the urgency of addressing environmental degradation in the context of global development. Over the last decade, these pillars have become central to Planetary Health, the focus of this review, which is a growing field that acknowledges the intertwined nature of the environmental, health, and equity crises of the Anthropocene (1) (**Figure 1**).

The remainder of this review is organized as follows. Section 2 identifies the underlying drivers of global environmental change, such as demographic shifts, governance failures, and resource extraction, that accelerate the degradation of the Earth systems and the transgression of PBs. Section 3 explores large-scale disruptions of the Earth system—like climate change and biodiversity loss—and their synergistic effects. Section 4 describes the health impacts of these large-scale disruptions, such as food and water insecurity and infectious disease spread. Section 5 addresses the inequitable health burdens on populations that face disproportionate exposure to environmental hazards and have limited adaptive capacity. Through the lens of Earth system justice (ESJ), the review emphasizes the need for just, systemic change. Section 6 discusses solutions, including clean energy, sustainable agriculture, and circular economies, and calls for cross-sector collaboration that will lead to governance, education, and economic reform to ensure a just, resilient, and health-focused future.

### 1.1. Emergence of Planetary Health

Introduced by The Rockefeller Foundation–*Lancet* Commission in 2015 (1), Planetary Health addresses the escalating impacts of global environmental changes on human health and well-being, and on the whole web of life on Earth, while highlighting the deep transformative changes that

are essential for sustaining and advancing global health. The Planetary Health Alliance defines Planetary Health as “a solutions-oriented, transdisciplinary field and social movement focused on analyzing and addressing the impacts of human disruptions to Earth’s natural systems on human health and all life on Earth” (see <https://www.planetaryhealthalliance.org/planetary-health>). Planetary Health unites diverse scientific disciplines and knowledge forms and emphasizes the interdependence of human health with the health of other species, ecosystems, and ultimately Earth’s natural life support systems while promoting stewardship to sustain human well-being through an integrated approach (8). Planetary Health calls for just and systemic solutions to global environmental challenges, overcoming their root causes, recognizing disparities in both contributions to and impacts from natural systems degradation, and ensuring that the human populations most affected are not left behind (9, 10) (see the sidebar titled Comparison with Other Frameworks).

Planetary Health aligns closely with the SDGs, underscoring that a healthy and resilient environment is essential for development and human well-being (17). Embedding Planetary Health principles into the post-2030 national and global policy agenda offers an opportunity to ensure harmonization between ecosystem integrity and development.

Building on this foundation, the Planetary Health Alliance, comprising more than 500 organizations across 79 countries, has been instrumental in advancing research, policy, and educational initiatives aimed at translating Planetary Health into action (11). Through the collaboration of scientists, policy makers, and community leaders, the Planetary Health movement encourages work across various sectors to reduce environmental threats and improve human well-being.

## 2. EXAMINING THE DRIVERS OF LARGE-SCALE ENVIRONMENTAL CHANGES

This section examines the underlying drivers of large-scale environmental change, including demographic transitions, technological advances, societal consumption patterns, and governance inefficiencies. It explores how they operate independently and in concert to destabilize Earth’s

### COMPARISON WITH OTHER FRAMEWORKS

Planetary Health aligns with other approaches that link human, animal, and environmental health, such as One Health and EcoHealth (11). Initially centered on zoonotic diseases, One Health has recently expanded its scope to address broader health implications from human–animal–environment interactions (14), promoting collaboration across veterinary, human health, and environmental sectors to tackle emerging health threats (e.g., zoonotic diseases and antimicrobial resistance). EcoHealth emphasizes ecosystem-centered perspectives, acknowledging the importance of healthy ecosystems in promoting human health (14).

Planetary Health, however, uniquely addresses the large-scale and accelerating pace of environmental changes, such as biodiversity loss and climate change, that destabilize the Earth system. While One Health and EcoHealth prioritize mainly specific disease or ecological dynamics, Planetary Health adds a focus on human health, addresses systemic issues, and explores how environmental deterioration can have cascading and far-reaching consequences—geographically and over time—on human well-being. Drawing on insights from these frameworks, Planetary Health promotes an inclusive and transdisciplinary approach to solutions that are both just and globally relevant (8, 10). Further dynamic development of each of these approaches should involve close exchange between the relevant communities, acknowledging their strengths and specificities and with a view to a common vision, rather than competition (15, 16).

natural systems and accelerate the transgression of PBs. By describing each factor, we aim to clarify its significance and individual role in advancing global ecological strain and the cumulative impact of these drivers on critical natural systems.

### 2.1. Demographic Transitions

Demographic shifts and rising resource demand are key drivers of environmental changes (18). With the global population now surpassing eight billion, demands for vital resources such as food, water, and energy (19; see <https://population.un.org/wpp>) place increasing pressure on natural systems, leading to deforestation, water scarcity, loss of biodiversity, pollution, and urban sprawl (20). Additionally, increases in life expectancy and rural-to-urban migration create lifestyle shifts (i.e., more demand for services and products) that compound strains on ecosystems. At the same time, urbanization may reduce the per capita environmental impact, depending on how cities are designed (21). However, population growth as a driver of global environmental change must be discussed critically. While population growth is highest in low- and middle-income countries (LMICs), high-income nations—home to most of the world's wealth—are responsible for the highest share of both resource use and emissions (e.g., the wealthiest 10% consume as much energy as the poorest 80%) (22). Furthermore, high birth rates are increasingly recognized as an effect of gender-based discrimination and transgression of sexual and reproductive rights, combined with socioeconomic deficiencies and restricted access to education, rather than as a primary cause of environmental pressure (23).

### 2.2. Technological Advances in Resource Extraction

Technological advances through mechanization and automation have greatly improved the efficiency of resource extraction in industries such as mining, drilling, and forestry (24, 25). For example, automated equipment and remote-controlled systems in mining have enabled mining operations that now regularly reach depths of 1,000–3,000 m or more (25). These innovations aim to meet the growing demands for raw materials and energy to produce the goods and services of consumption-driven societies (7). However, these advances carry serious environmental downsides, leading to habitat destruction, biodiversity loss, soil degradation, and heightened pollution (26). Despite the call for incorporating efficient practices, such as Industry 4.0 technologies (27), extraction industries remain energy inefficient and adopt more sustainable technologies at low rates (28). Paradoxically, while potential efficiencies aim to conserve resources, they can result in increased total resource use and emissions, a phenomenon known as the rebound effect (29).

### 2.3. Industrialization

Industrialization has been pivotal for the improvement of living standards, particularly in high-income countries, but has also contributed significantly to environmental degradation. Fossil fuel-based energy in industry is the third leading source of carbon dioxide (CO<sub>2</sub>) emissions globally (30), and industrial operations, including manufacturing and chemical production, release hazardous pollutants into the air, water, and soil. These pollutants include particulate matter, organic and nonorganic compounds, and greenhouse gases (31, 32). Industrial wastewater is frequently dumped into rivers, lakes, and oceans, degrading water quality and adversely affecting aquatic environments and thereby posing a risk to biodiversity and overall ecosystem health (33). The negative consequences of industrialization can be exacerbated, particularly in LMICs, when inadequate regulatory oversight or environmental protections are not in place (31).

## 2.4. Societal Values and Economic Priorities

Societal values that prioritize economic growth and consumerism, while neglecting the interconnectedness of humans and nature, favor linear and extractive economic models. Such models underpin the exploitation of resources and generation of emissions without adequately accounting for externalities in the form of environmental harm or negative direct health impacts (19, 34). This inadequate accounting for externalities accelerates environmental changes like deforestation, pollution, and biodiversity loss while frequently neglecting the short- and long-term impacts on ecosystems and human well-being (35, 36).

In addition, the global political economy of resource extraction is often dominated by foreign investments, especially from the Global North, that exploit resources in the Global South without the consensus of affected communities, their just compensation, or the equitable sharing of benefits arising from the use of resources (37). This extractive imperialism, which often follows colonial patterns, prioritizes resource exploitation to fulfill global demands, especially of the wealthy, over local communities' environmental, economic, and social well-being (35, 36). These dynamics are well-documented in regions like Latin America and sub-Saharan Africa, where policies focused on intensive resource extraction exacerbate social gaps while keeping the local economy reliant on unsustainable practices and trapped in global dependencies (35). However, contemporary resource extraction dynamics extend beyond colonial patterns. Increasingly, South–South interactions, as in Chinese, Indian, and Gulf state investments across Africa, Asia, and Latin America, are reshaping the landscape of exploitation (38, 39).

## 2.5. Governance Failures

Inefficient, ineffective, or detrimental governance exacerbates environmental challenges through procedural failures, including unaccountability, policy delay, nontransparency, inequity, and exclusion. These failures perpetuate global and local power disparities, favoring powerful interests over marginalized groups, prioritizing short-term gains, and often overlooking structural causes of environmental decline (40–44). Policy efforts designed to mitigate or reverse environmental degradation also frequently lack efficient accountability measures. Inadequate coordination between national and international bodies as well as nonstate actors—especially when combined with increasing geopolitical tensions—can lead to policy incoherence, stagnation, or entrenchment (15, 45, 46). Additionally, overcentralized governance structures tend to disempower and restrict participation from marginalized and impacted communities, weakening credibility and further fragmenting governance (47, 48).

## 2.6. Rapid Urbanization

Cities are home to more than half of the world's population, with the highest growth rates occurring in small and midsize cities (49). They contribute 70% of global energy consumption and CO<sub>2</sub> emissions (49). Urbanization can lead to both positive and negative environmental outcomes as well as direct health outcomes, depending on context and urban planning quality. Well-implemented urbanization can reduce per capita resource consumption, improve access to services and infrastructure, and boost well-being. However, in many contexts, particularly in LMICs, rapid urbanization often leads to deficiently planned settlements lacking adequate infrastructure, thereby increasing environmental and health challenges due to limited clean water, sanitation, and health care (50).

Globally, urbanization contributes significantly to habitat destruction and fragmentation that significantly affects wildlife and ecosystems (50), transforming landscapes such as forests, wetlands, and farmlands into commercial, residential, and industrial areas. This process leads to a decline

in biodiversity and nature's contributions to people, which in turn have consequences for cities (51, 52). The local modification of land surfaces, the construction of urban infrastructure, and inadequate waste and pollution management lead to soil erosion; impaired water infiltration; contamination of water, soil, and air; decreased air circulation; and the urban heat island effect (31, 51).

Expanding and supplying cities also often rely on distant resources, which can lead to unsustainable land system changes such as deforestation and degradation beyond the city boundaries (51). Globally, cities often show a linear metabolism, characterized by a large inflow of external resources and an outflow of quantities of emissions, waste (e.g., municipal or industrial), and pollutants, with impacts on ecosystems and public health from the local to the global scale (31, 32).

## 2.7. Agricultural Practices and Expansion

Agricultural expansion and intensive farming practices greatly contribute to environmental degradation, which in turn increasingly imperils agricultural production (53, 54). Increasing global demand for food, agricultural commodities, by-products, and animal feed has led to the widespread adoption of monoculture farming and excessive use of fertilizers and pesticides. Importantly, the production of animal food products contributes disproportionately to the environmental impacts of agriculture (55).

Nutrient runoff, especially of nitrogen and phosphorus, and the release of agrochemical residues lead to eutrophication and soil, water, and air pollution, which significantly affect animals, plants, and ecosystems (53, 54). Moreover, intensive irrigation methods exacerbate water scarcity by draining aquifers and rivers, particularly in arid regions, where soil salinization is a concern (53). Agricultural expansion contributes to deforestation, desertification, and land degradation, with around 420 million hectares lost since 1990, affecting soil health and the function of land as a major carbon sink (53, 54). However, for reasons such as land speculation and poor management, not all land cleared for agricultural purposes transitions into sustained agricultural use; instead, it often leads to degraded or abandoned deforested areas, particularly in tropical regions where deforestation is driven largely by livestock and crop demands for export (56). Combined, land system changes for agricultural purposes contribute to nearly a quarter of global greenhouse gas emissions (52).

Understanding the underlying causes of large-scale environmental change provides insight into the mechanisms accelerating ecological degradation. Building on this insight, Section 3 examines how these forces manifest as large-scale changes across Earth's natural systems—such as shifts in climate stability, biodiversity, and resource depletion—that collectively threaten human health.

## 3. ANTHROPOGENIC EARTH SYSTEM CHANGES

Human activities disrupt the Earth system at an alarming and often accelerating pace (**Table 1**). This section examines how the drivers discussed in Section 2 manifest as large-scale changes across Earth's natural systems—such as shifts in climate stability, biodiversity loss, changes in biogeochemical cycles, and resource depletion. These changes are substantially reshaping the planet, impairing Earth's capacity to buffer change. The loss of stability and resilience of the Earth system is tracked by the widely recognized PBs framework (see the sidebar titled *The Planetary Boundaries Framework: Defining the Safe Operating Space for Humanity*). Six of the nine PBs are currently transgressed, and trends for most boundaries point toward further transgression, meaning that humanity is moving deeper into the zone of increasing risk and uncertainty (6). Earth system changes are collectively threatening human health and have far-reaching implications for the stability and resilience of societies and ecosystems.

Table 1 Anthropogenic Earth system changes and their impacts

Disruption area	Key drivers	Key metrics	Selected social and ecological impacts
Disruption to the global climate system	Burning of fossil fuels, deforestation, and industrial and agricultural activities release greenhouse gases into the atmosphere (30, 40).	Current atmospheric CO <sub>2</sub> of 417 ppm exceeds the Planetary Boundary for climate change (6). Global temperature has increased by 0.95 to 1.20°C compared with preindustrial levels (30). The year 2023 marked the highest recorded temperatures for land and sea (6). Global average temperature is expected to rise by 3.1°C by the century's end if only the current climate policies are implemented (6, 59).	The frequency of extreme weather events such as droughts, storms, and heat waves (58) is increasing. Extreme drought now affects 47% of global land, up from 18% in the 1950s (58). Accelerated glacier melt raises sea levels, endangering coastal areas (58). Coastal ecosystems face heightened storm damage due to warmer oceans (58). Ecosystems and vulnerable communities' water and food security are under threat (61). There are significant socioeconomic and health risks, especially for low-income regions (61).
Widespread pollution of air, water, and soils	Pollution from industrial and vehicle emissions as well as agriculture (31, 32). Water sources are contaminated by industrial waste, agricultural runoff, sewage, microplastics, pharmaceuticals, and heavy metals like mercury, lead, and cadmium (31, 32). Soils are polluted by improper waste disposal, pesticide overuse, and heavy metals (31).	Primary atmospheric pollutants include PM <sub>2.5</sub> and toxic gases such as nitrogen dioxide and sulfur dioxide (62, 63). Annual emissions of sulfur dioxide and nitrogen oxides are 109.30 and 10.29 million tons per year, respectively (7). Annual mean PM <sub>2.5</sub> concentrations in highly polluted cities in East and South Asia are as high as 25.8 µg/m <sup>3</sup> (7). Up to 25 (0.13–25) million metric tons of micro- and nanoplastics are deposited in oceans annually (76). The Planetary Boundary for novel entities is transgressed (6).	Pollution degrades water quality and harms aquatic biodiversity (31, 32). Microplastics disrupt trophic chains, causing toxin bioaccumulation (31, 32). Soil pollution affects agricultural productivity and food security (31). Aerosol loading is influencing the climate system (6).
Rapid loss of biodiversity and biosphere integrity	Deforestation, habitat destruction, resource exploitation, urban expansion, pollution, aquatic habitat loss, and climate change (6, 53, 65).	Approximately one million species face extinction (36, 43). Extinction rates are tens to hundreds of times above historical averages (53). Vertebrate populations declined by 69% from 1970 to 2022 (65). Marine biodiversity, especially food species, has declined as a result of overfishing (66). Extinction rate (measure of genetic diversity) and human appropriation of net primary production (measure of functional integrity) transgress safe Planetary Boundaries (6).	The biosphere provides a wide range of nature's contributions to people that are crucial for human health and well-being. Key ecological functions such as pollination, seed dispersal, nutrient cycling, and water purification are disrupted, with socioeconomic consequences (6).

(Continued)

Table 1 (Continued)

Disruption area	Key drivers	Key metrics	Selected social and ecological impacts
Reconfiguration of biogeochemical cycles	Earth's carbon, phosphorus, and nitrogen cycles have undergone anthropogenic changes (40). Fossil fuel combustion and land use changes raise CO <sub>2</sub> levels (40). Synthetic fertilizers disrupt the nitrogen and phosphorus cycles (6). Intensive agriculture and unsustainable food production are increasing (6).	CO <sub>2</sub> levels exceed 417 ppm, well above historical averages of the past 800,000 years (6). The annual amount of anthropogenically fixed nitrogen applied to the agricultural system is ~190 Tg, transgressing the safe global Planetary Boundary by more than 200% (6). Up to 32.5 Tg of phosphorus is applied yearly to croplands, transgressing the safe regional-level Planetary Boundary (6).	Excess nitrogen and phosphorus in freshwater and oceans can lead to eutrophication, harmful algal blooms, dead zones, biodiversity loss, and damage to freshwater and marine ecosystems (6, 77). These disruptions degrade water quality, threaten food security, and impair ecosystem functions (6).
Degradation of land-based ecosystems	Agricultural expansion, urbanization, and large-scale infrastructure development (67).	Around 178 million hectares of forest were lost over the last 3 decades (67). Approximately 9.3 million hectares were lost annually in tropical forests from 2015 to 2020 (67). Agriculture, forestry, and land use changes also contribute up to 23% of greenhouse gas emissions (52). The Planetary Boundary for land system change has been transgressed (6).	Major environmental impacts of land system change include habitat destruction as well as altered carbon storage and hydrological cycles (67). Deforestation worsens biodiversity loss, accelerates climate change, and disrupts ecosystem services (52). Urban growth restricts wildlife movement and reduces ecosystem services as a result of habitat fragmentation (52).
Resource scarcity	Key resources like water and arable land are overused and mismanaged (70). Water is extracted for agriculture, urban, and industrial use (70). Unsustainable farming, soil erosion, desertification, and urban expansion threaten fertile land (54). Resources are overexploited, and water and land governance is inadequate. Climate change intensifies droughts and alters precipitation patterns (54).	Agriculture uses 70% of global freshwater, depleting rivers and aquifers (70, 71). Planetary Boundary for freshwater change is transgressed (for blue and green water) (6). Approximately 10 million hectares of arable land are lost annually to salinization and desertification (54, 72).	Rivers and aquifers are depleted (70, 71). Around half of the global population faces seasonal water shortages (70). Regions with inefficient water management, like sub-Saharan Africa and South Asia, are heavily affected (54, 71). Loss of fertile land reduces agricultural productivity (54). Food security and livelihoods are threatened by arable land loss (54, 72).
Biophysical ocean changes	Climate change and other human-driven changes result in major biophysical changes in oceans (73, 74). Sea surface temperatures are rising as a result of global warming (74). CO <sub>2</sub> absorption causes ocean acidification (74). Nutrient overflow and global warming cause deoxygenation and dead zones (75).	Sea surface temperatures may rise by 1.5 to 3.5°C and ocean pH could decline by 0.16 to 0.44 units by the end of this century under high emissions (74). The Planetary Boundary for ocean acidification is currently close to being transgressed (6). Global ocean oxygen levels have decreased by 0.5% to 3.3% since 1970 (74).	Marine ecosystems, food webs and species distribution are influenced by rising temperatures, acidification, nutrient overflow, and deoxygenation (73–75). For instance, coral reefs and shellfish are threatened by pH changes (74), and expansion of low-oxygen dead zones leads to habitat and biodiversity loss (75).

Central to these human-caused disruptions is climate change, which is caused by a steady rise in atmospheric CO<sub>2</sub> and other greenhouse gases, primarily from fossil fuel combustion and deforestation (30, 57), and has led to increasing average global temperatures (7). The disruption of the climate system is also leading to more frequent and severe extreme events, like droughts, heat waves, and storms (58). If only the current climate policies are implemented, the United Nations Environment Programme expects an increase in average global temperature of 3.1°C (range: 1.9–3.8°C) by the end of this century (59). With such a change, billions of people would be exposed to wet-bulb temperatures higher than 32°C (60), and agricultural productivity and water availability would be disrupted worldwide (6, 61). Melting glaciers and rising sea levels, combined with biodiversity loss, would put coastal habitats (e.g., wetlands, coral reefs, mangroves) and urban areas at risk (58). Climate shifts are also intensifying socioeconomic pressures and health risks, especially in marginalized and low-income communities that are particularly reliant on intact ecosystems and have limited adaptive capacity (61).

Environmental degradation is exacerbated by widespread pollution of air, soil, and water. Driven mainly by industrial emissions, vehicle exhaust, and agricultural activities, air pollution includes the harmful accumulation of pollutants like particulate matter (PM<sub>2.5</sub>) and toxic gases (e.g., nitrogen oxides, sulfur dioxide) (31, 32, 62, 63). Pollution due to industrial waste, agricultural runoff, and untreated sewage degrades water quality and harms aquatic ecosystems through the accumulation of noxious substances such as pharmaceuticals, heavy metals, and microplastics (31, 32). Soil pollution, caused primarily by excessive pesticide use, improper waste disposal, and industrial activity, can lead to the loss of soil fertility, disrupt microbial communities, and reduce the land's capacity to support vegetation (31). These forms of pollution collectively degrade ecosystem integrity, disrupt natural nutrient cycles, and threaten the resilience of habitats essential for biodiversity (31).

Biodiversity loss has accelerated sharply as a result of land use changes, pollution, and climate change, placing around one million species at risk of extinction (53, 64, 65). This rapid species loss, with rates of extinction far exceeding historical baselines, harms nature's contributions to people, including pollination, nutrient cycling, and water purification (6). Overfishing, pollution, and changes in marine biological and chemical composition also pose risks for marine biodiversity (66). The biosphere's capacity to support Earth system resilience is further compromised by declines in genetic diversity and increasing human appropriation of net primary production, signaling that change in biosphere integrity has breached safe planetary limits (6).

Biogeochemical cycles, especially those of carbon, nitrogen, and phosphorus, have also been fundamentally altered by human activity. Nutrient overload from excessive use of synthetic fertilizers leads to nitrogen and phosphorus accumulation in soil and water, which contributes to eutrophication, biodiversity loss, and compounding pressures on freshwater and marine ecosystems (6). These unsustainable agricultural practices have disrupted these cycles beyond safe PBs, stressing food security and ecosystem functionality (6).

Driven mainly by intensive changes in land use (e.g., urbanization, monoculture farming), land-based ecosystems are experiencing extensive degradation due to deforestation, desertification, erosion, soil degradation, and natural pasture loss (67, 68). These changes also lead to biodiversity loss, increased carbon emission, reduced carbon sequestration, habitat fragmentation, and loss of nature's contributions to people, such as the regulation of the hydrological cycle (52, 69). Simultaneously, vital resources such as freshwater and arable land become increasingly scarce, threatening global food production (69). This scarcity is driven primarily by unsustainable agricultural practices that consume approximately 70% of global freshwater and deplete water sources, especially in regions under water stress (54, 70, 71), and by erosion, desertification, climate change, poor resource governance, and urban expansion (54, 72).

Finally, the world's oceans are experiencing significant biophysical changes due to climate change and other human-caused disruptions. Rising sea surface temperatures, ocean acidification, and deoxygenation attributed to nutrient (e.g., phosphorus and nitrogen) overflow and global warming—alongside overfishing—are increasingly harmful to marine life and ecosystems (73, 74, 75). These processes threaten vulnerable species, like coral reefs and shellfish, and worsen the decline of marine habitats and biodiversity, which could cause the collapse of marine food webs and significantly alter species distribution (75).

### 3.1. Interactions Among Changes and Tipping Elements

Earth system changes do not happen independently; they interact in complex, sometimes unpredictable ways and can lead to synergistic amplifying effects over Earth's natural systems and, subsequently, human well-being. The interconnectedness of Earth's natural systems means that disruptions in one can trigger cascading effects on others, posing catastrophic scenarios that risk human well-being (78).

Large-scale changes can also induce self-reinforcing feedback loops, as captured by the concept of climate tipping points that, once surpassed, are irreversible and can trigger domino effects across the global climate system (12). Examples for such dynamics are the vicious cycles of deforestation, global warming, and forest fires as well as the cycle between permafrost melting and carbon release from melting soils or rapidly melting ice sheets that allow for the intrusion of relatively warmer water, which in turn is speeding up the melting of those ice sheets (79).

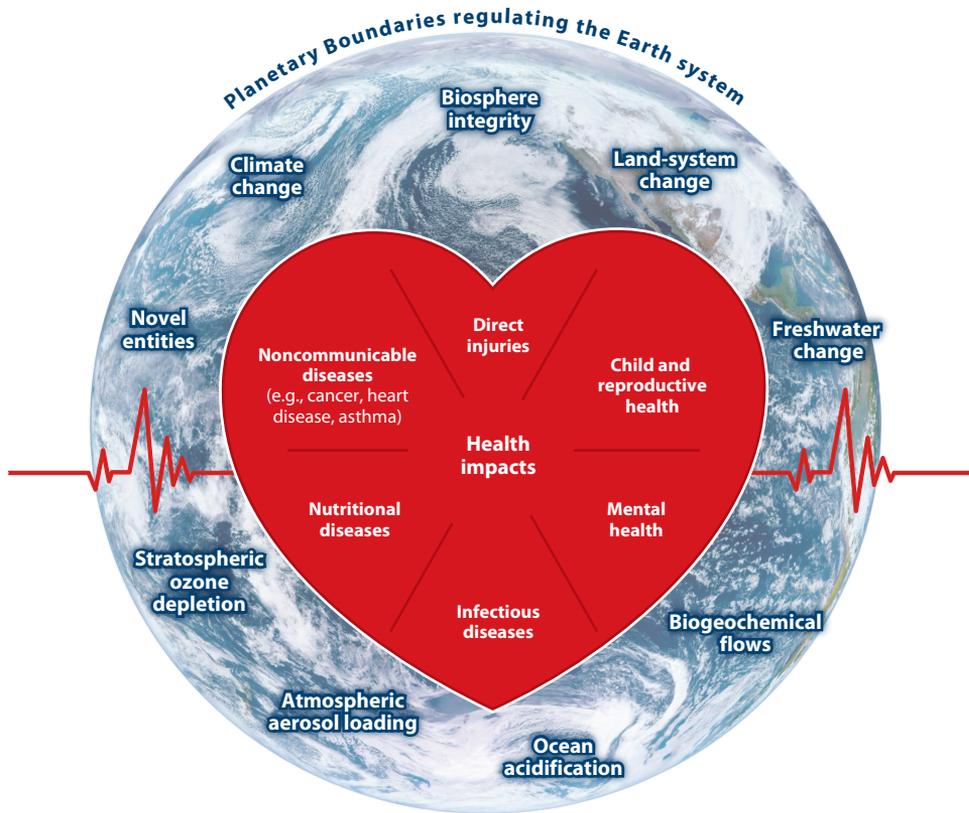
Important tipping elements also include alterations of atmospheric circulations such as the Sahel/West African monsoon, tropical coral reef die-off, Amazon rainforest dieback, and collapse of the Atlantic Meridional Overturning Circulation (12). Irreversible tipping of some of these systems could occur at 1 to 2°C above preindustrial temperatures (12, 78). However, the nonlinear dynamics complicate predictability but signify that relatively small changes can trigger disproportionately large outcomes (80). Their irreversibility points to the need to mitigate potential changes from the outset rather than relying on any potential reversal in the future. Understanding and anticipating tipping elements and interactions between Earth system changes are essential for effective mitigation strategies and for addressing the cascading effects and health impacts that can arise from these dynamics (81).

## 4. DIRECT AND INDIRECT IMPACTS ON HUMAN HEALTH AND WELL-BEING

The core insight of Planetary Health is that the Earth crisis is fueling a global health crisis. In the health professions, there is growing recognition that we can no longer safeguard human health while the natural life-support systems that we all depend upon deteriorate under the weight of humanity's ecological footprint. Evidence abounds that each Earth system change tracked by the Planetary Boundaries framework has substantial implications for human health (81) (**Figure 2**; see the sidebar titled Human Health Implications of the Planetary Boundaries Framework). The health impacts are diverse and far-reaching and are likely to be responsible for most of the global burden of disease over the next century (82). They manifest in various health dimensions, such as food security, communicable diseases, and mental health. This section reviews the most critical impacts of large-scale global environmental changes on different dimensions of human health.

### 4.1. Nutrition

The deterioration of Earth's natural systems significantly threatens food security, affecting crop yields and nutritional quality. Warmer climates and altered rainfall patterns, especially in the



**Figure 2**

Human health and well-being are influenced by Planetary Boundaries and embedded within the state of the Earth system. Figure adapted with permission from <https://planetaryhealthalliance.org/planetary-health-schematic>, copyright 2025 Planetary Health Alliance. Earth image adapted from an Adobe Stock image by Gizem Geçim Kandal (<https://stock.adobe.com>; file number 489137253).

tropics, are projected to decrease yields of crops like maize and wheat by around 25% for each degree of temperature increase (83). Elevated CO<sub>2</sub> concentration also leads to decreased nutritional quality, including a 3–17% drop in the zinc, iron, and protein levels of staple foods such as wheat, rice, and legumes (83–85). This reduction in nutritional quality exacerbates nutrient deficiencies, particularly in regions with already high malnutrition rates (83–85). Nutrient overload in soils, paradoxically, also reduces agricultural productivity (86).

Extreme weather events, worsened by climate change, pose risks to agricultural productivity. Flooding and droughts disrupt crop yields, compromise food supply chains, and exacerbate the spread of crop diseases, disproportionately affecting low-income regions (83, 87). Warmer temperatures boost pest metabolic rates, increasing pest predation and thereby reducing crop yields even further (88). Pollinator declines also threaten yields of pollinator-dependent crops, reducing access to fruits, vegetables, and nuts, foods that could prevent around half a million deaths annually (89). The combined impacts of these disturbances lead to a cycle of decreased food supply and heightened malnutrition rates, which especially affect at-risk groups in areas already struggling with food insecurity (83).

## HUMAN HEALTH IMPLICATIONS OF THE PLANETARY BOUNDARIES FRAMEWORK

The PBs framework and its recent assessment are highly relevant to human health. On the one hand, the framework is tracking Earth system changes that all have significant adverse human health impacts in the short term, in many cases (e.g., aerosol loading and climate change) even well below the safe boundary thresholds (81). Since these health risks can emerge independently from large-scale Earth system destabilization, respecting the PBs is not sufficient to safeguard human health, contrary to a common misconception. Indeed, even more ambitious action is required to comprehensively protect human health from the risks of Earth system change (81).

On the other hand, transgression of PBs, crossing of tipping points and loss of Earth system resilience lead to further acceleration of these changes, which dramatically exacerbates their health risks in the long term (81). Furthermore, large-scale disruptions and irreversible shifts in the Earth's biosphere and climate system can fundamentally destabilize aspects of human societies, including food, health, and economic systems, and deepen social inequalities, increasing vulnerability. In addition, as societal coping capacities are diminished, adaptation options become more limited and likely less effective. Coming back to, and staying within, the safe operating space defined by the PBs is urgently necessary to sustain healthy societies for future generations and to expand the number of viable and desirable future trajectories. As evidence is mounting that Earth system change is already severely compromising human health, it is becoming increasingly clear that a stable Earth system with resilient ecosystems is a fundamental prerequisite for human health in both the short and long term (81).

### 4.2. Infectious Diseases

The connections among climate change, biodiversity loss, and rising infectious diseases, especially vector-borne illnesses, are increasingly clear (90). Rising temperatures and altered rainfall patterns can shift the geographical range and seasonal activity of vectors such as mosquitoes, ticks, and flies, increasing the spread of diseases like dengue fever, leishmaniasis, Lyme disease, West Nile virus, and potentially malaria (91–94). For instance, deforestation can increase malaria by altering, among other things, the available breeding habitat of *Anopheles* mosquitoes; however, a high malaria burden can also reduce deforestation (95). Additionally, the number of months suitable for malaria transmission is increasing, particularly in areas at heightened risk, such as the African and Central American highlands (91).

Similarly, dengue and other arboviruses have spread beyond the tropics as a result of rising temperatures and prolonged rainy seasons. Endemic in more than 100 countries, dengue now exceeds 400 million cases yearly (96), linked to the proliferation of *Aedes aegypti* mosquitoes that flourish in humid and warm conditions. Deforestation and urbanization contribute to the spread of Zika virus and yellow fever, as humans encounter wildlife and zoonotic pathogens more frequently (92, 97). Similarly, in areas like the Amazon, deforestation, loss of habitats, and wildlife displacement are driving the emergence of novel zoonotic diseases and pathogen spillover (92, 98).

Climate change, deforestation, and pollution also elevate the risk of bacterial infections. Rising temperatures, for example, significantly expand habitats for pathogens like non-cholerae *Vibrio* species, increasing infection rates in new areas (91). Pollution and extreme weather events leading to floods also contribute to the spread of other waterborne bacteria, such as *Vibrio cholerae* and *Leptospira* (99).

### 4.3. Noncommunicable Diseases

Noncommunicable diseases (NCDs) are now the leading global cause of morbidity and mortality; environmental pollutants significantly contribute to their rise. Pollution is responsible for 16%

of global deaths, 70% of which are linked to NCDs (32). In LMICs, an estimated 25% of total deaths are linked to pollution (32) due to inadequate enforcement of environmental standards and weaker health care systems (32).

Exposure to environmental pollutants, such as airborne particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>) from industrial activity and transport-related emissions as well as heavy metals (e.g., cadmium, lead, chromium) in water and soil, increase the risk of cancer, cardiovascular diseases, and chronic respiratory diseases (100, 101). In areas with high vehicular density, pollutants like nitrogen oxides, carbon monoxide, and sulfur dioxide from burning fossil fuels increase the risks of these diseases (101). Prolonged pollutant inhalation, especially in urban and densely populated areas, is linked to decreased lung capacity, asthma, and chronic obstructive pulmonary disease.

Beyond pollution, other pathways of environmental change contribute to NCD risk. For example, climate change is increasing heat exposure, which leads to increased cardiovascular and respiratory mortality. From 2000 to 2019, for instance, an average of 489,000 deaths per year were related to heat (102), a number that also includes deaths from acute heat illness (see Section 4.5). Pollinator declines reduce access to healthy foods (e.g., fruits, vegetables, and nuts), leading to nearly half a million annual deaths from cardiovascular disease, stroke, and certain cancers (84, 89). Additionally, extreme weather events contribute to long-term health impacts; in the United States, an estimated three to five million deaths since 1915 are attributable to tropical cyclones, many of which manifest later in life as NCDs (103).

#### 4.4. Direct Injury and Displacement

The growing number and severity of natural disasters, exacerbated by climate change and land use changes, increase direct injuries and fatalities. Harmful extreme weather events such as heat waves, hurricanes, floods, droughts, and wildfires now occur more frequently. Heat exposure can lead to heat injury in terms of acute heat illness, including heat stroke, when the body's thermoregulatory capacity is exceeded. With a global temperature rise of 1°C, an estimated 565 million people are exposed to wet-bulb temperatures over 32°C for at least 1 day per year (7).

Cities experience worsened heat effects due to the urban heat island effect, especially in urban areas lacking adequate mitigation measures (102). Heat waves also strain health services, emergency responders, and the supply of essential services and threaten livelihoods and food security as farmers lose their crops or livestock because of excessive heat (16).

Beyond heat waves, other extreme weather events are escalating in intensity (30). Tropical storms and hurricanes displace dozens of millions of people yearly and directly cause thousands of deaths (16, 104, 105). Climate change and the repercussions of disasters intertwine with societal factors like violence and insecurity, creating greater vulnerability to displacement within and across borders (30). In 2023, natural disasters caused the internal displacement of 26 million people, and “environmental refugees” are on the rise (106). By 2050, more than a billion people could be displaced due to sea level rise, disruptions to monsoon systems, desertification, and droughts (107). The health risks faced by displaced populations are compounded by a lack of access to stable living conditions, adequate sanitation, health care, and essential resources such as clean water and food.

#### 4.5. Sexual and Reproductive Health

Global environmental changes significantly affect sexual and reproductive health, leading to adverse maternal, fetal, and newborn outcomes (108, 109). Exacerbated by climate change, food insecurity, air pollution, water shortages, and extreme heat can increase the risk of preterm birth and nutritional deficiencies, particularly among disadvantaged populations (109). Malnutrition, anemia, and preeclampsia are of particular concern in food-insecure regions (109) and are linked to

stunting, developmental delays, and higher infant mortality. Increased groundwater salinity from coastal intrusion and sea level rise raises the risk of preeclampsia/eclampsia in low-elevation coastal zones (110). Finally, extreme weather events like floods and heat waves disrupt the availability of sexual and reproductive health care, translating to a higher rate of perinatal complications (109).

#### **4.6. Mental Health**

Global environmental changes affect mental health in a variety of ways (58), for instance, by increasing anxiety, depression, and posttraumatic stress disorder (PTSD). Recent studies link particulate air pollution to higher postpartum depression rates, highlighting pervasive and widespread but subtle impacts on mental health (111). Eco-anxiety, especially in youth, is associated with poorer mental health outcomes (112). Climate change and extreme weather events disrupt social and economic systems, causing widespread psychological distress (113). Additionally, traumatic disasters like hurricanes, floods, prolonged droughts, severe heat waves, and wildfires increase rates of PTSD, depression, suicide, and anxiety (114). Compounded by displacement and conflict, mental health impacts disproportionately affect marginalized populations, older adults, and Indigenous Peoples (110).

### **5. INEQUITY IN ENVIRONMENTAL HEALTH IMPACTS**

Vulnerable populations, including low-income communities and marginalized racial and ethnic groups, experience the most significant health impacts from global environmental changes as a result of low adaptation capacity, political and societal exclusion, and limited access to health care, financial resources, and technologies (115). Intersectionality, a crucial concept for understanding compounded risk, highlights the increased vulnerabilities connected to interacting factors like race, ethnicity, income, gender, and age and critically examines their root causes (116).

In addition, vulnerable populations often suffer from greater exposure to environmental hazards, such as heightened pollution, or extreme events, such as floods, droughts, and heat waves, due to the geographical location of their homes (117). They often lack the means of mitigating these risks, such as access to adaptive infrastructure and technologies or, if required, the ability to relocate to safer areas (117). Vulnerable communities facing disasters also find it harder to recover and rebuild because of financial constraints and limited social support systems (118). Over time, these differences in exposure and recovery increase health inequities (117, 118).

Power dynamics shape both environmental degradation and inequitable health impacts (117). Globally, the wealthiest 5% consume more resources than the poorest half (91), and despite contributing to only a small fraction of environmental degradation, lower-income groups bear the disproportionate impact of environmental changes (59, 115). This disparity perpetuates the exploitative dynamics that exacerbate vulnerabilities. At the same time, high-income groups broaden disparities by shaping policies to their advantage while externalizing environmental costs with minimal accountability (115, 119).

Entrenched and inequitable power structures also obstruct meaningful global action on environmental justice, limiting marginalized communities' participation in policy spaces (117). Even well-intentioned initiatives, such as bioenergy and carbon capture, often add to the challenges faced by low-income communities, aggravating issues like food insecurity (117).

#### **5.1. Transforming Back to the Safe and Just Corridor Is Critical for Human Health**

As in Planetary Health, the profound role of justice has been increasingly recognized in Earth system science. In particular, the framework of “safe and just Earth system boundaries” (ESBs)

assesses five of the PBs for justice (120, 121). Advancing from the concept of a safe operating space, this framework defines a “safe and just corridor” (120, p. 104) for humanity on Earth. The ceiling of this corridor is the maximum allowed pressure on the Earth system, on the one hand, to maintain long-term Earth system resilience (the safe dimension, similar to the PBs) and, on the other hand, to avoid any significant harm to people (i.e., essentially widespread adverse human health impacts) at the same time (the just dimension). In some cases, a just operating space is stricter than a safe operating space, such as for climate change and atmospheric aerosol loading, as health risks can occur well before safe boundaries are transgressed (7) (see the sidebar titled Human Health Implications of the Planetary Boundaries Framework). The floor of the safe and just corridor is determined by the pressure on the Earth system that is (based on our current systems) required to provide minimum access to essential resources for all people in terms of, for example, food, water, and a sustainable energy supply, which are important prerequisites for human health (122). The normative foundation of the just dimension of the ESBs framework is the concept of Earth system justice (ESJ). The three pillars of ESJ are intragenerational justice (between communities and countries), intergenerational justice (between past, present, and future generations), and interspecies justice in a stable Earth system, all of which address topics important for Planetary Health, as described above (7). Transforming back to this safe and just corridor (i.e., safeguarding human health in the short and long term by meeting the minimum needs of all people while simultaneously reducing pressure on the Earth system) will require major transformations and a drastic reduction in inequalities (7).

## 6. SOLUTIONS FOR RAPID TRANSFORMATIONAL CHANGE

The health, humanitarian, and ecosystem impacts of the Earth crisis necessitate rapid, systemic changes to sustain and regenerate essential natural life support systems. A Planetary Health approach emphasizes solutions that prioritize cobenefits, avoid unintended consequences, identify root causes of vulnerability, and incorporate systemic approaches to reducing risk and uncertainty. Importantly, there is no one-size-fits-all solution; instead, diverse, context-specific approaches are required.

These transformations, often collectively referred to as the Great Transition (131), require technological and policy changes to food and energy systems, the built environment, and manufacturing. However, such advances are insufficient. In addition, a profound shift in systemic drivers of environmental degradation, sociopolitical structures, value, and economic systems in the pursuit of profit and short-term gains is necessary. The Great Transition centers on promoting global solidarity, well-being, social justice, intergenerational/interspecies justice, the redress of persistent inequities from colonial legacies, reconnection of humanity to nature, and a move away from unchecked consumerism and environmental exploitation. The Great Transition highlights that the environmental and health crises are intertwined and require systemic solutions that span beyond borders and sectors.

An essential call from the Planetary Health community is for stronger collaboration to broaden the constituency for change, as emphasized by the São Paulo Declaration and the Planetary Health Roadmap and Action Plan (132) (see the sidebar titled The Planetary Health Roadmap and Action Plan). In this spirit, recent collaboration between the Earth system science and Planetary Health communities must be deepened and sustained by continuous support and cultivation (81). Integrating health into Earth system science, complementing boundary evaluations with human health risk assessments, and building on Earth system concepts such as the PBs and ESBs within Planetary Health could help enhance transdisciplinary methodology, increase coherence, and synchronize the overarching narrative (O. Masztalerz, P. Harich, H. Kleineberg-Massuthe, N.J. Lambrecht,

## THE PLANETARY HEALTH ROADMAP AND ACTION PLAN

The Planetary Health Roadmap and Action Plan, endorsed at the 2024 Planetary Health Annual Meeting in Kuala Lumpur, Malaysia, provides a strategic framework for rapid transformation to protect the health of the planet and achieve the Great Transition. The Roadmap recognizes that the degradation of Earth's natural systems and the decline in global health are intertwined and emphasizes that achieving this transformation requires rethinking governance, education, business, and communication practices so that future development aligns with Planetary Health goals.

Central to the Roadmap is a call for governance reform, which urges policy makers to abandon outdated, growth-focused models that threaten environmental sustainability (133) and to adopt frameworks emphasizing cross-sector collaboration as well as ecological and social stability (134). To support governance reform, research in Earth systems governance must develop adaptive structures that prioritize equity and resilience while addressing the synergistic impacts of environmental degradation on marginalized communities (10).

The call to transform education, another pillar of the Roadmap, advocates for integrating Planetary Health into curricula at all educational levels. This transformation aims to equip future leaders with the transdisciplinary knowledge needed to address complex environmental and health challenges, fostering behavior change and new generations that value sustainability and resilience (135).

The private sector is urged to align with Planetary Health principles and transition to circular economy models that prioritize resource efficiency, ethical sourcing, and long-term sustainability over short-term profits (136). Collaborative research and sustainable business models can translate to technologies that align with ecological and social boundaries, which are essential for creating a regenerative and distributive economy. By partnering with academic institutions, businesses can fund and advance research that identifies scalable ways to reduce environmental footprints while promoting social equity.

Finally, effective communication and advocacy are essential to bridge the gap between scientific research and public engagement (132). Narratives that resonate with diverse audiences—policy makers, business leaders, and citizens—are crucial (137).

L.M. Pörtner, et al., “Exploring Earth system concepts from a Planetary Health perspective,” manuscript in preparation). Stronger collaboration will also help inform a Planetary Health in all policies approach, which could help identify win-win solutions (and avoid lose-lose options) for human health and stabilize the Earth system by identifying and overcoming trade-offs and implementation barriers and preventing maladaptation (81).

Such an integrated approach also helps broaden the constituency for transformational change of societies so as to ultimately overcome the intertwined environmental, health, and equity crises of the Anthropocene (81). This cross-sectoral cooperation will require permanent platforms for transdisciplinary exchange and as well as more ambitious interdisciplinary funding of science and project implementation. Planetary Health solutions, described individually in the following subsections, should be understood and applied through this integrated, holistic lens.

### 6.1. Reimagining Energy Systems

Decarbonizing the global energy system is essential to address climate change and reduce air pollution. Renewable energy technologies, including wind, solar, hydro, and geothermal, are displacing fossil fuel-based energy and are now economically viable. Estimates indicate that solar power could increase by 8- to 28-fold and wind power by 3- to 12-fold by 2050, which would drastically reduce emissions (138). Breakthroughs in energy storage, such as in batteries, are enhancing the reliability and resilience of renewables, supporting year-round power-grid stability

## CRITICALLY DISCUSSING INNOVATIONS IN CARBON TECHNOLOGY AND INDUSTRY

As the global economy shifts toward sustainability, clean technologies and materials, carbon utilization and removal technologies, and sustainable industrial practices are essential for addressing climate change and resource efficiency. For example, more efficient solar and wind energy technologies, improved battery storage, and alternatives to materials like cement are crucial in keeping our planet within safe boundaries (30).

However, these advances need to be discussed critically. Carbon capture, for example, is promoted as essential for reducing carbon emissions, and technologies like direct air capture (DAC) can remove up to 5 Gt of CO<sub>2</sub> annually by 2050 if scaled effectively (171). However, scalability is still in question, and DAC is frequently used as a justification to sustain fossil fuel dependency, rather than drive the transformational change needed for sustainability (171).

Waste-to-energy technologies in, for example, agricultural or sewage systems reduce waste while enhancing sustainability through energy production and carbon efficiency (171, 172). However, similarly to DAC, ensuring that these solutions support genuine reductions in fossil fuel dependency, rather than extending it, is crucial for achieving climate goals.

Geoengineering, such as solar radiation management, has also been proposed as a possible intervention, although its potential consequences remain controversial (7). Implementing cleaner and more efficient production methods can also improve resource efficiency and reduce emissions; for example, incorporating Industry 4.0 principles can increase industrial productivity by up to 30% while reducing energy and resource consumption (27).

(139, 140). However, alternative energies require sustainable management to prevent new ecological burdens from extraction of raw materials and waste from component manufacturing (141). Decentralized systems, like microgrids, ensure access to energy for distant and marginalized communities, increasing resilience against severe weather conditions exacerbated by climate change (139).

Governmental policies, such as stopping subsidies and introducing carbon pricing initiatives, are critical for the adoption of renewable energy technologies and for the phasing out of fossil fuels. Adequate policy implementation could lead to a 57% decrease in energy-related CO<sub>2</sub> emissions by 2050 while reducing pollution-related deaths (63) (see the sidebar titled *Critically Discussing Innovations in Carbon Technology and Industry*).

### 6.2. Transforming Food Systems

Transforming food systems is crucial for mitigating biodiversity loss, land use change, water scarcity, and climate change; food systems are responsible for roughly one-quarter of all greenhouse gases. Transforming the global food system not only is feasible but also offers economic benefits worth at least US\$5 trillion per year by 2050, which is much more than such a transformation would cost (US\$200–500 billion per year by 2050) (142). Sustainable intensification practices, such as precision agriculture, agroecology, regenerative agriculture, and integrated pest management, reduce chemical fertilizer and pesticide use, promote biodiversity, conserve water, reduce nitrogen and phosphorus pollution, decrease greenhouse gases, prevent land degradation, and improve soil health, all while mitigating global environmental impacts and maintaining ecosystem resilience and food security (10, 87, 143–145). Restoring traditional local food systems, based on local and Indigenous agroecological knowledge, cultural preservation, and collective agency, could also have substantial benefits (146).

Dietary shifts, through reforms that enable people to make choices that support cobenefits, are equally critical. Shifts include reducing consumption of highly resource-intensive foods that drive

deforestation, water scarcity, and greenhouse gas emissions, such as red meat from commercial livestock farming, and incorporating alternative protein sources (143, 147). Adopting alternative high-nutritional-value proteins, such as plant-based proteins, insects, and imitation meats, could reduce agricultural land use by up to 60%, as livestock requires land for both grazing and producing animal feed (147, 148). Shifting to mostly plant diets would also have significant direct health benefits that would make up the largest share of the avoided hidden costs when the global food system is sustainably transformed (142).

Decreasing food waste and food loss, which account for one-third of all food produced, is another vital priority to reduce the environmental impact of food systems while enhancing food security (143, 149). Improved technologies for supply-chain efficiency through improved storage and distribution, alongside policies promoting food recovery and redistribution, are steps toward combating this challenge (144).

### **6.3. Reinventing Transportation Systems and Built Environments**

Transport currently accounts for nearly 25% of global CO<sub>2</sub> emissions (150–152). Reducing emissions and pollutants and enhancing urban livability require the expansion of sustainable transportation policies that enhance efficient public transit, adoption of electric vehicles (EVs), active transport strategies, and development of sustainable transportation infrastructure. These transformations could reduce urban air pollution and carbon emissions significantly by lowering the number and density of individual vehicles and encouraging a shift away from combustion engines toward EVs (153). At the same time, active mobility has a wide range of direct health benefits, including prevention of chronic disease (15). Although adopting EVs is crucial for reducing transport-related emissions, it also requires coordination across the energy, infrastructure, and transport sectors (150). Nonetheless, solely replacing combustion engines with EVs can lead to unintended environmental consequences, like increased mining and eventual battery waste. A Planetary Health–informed approach prioritizes reducing overall vehicle dependency, promoting public transit, and enhancing sustainable urban design (150–152).

The use of green urban planning strategies, which integrate green spaces, energy-efficient infrastructure, and compact mixed-use developments, in addition to construction methods that incorporate sustainable materials and energy-efficient designs can significantly lessen environmental impacts. For example, green spaces and the shade they provide counter the urban heat island effect, improve air quality, and reduce flood risks through natural drainage (49). Green spaces also provide essential ecological functions for human well-being. Access to nature within cities has been linked to improved mental health, reduced stress, and enhanced physical activity (154).

Upgrading structures and retrofitting with energy-saving technologies further diminish energy consumption, emissions, and operational expenses (49). Sustainable urban design is crucial in helping cities withstand the effects of climate change, and a holistic approach to city planning is vital to mitigating environmental impacts while improving urban resilience and quality of life. Importantly, unintended adverse consequences of urban greening and transformations, such as green gentrification, need to be avoided to prevent maladaptation (155–157).

### **6.4. Transforming Economic Systems**

Transforming consumptogenic and growth-based economic systems is key for sustainability, justice, and well-being (46). The World Health Organization's Health for All report (158) and the United Nations' Pact for the Future (159) indicate a need to reorient economic systems toward human and planetary flourishing rather than the pursuit of economic growth at all costs. In

addition, the interdisciplinary Earth4All initiative proposes a range of measures to achieve major economic turnarounds (160). Critical changes will also require shifts in accounting, reassessment of the allocation of subsidies and taxes, alternative progress indicators, distributive justice, and new forms of risk and asset management (7).

Example of such an approach are well-being economies that prioritize health, social, and ecological well-being over increases in gross domestic product (161). Nations like New Zealand and Scotland have already incorporated well-being economies into planning (162). Frameworks like doughnut economics advocate that everyone can access basic needs while respecting ecological boundaries (161), while postgrowth and degrowth models, both connected to the principle of sufficiency (i.e., how much is “enough”), are increasingly discussed as promising concepts (163–165). Central to these approaches is the achievement of better social outcomes with lower biophysical resource use (166).

Adopting circular economic principles, such as resource/material efficiency, waste minimization, sustainable manufacturing, and product life-cycle management, is also critical (167, 168). The transition to a circular economy could produce economic benefits while reducing the environmental footprint (168). In parallel, holistic approaches to circularity call for circular societies, emphasizing the redistribution of wealth, knowledge, technology, and power (169).

Finally, sustainable finance channels investments that support environmental sustainability while deterring financing of harmful ecological practices (e.g., fossil fuel extraction). Sustainable financing requires new indicators of return on investment that measure real environmental costs of investments, including externalities, and can capture cobenefits. Green bonds play a role in funding initiatives geared toward environmental benefits such as renewable energy and sustainable agriculture. To meet the Paris Agreement targets, the world will need an estimated US\$53 trillion of financing (170). Environmental, social, and governance criteria are increasingly gaining traction among investors who are steering investments toward businesses that adhere to defined sustainability standards (170). Recent research in countries like China highlights the impact of sustainable financing supporting low-carbon economies and the decoupling of economic growth from intense resource use (170).

## 6.5. Social, Behavioral, Narrative, and Value Change

Achieving the transformative objectives of Planetary Health requires reimagining humanity’s relationship with Earth through a philosophical and cultural shift recognizing the intrinsic value of nature and acknowledging interdependence between all of the life forms and nonliving elements of our planet (see the sidebar titled *The Role of Arts, Humanities, and Faith Traditions*). Conventional anthropocentric perspectives, through consumerism and extractivism, foster an exploitative and top-down relationship with nature. Addressing ongoing polycrises demands reshaping narratives, emphasizing sustainability, environmental stewardship, and the interconnectedness of human and ecological health (124, 131, 174) (see the sidebar titled *Ecological Civilization and Implementation in China*).

Conceptually reframing health and how it is measured is vital to recognizing interdependencies between human well-being and the health of the planet (175, 176). Educational institutions at all levels, the media, and civil society are crucial in promoting these perspectives. Education for sustainable development and public awareness campaigns empower communities toward collective action fostering sustainability, lifelong learning, and enabling individuals to address environmental crises (177). Planetary Health education connects environmental and social challenges, preparing future leaders for transdisciplinary actions to protect the environment while promoting global health (178).

## THE ROLE OF ARTS, HUMANITIES, AND FAITH TRADITIONS

The arts, humanities, and faith traditions can uniquely contribute to transformative change by providing platforms for storytelling, cultural expression, and ethical reflection. Visual art, literature, poetry, and cinema can communicate ecological concepts in easy-to-understand and emotionally impactful ways. Arts and the humanities enable individuals to envision future possibilities and reshape their connection with nature; they promote critical thinking and ethical inquiry into dominant anthropocentric worldviews, motivating collective efforts toward sustainability (124, 131). History, philosophy, and literature uncover the origins of today's challenges, including attitudes toward nature, while offering perspectives on cultural reform (131).

Faith traditions also play an essential role in this cultural shift, in that many align with Planetary Health values such as stewardship, humility, and care for creation. Religious leaders have the potential to mobilize their communities, offering ethical guidance on sustainable ways of living. Pope Francis's (173) *Laudato si'*, for example, addresses environmental stewardship and advocates for a new relationship with nature. Various religious beliefs highlight the sanctity of nature and the moral and ethical responsibility to safeguard it (174).

## ECOLOGICAL CIVILIZATION AND IMPLEMENTATION IN CHINA

China's Ecological Civilization framework integrates environmental sustainability into national policy, aligning with Planetary Health principles and the United Nations SDGs. Ecological Civilization draws from ecological sciences and environmental philosophy to advocate for a sustainable development model and for balance between human development and natural systems.

Key milestones include the adoption of the framework by the 2007 Party Congress and its inclusion in the 2018 Constitution. It is now a core component of the Chinese Dream, emphasizing harmony between humanity and nature. Below are the key initiatives and their impacts (192–195):

- Ecological redlines, which protect 25% of China's land, safeguarding biodiversity, water retention, and carbon sinks.
- The Great Green Wall, which counters the expansion of the Gobi Desert with forests that act as windbreaks across 4,500 km.
- The South-to-North Water Diversion Project, which transfers water to address water scarcity in northern China, supporting urban and agricultural needs.
- The Yangtze River and Tai Lake cleanup, which restores major rivers and lakes as well as their surrounding ecosystems, reduces industrial pollution, restores wetlands, and enhances wastewater treatment.
- The Blue Sky Defense Campaign, which reduces air pollution in major cities such as Beijing by restricting coal use and promoting clean energy. Air pollution management initiatives aim to reduce emissions with higher toxicities.

Despite these advances, challenges persist, including transitioning to clean energy in a coal-rich and coal-dependent country as well as enforcing environmental regulations amid economic pressures (196).

While Ecological Civilization does not explicitly reference the PBs or ESBs, its systems-based policies, rooted in the philosophy that “green mountains and clear waters are equal to mountains of gold and silver,” support key PBs like climate change and biosphere integrity, thus offering a scalable model for Planetary Health to balance economic and ecological priorities.

Behavioral and corporate incentives play an essential role in promoting sustainable practices. Governments can introduce mechanisms like carbon pricing, and tax breaks or subsidies for win-win scenarios, to encourage individuals and corporations to adopt more sustainable behaviors and make environmentally sound decisions (179).

However, this transformation is about not only promoting “new” ideas but also learning from well-established knowledge systems that offer invaluable insights. For example, Indigenous Peoples and Indigenous knowledge systems often see humans as integrated into nature rather than separate from or above it, promoting ecocentric values that emphasize respect, reciprocity, long-term planning, and balance with the environment (124) (see the sidebar titled Reflections on Indigenous Planetary Health from an Indigenous Scholar).

### REFLECTIONS ON INDIGENOUS PLANETARY HEALTH FROM AN INDIGENOUS SCHOLAR (NICOLE REDVERS)

The understanding of PBs has been inherent within Indigenous communities for millennia. Indigenous communities have clear traditional protocols (i.e., guidelines) that govern how many animals or plants to take, how to keep the land and water clean, and how to prevent overconsumption within an environment of finite resources. The understanding of boundaries is not limited to the physical world or the physical limits that need to be in place to ensure a healthy environment but also encompasses the mental, emotional, and spiritual world (123). It is clearly understood that when a human overuses the environment past its limit, the cause is much deeper than physical actions and consequences. Instead, the cause may be a disconnection of the self from the community, a disconnection from Earth-centric value systems, and a lack of understanding of the relational connectivity of people to the land needed to keep the world in balance (e.g., Natural Law) (123, 124). Accordingly, the understanding that all life forms are completely dependent on the health of the planet is embedded within many Indigenous knowledge systems.

Although the English-language term Planetary Health, and its modern conceptualization within academic circles, has been around for only a decade, the concept underlying Planetary Health is not new. Indigenous Peoples have numerous language concepts and words with translations that ultimately embody the understanding of Mother Earth’s well-being. These understandings can apply to certain elements of ecosystems (e.g., the health of water), the planet itself, and even the cosmos. For example, *Nats’ejū Tu* means “water healing” in one dialect of the Dene language. Indigenous languages are often verb-based and not noun-based, so “health” as a transient state is not really conceptualized but instead regarded as the process of being in a state of “healing.” This concept applies to the innate understandings of Mother Earth’s health, which is viewed from a place of interdependence and interconnectedness to all other elements and beings on the planet.

As such, modern conceptualizations of Planetary Health are often disconnected from the many knowledge traditions that form the basis for ensuring that Mother Earth is always in a state of healing. Although Indigenous Peoples have always had clear understandings of Planetary Health through their own languages, only in 2018 and 2019 did Indigenous scholars start to leverage the use of the academically derived term Planetary Health (125–127). Alongside this increase in use of the term came an increased interest in having Indigenous participation within various international mechanisms, as well as an increasing interest in Indigenous knowledge systems in a time of global crises. Despite these seeming alignments in motives between the field of Planetary Health and Indigenous conceptualizations of Planetary Health, Indigenous Peoples have not been afraid to call out the gaps, inequities, and perceived colonial undertones of some elements of these movements (e.g., Planetary Health and One Health), which, as in most scientific circles, have historically tended to view Indigenous knowledges as low on the evidence hierarchy (128).

The devaluing of Indigenous knowledges (97) by non-Indigenous science has been layered on continued social, political, and economic discrimination (including violence) (129); Indigenous Peoples are often the most affected

(Continued)

*(Continued)*

by climate change despite contributing the least to its cause (130). Nevertheless, collaboration among Indigenous, local, and scientific knowledge systems is widely recognized as enhancing the effectiveness of climate action. Such collaboration is compatible with maintaining the autonomy and distinctiveness of each knowledge system, and the careful design of governance mechanisms can assure the autonomy of each system while promoting their joint efficacy (130).

Indigenous scholars, therefore, have increasingly recognized the usefulness of the Planetary Health field as a leverage point while also being strong in the need for the field to ground itself within the respect for multiple ways of knowing while centering justice and rights-based approaches for Indigenous Peoples. Recognizing the disproportionate burden on Indigenous populations from global environment change, while also appreciating that Indigenous Peoples are key environmental stewards and leaders within the area, is crucial for the Planetary Health agenda to be realized (124).

## **6.6. Governance Reform**

Advancing Planetary Health governance requires transformations in policy and institutions to address the environmental drivers of health impacts effectively and equitably. Planetary Health governance reforms should replace siloed approaches with cross-sectoral strategies that address complex challenges systematically and simultaneously at global, regional, and local levels. As principles of Planetary Health governance, accountability, transparency, equity, participation, the rule of law, and responsiveness offer a framework to strengthen a just and sustainable future.

Accountability ensures that decision-makers and institutions adhere to laws, policies, and commitments (e.g., SDGs, Paris Agreement) and answer to their constituents, building a culture of compliance and momentum for transformational change (46, 180). Transparency and subsequent trust in governance allow interested parties to make informed decisions; promote mutual compliance, equity, and fair participation; and reduce corruption and the undue influence of vested interests (181). Equity mandates that policies go beyond aggregate benefits to address specific impacts on vulnerable populations that are more likely to be excluded from governance processes, supporting inclusive outcomes (182).

Participation and inclusiveness allow for the incorporation of diverse perspectives, especially those of Indigenous Peoples, future generations, and marginalized groups, legitimizing decisions through representation and being vital for implementation (48). The rule of law facilitates compliance and cooperation and supports human rights, ensuring laws are applied equally to protect health and the environment (183). Responsiveness requires policies to adapt based on new scientific evidence, concerns of impacted communities, and the dynamic nature of environmental threats.

At the global level, frameworks like the SDGs and the United Nations Pact for the Future explicitly underscore governance as essential for sustainable development, focusing on accountability, inclusivity, transparency, and trust building in multilateral processes (184, 185). These strategies collectively support a holistic, coordinated approach to achieve Planetary Health goals across governance levels.

## **6.7. Strengthening Community Resilience and Local Collaboration**

Building community resilience and fostering collaboration are critical for adapting to global environmental change. A multipronged approach is required, including developing robust

infrastructure, community disaster preparedness plans, and community-based/informed adaptation strategies, all while avoiding maladaptation (186, 187). Examples like early warning systems and climate change–resilient infrastructure, such as climate-resilient housing and flood management systems, reduce casualties and decrease property and infrastructure loss while increasing long-term resilience (188).

Strengthening health systems, integrating environmental risks into public health, and enhancing the capacities of human resources for health are also vital in facing global environmental uncertainty and improving emergency response capabilities. Climate-resilient health services ensure service continuity amid climate-induced disruptions and can signify that communities remain resilient in the face of environmental threats (188, 189).

Supporting context-specific innovations driven by grassroots movements and participatory planning ensures that adaptation strategies are locally relevant and grounded in local realities. Engaging local communities in decision-making, bottom-up approaches, and improvement of local/global governance also empowers communities to take ownership of their sustainability efforts (1).

## 6.8. Achieving Earth System Justice and Social Equity

Achieving environmental justice and health/social equity requires addressing deep-rooted social and economic inequities that contribute to environmental health disparities while embracing intergenerational and interspecies justice (117). The recent concept of ESJ (see Section 5) unifies essential Planetary Health principles, framing justice as inherently connected to environmental sustainability and human health (7). Inclusive and nontokenistic decision-making processes are crucial to achieving ESJ and can help mitigate historical disparities, prioritizing voices of marginalized communities and their political representation as well as ensuring their participation in shaping policies that affect their lives now and into the future (190).

ESJ goes beyond addressing existing and historical disparities; it also includes preventing future injustices. Policies and solutions that favor powerful groups who have benefited disproportionately from environmental resources are prevented, while current and long-term health and social consequences for those who are least responsible for environmental degradation are decreased (117, 191). A central tenet is the just distribution of power and resources, fostering resilience and granting universal access to basic needs such as health care, education, and other social services (117, 191). Holding accountable those who have primarily caused and benefited from environmental harm is also critical.

## 7. CONCLUSION

How we currently live, produce, consume, and exploit nature destabilizes the Earth system, upon which our health fundamentally depends. Crossing critical environmental thresholds poses escalating and cascading threats to food security, human health, and global well-being. These crises demand immediate and cohesive action. To secure a livable and thriving future for humanity and all life on Earth, transformative and systemic change that aligns our ways of living within PBs—a Great Transition—is urgently needed.

Achieving this transition is as much a technical challenge as it is a profound moral and justice imperative. An ESJ approach should be at the core of this transformation, encompassing policy and action, and it must extend intergenerationally to ensure that future generations inherit a planet able to sustain healthy and dignified lives.

The scale of change required is monumental but achievable. To navigate this transition, cross-sectoral and transdisciplinary solutions must be cohesively implemented. Governance and

education reforms, technological advances, transformation of cities and food systems, and economic restructuring, all anchored in expanding knowledge systems and equity, are critical. We can only stabilize and regenerate our planet's life support systems by harmonizing our relationship with nature and prioritizing ecological and social well-being.

## DISCLOSURE STATEMENT

O.M. is a research analyst for the German Advisory Council on Global Change (WBGU), a scientific council advising the German federal government on global environmental change. In the past 3 years, he has received honoraria for lectures on Planetary Health from various German universities, the Hans Böckler Foundation, GesundheitsAkademie e. V., and the ERASMUS+ Programme, as well as for articles on the topic from the publishers Springer, ecomed Medizin, and Gentner.

## AUTHOR CONTRIBUTIONS

C.A.F.G. led the conceptualization, methodology, original draft writing, and project administration, with substantial contributions from S.S.M., N.R., and O.M. S.S.M., N.R., and O.M. also played key roles in reviewing and editing and contributed to resources, visualization, and validation. J.S.J., O.L.-H., J.M., and A.L.P. supported the review and editing and contributed key insights and resources. J.R. provided critical revisions, validation, and input aligning the review with global frameworks. All authors reviewed and approved the final manuscript.

## ACKNOWLEDGMENTS

The authors thank Wendel Mora Rivera for help with formatting the article and citations, Jessica Kronstadt for editorial comments prior to submission, and Jun Yang for help in shaping the sidebar titled Ecological Civilization and Implementation in China.

## LITERATURE CITED

1. Whitmee S, Haines A, Beyrer C, Boltz F, Capon AG, et al. 2015. Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on Planetary Health. *Lancet* 386(10007):1973–2028
2. Dattani S, Rodés-Guirao L, Ritchie H, Ortiz-Ospina E, Roser M. 2023. *Life expectancy*. Rep., Our World in Data. <https://ourworldindata.org/life-expectancy>
3. Piketty T. 2022. *A Brief History of Equality*. Cambridge University Press
4. United Nations. 2024. *The Sustainable Development Goals Report 2024*. DESA Publications. <https://desapublications.un.org/publications/sustainable-development-goals-report-2024>
5. Food and Agriculture Organization of the United Nations (FAO), International Fund for Agricultural Development (IFAD), United Nations Children's Fund (UNICEF), World Food Programme (WFP), World Health Organization (WHO). 2024. *The state of food security and nutrition in the world, 2024*. Rep., FAO, IFAD, UNICEF, WFP, WHO. <https://openknowledge.fao.org/handle/20.500.14283/cd1254en>
6. Richardson K, Steffen W, Lucht W, Bendtsen J, Cornell SE, et al. 2023. Earth beyond six of nine planetary boundaries. *Sci. Adv.* 9(37):eadh2458
7. Gupta J, Bai X, Liverman DM, Rockström J, Qin D, et al. 2024. A just world on a safe planet: a *Lancet Planetary Health*–Earth Commission report on Earth-system boundaries, translations, and transformations. *Lancet Planet. Health* 8(10):E813–73
8. Haines A, Frumkin H. 2021. *Planetary Health: Safeguarding Human Health and the Environment in the Anthropocene*. Cambridge University Press
9. Redvers N. 2021. The determinants of Planetary Health. *Lancet Planet. Health* 5(3):e111–12

10. Myers SS. 2017. Planetary Health: protecting human health on a rapidly changing planet. *Lancet* 390(10114):2860–68
11. de Castañeda RR, Villers J, Faerron Guzmán CA, Eslanloo T, de Paula N, et al. 2023. One Health and Planetary Health research: leveraging differences to grow together. *Lancet Planet. Health* 7(2):e109–11
12. Armstrong McKay DI, Staal A, Abrams JF, Winkelmann R, Sakschewski B, et al. 2022. Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* 377(6611):eabn7950
13. Caesar L, Sakschewski B, Andersen LS, Beringer T, Braun J, et al. 2024. *Planetary Health Check 2024: a scientific assessment of the state of the planet*. Rep., Policy Commons. [https://policycommons.net/artifacts/16632857/planetaryhealthcheck2024\\_report/17517710](https://policycommons.net/artifacts/16632857/planetaryhealthcheck2024_report/17517710)
14. Harrison S, Kivuti-Bitok L, Macmillan A, Priest P. 2019. EcoHealth and One Health: a theory-focused review in response to calls for convergence. *Environ. Int.* 132:105058
15. German Advisory Council on Global Change (WBGU). 2023. *Healthy living on a healthy planet*. Flagship Rep., WBGU. <https://www.wbgu.de/en/publications/publication/healthyliving>
16. Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, et al., eds. 2023. *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press
17. Stockholm Resilience Centre. 2016. *The SDGs wedding cake*. Res. Rep., Stockholm Resilience Centre. <https://www.stockholmresilience.org/research/research-news/2016-06-14-the-sdgs-wedding-cake.html>
18. Dong K, Hochman G, Zhang Y, Sun R, Li H, Liao H. 2018. CO<sub>2</sub> emissions, economic and population growth, and renewable energy: empirical evidence across regions. *Energy Econ.* 75:180–92
19. Sadigov R. 2022. Rapid growth of the world population and its socioeconomic results. *Sci. World J.* 2022(1):8110229
20. DeFries RS, Rudel T, Uriarte M, Hansen M. 2010. Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nat. Geosci.* 3(3):178–81
21. Hickel J. 2021. *Less Is More*. Penguin
22. Oswald Y, Owen A, Steinberger JK. 2020. Large inequality in international and intranational energy footprints between income groups and across consumption categories. *Nat. Energy* 5(3):231–39
23. Gupta J, Scholtens J, Perch L, Dankelman I, Seager J, et al. 2020. Re-imagining the driver–pressure–state–impact–response framework from an equity and inclusive development perspective. *Sustain. Sci.* 15(2):503–20
24. Svampa M. 2019. *Las fronteras del neoextractivismo en América Latina: Conflictos socioambientales, giro ecoterritorial y nuevas dependencias*. Bielefeld University Press
25. Ranjith PG, Zhao J, Ju M, De Silva RVS, Rathnaweera TD, Bandara AKMS. 2017. Opportunities and challenges in deep mining: a brief review. *Engineering* 3(4):546–51
26. Venables AJ. 2016. Using natural resources for development: Why has it proven so difficult? *J. Econ. Perspect.* 30(1):161–84
27. Zhou K, Liu T, Zhou L. 2015. Industry 4.0: towards future industrial opportunities and challenges. In *2015 12th International Conference on Fuzzy Systems and Knowledge Discovery (FSKD)*. IEEE
28. Allcott H, Greenstone M. 2012. Is there an energy efficiency gap? *J. Econ. Perspect.* 26(1):3–28
29. Sorrell S, Dimitropoulos J. 2008. The rebound effect: microeconomic definitions, limitations and extensions. *Ecol. Econ.* 65(3):636–49
30. Core Writ. Team, Lee H, Romero J, eds. 2023. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press
31. Fuller R, Landrigan PJ, Balakrishnan K, Bathan G, Bose-O'Reilly S, et al. 2022. Pollution and health: a progress update. *Lancet Planet. Health* 6(6):e535–47
32. Landrigan PJ, Fuller R, Acosta NJR, Adeyi O, Arnold R, et al. 2018. The *Lancet* Commission on Pollution and Health. *Lancet* 391(10119):462–512
33. Ibrahim AA, Ibrahim MA, Yusuf AG. 2021. Implications of industrial effluents on surface water and ground water. *World J. Adv. Res. Rev.* 9(3):330–36
34. Ghebreyesus TA. 2023. Achieving health for all requires action on the economic and commercial determinants of health. *Lancet* 401(10383):1137–39

35. Veltmeyer H. 2013. The political economy of natural resource extraction: a new model or extractive imperialism? *Can. J. Dev. Stud./Rev. Can. Études Dév.* 34(1):79–95
36. Chagnon CW, Durante F, Gills BK, Hagolani-Albov SE, Hokkanen S, et al. 2022. From extractivism to global extractivism: the evolution of an organizing concept. *J. Peasant Stud.* 49(4):760–92
37. Sultana F. 2023. Whose growth in whose planetary boundaries? Decolonising planetary justice in the Anthropocene. *Geo* 10(2):e00128
38. Munyati C. 2024. Africa and the Gulf states: a new economic partnership. *World Economic Forum*, April 28. <https://www.weforum.org/stories/2024/04/africa-gcc-gulf-economy-partnership-emerging>
39. Carmody PR. 2016. *The New Scramble for Africa*. Wiley. 2nd ed.
40. Armitage D, de Loë R, Plummer R. 2012. Environmental governance and its implications for conservation practice. *Conserv. Lett.* 5(4):245–55
41. Bragdon S. 2020. Global legal constraints: how the international system fails small-scale farmers and agricultural biodiversity, harming human and planetary health, and what to do about it. *Am. Univ. Int. Law Rev.* 36(1):1
42. Friel S, Arthur M, Frank N. 2022. Power and the planetary health equity crisis. *Lancet* 400(10358):1085–87
43. Krieger N. 2020. Climate crisis, health equity, and democratic governance: the need to act together. *J. Public Health Policy* 41(1):4–10
44. Phipps D. 2022. *Switching from stakeholder*. Res. Rep., Research Impact Canada. <https://researchimpact.ca/featured/switching-from-stakeholder>
45. Kramer RC. 2013. Carbon in the atmosphere and power in America: climate change as state-corporate crime. *J. Crime Justice* 36(2):153–70
46. Clark H. 2015. Governance for planetary health and sustainable development. *Lancet* 386(10007):e39–41
47. Kashwan P, Biermann F, Gupta A, Okereke C. 2020. Planetary justice: prioritizing the poor in Earth system governance. *Earth Syst. Gov.* 6:100075
48. Zeinali Z, Bulc B, Lal A, van Daalen KR, Campbell-Lendrum D, et al. 2020. A roadmap for intergenerational leadership in Planetary Health. *Lancet Planet. Health* 4(8):e306–8
49. UN Habitat. 2022. *World cities report 2022: envisioning the future of cities*. Rep., United Nations. [https://unhabitat.org/sites/default/files/2022/06/wcr\\_2022.pdf](https://unhabitat.org/sites/default/files/2022/06/wcr_2022.pdf)
50. Liu Z, He C, Wu J. 2016. The relationship between habitat loss and fragmentation during urbanization: an empirical evaluation from 16 world cities. *PLOS ONE* 11(4):e0154613
51. He C, Liu Z, Tian J, Ma Q. 2014. Urban expansion dynamics and natural habitat loss in China: a multiscale landscape perspective. *Glob. Change Biol.* 20(9):2886–902
52. Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner H-O, et al., eds. 2019. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Cambridge University Press
53. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). 2019. *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Rep., IPBES. <https://zenodo.org/records/6417333>
54. Food and Agriculture Organization of the United Nations (FAO). 2021. *The state of the world's land and water resources for food and agriculture—systems at breaking points*. Rep., FAO. <https://openknowledge.fao.org/server/api/core/bitstreams/bc8810ae-2a13-4cfe-b019-339158c7e608/content/cb7654en.html>
55. Hilborn R, Banobi J, Hall SJ, Pucylowski T, Walsworth TE. 2018. The environmental cost of animal source foods. *Front. Ecol. Environ.* 16(6):329–35
56. Pendrill F, Gardner TA, Meyfroidt P, Persson UM, Adams J, et al. 2022. Disentangling the numbers behind agriculture-driven tropical deforestation. *Science* 377(6611):eabm9267
57. National Ocean and Atmospheric Administration. 2023. *2023 global climate report*. Rep., National Centers for Environmental Information
58. Romanello M, di Napoli C, Green C, Kennard H, Lampard P, et al. 2023. The 2023 report of the *Lancet* Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. *Lancet* 402(10419):2346–94

59. United Nations Environment Programme (UNEP). 2024. *Emissions gap report 2024*. Rep., UNEP. <https://www.unep.org/resources/emissions-gap-report-2024>
60. Lenton TM, Xu C, Abrams JF, Ghadiali A, Loriani S, et al. 2023. Quantifying the human cost of global warming. *Nat. Sustain.* 6(10):1237–47
61. United Nations Environment Programme (UNEP). *Emissions gap report 2022*. Rep., UNEP. <https://www.unep.org/resources/emissions-gap-report-2022>
62. World Health Organization (WHO). 2021. *WHO global air quality guidelines: particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. Rep., WHO. <https://apps.who.int/iris/handle/10665/345329>
63. Lelieveld J, Haines A, Burnett R, Tonne C, Klingmüller K, et al. 2023. Air pollution deaths attributable to fossil fuels: observational and modelling study. *BMJ* 383:e077784
64. United Nations Convention on Biological Diversity (CBD). 2021. *Post-2020 Global Biodiversity Framework*. Rep., United Nations Environment Programme. <https://www.unep.org/resources/publication/1st-draft-post-2020-global-biodiversity-framework>
65. World Wide Fund for Nature. 2022. *Living Planet Report 2022: building a nature-positive society*. Rep., World Wide Fund for Nature. [https://wwfint.awsassets.panda.org/downloads/embargo\\_13\\_10\\_2022\\_lpr\\_2022\\_full\\_report\\_single\\_page\\_1.pdf](https://wwfint.awsassets.panda.org/downloads/embargo_13_10_2022_lpr_2022_full_report_single_page_1.pdf)
66. Food and Agriculture Organization of the United Nations (FAO). 2016. *The state of world fisheries and aquaculture 2016 (SOFLA)*. Rep., FAO. <https://www.fao.org/family-farming/detail/en/c/465805>
67. Food and Agriculture Organization of the United Nations (FAO). 2020. *Global forest resources assessment 2020*. Rep., FAO. <http://www.fao.org/documents/card/en/c/ca8753en>
68. United Nations Convention to Combat Desertification (UNCCD). 2024. *The land story: country experiences with reporting on land degradation and drought*. Rep., UNCCD. <https://www.unccd.int/resources/publications/land-story-country-experiences-reporting-land-degradation-and-drought>
69. Global Commission on the Economics of Water (GCEW). 2024. *The economics of water: valuing the hydrological cycle as a global common good*. Rep., GCEW. <https://watercommission.org/publication/the-economics-of-water>
70. United Nations World Water Assessment Programme (WWAP). 2023. *UN World Water Development Report 2023*. Rep., WWAP. <https://www.unwater.org/publications/un-world-water-development-report-2023>
71. United Nations University Institute for Water Environment and Health (UNU INWEH). 2023. *Global water security 2023 assessment*. Rep., UNU INWEH. <https://www.unwater.org/news/unu-inweh-global-water-security-2023-assessment>
72. United Nations Convention to Combat Desertification (UNCCD). 2022. *Global Land Outlook 2*. Rep., UNCCD. <https://www.unccd.int/resources/global-land-outlook/glo2>
73. Intergovernmental Oceanographic Commission (IOC). 2020. *Global ocean science report 2020: charting capacity for ocean sustainability*. Rep., IOC. <https://unesdoc.unesco.org/ark:/48223/pf0000375147>
74. Kwiatkowski L, Torres O, Bopp L, Aumont O, Chamberlain M, et al. 2020. Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. *Biogeosciences* 17(13):3439–70
75. Breitburg D, Levin LA, Oschlies A, Grégoire M, Chavez FP, et al. 2018. Declining oxygen in the global ocean and coastal waters. *Science* 359(6371):eaam7240
76. Allen D, Allen S, Abbasi S, Baker A, Bergmann M, et al. 2022. Microplastics and nanoplastics in the marine–atmosphere environment. *Nat. Rev. Earth Environ.* 3(6):393–405
77. Springmann M, Clark M, Mason-D’Croz D, Wiebe K, Bodirsky BL, et al. 2018. Options for keeping the food system within environmental limits. *Nature* 562(7728):519–25
78. Lenton TM, Rockström J, Gaffney O, Rahmstorf S, Richardson K, et al. 2019. Climate tipping points—too risky to bet against. *Nature* 575(7784):592–95
79. Bradley AT, Hewitt IJ. 2024. Tipping point in ice-sheet grounding-zone melting due to ocean water intrusion. *Nat. Geosci.* 17(7):631–37
80. Anderies JM, Carpenter SR, Steffen W, Rockström J. 2013. The topology of non-linear global carbon dynamics: from tipping points to planetary boundaries. *Environ. Res. Lett.* 8:044048

81. Myers SS, Masztalerz O, Ahdoot S, Gabrysch S, Gupta J, et al. 2025. Connecting planetary boundaries and planetary health: a resilient and stable Earth system is crucial for human health. *Lancet* 406(10501):315–19. [https://doi.org/10.1016/S0140-6736\(25\)01256-5](https://doi.org/10.1016/S0140-6736(25)01256-5)
82. Myers S, Frumkin H. 2020. *Planetary Health: Protecting Nature to Protect Ourselves*. Island Press
83. Benton TG, Castro G, Fanzo J, Guinto RR, Hendriks S, et al. 2022. *Food security and health in a changing environment*. Rep., World Innovation Summit for Health. <https://wish.org.qa/research-report/food-security-and-health-in-a-changing-environment>
84. Myers SS, Zanutti A, Kloog I, Huybers P, Leakey ADB, et al. 2014. Increasing CO<sub>2</sub> threatens human nutrition. *Nature* 510(7503):139–42
85. Smith MR, Myers SS. 2018. Impact of anthropogenic CO<sub>2</sub> emissions on global human nutrition. *Nat. Clim. Change* 8(9):834–39
86. Majeed A, Muhammad Z. 2019. Salinity: a major agricultural problem—causes, impacts on crop productivity and management strategies. In *Plant Abiotic Stress Tolerance: Agronomic, Molecular and Biotechnological Approaches*, ed. M Hasanuzzaman, KR Hakeem, K Nahar, HF Alharby. Springer International Publishing
87. Li Y, He P, Shan Y, Li Y, Hang Y, et al. 2024. Reducing climate change impacts from the global food system through diet shifts. *Nat. Clim. Change* 14:943–53
88. Deutsch CA, Tewksbury JJ, Tigchelaar M, Battisti DS, Merrill SC, et al. 2018. Increase in crop losses to insect pests in a warming climate. *Science* 361(6405):916–19
89. Smith MR, Mueller ND, Springmann M, Sulser TB, Garibaldi LA, et al. 2022. Pollinator deficits, food consumption, and consequences for human health: a modeling study. *Environ. Health Perspect.* 130:127003
90. Mahon MB, Sack A, Aleuy OA, Barbera C, Brown E, et al. 2024. A meta-analysis on global change drivers and the risk of infectious disease. *Nature* 629(8013):830–36
91. Romanello M, McGushin A, Di Napoli C, Drummond P, Hughes N, et al. 2021. The 2021 report of the *Lancet* Countdown on health and climate change: code red for a healthy future. *Lancet* 398(10311):1619–62
92. Ellwanger JH, Kulmann-Leal B, Kaminski VL, Valverde-Villegas JM, Veiga ABGD, et al. 2020. Beyond diversity loss and climate change: impacts of Amazon deforestation on infectious diseases and public health. *An. Acad. Bras. Ciênc.* 92(1). <https://doi.org/10.1590/0001-37652020191375>
93. Ryan SJ, Lippi CA, Villena OC, Singh A, Murdock CC, Johnson LR. 2023. Mapping current and future thermal limits to suitability for malaria transmission by the invasive mosquito *Anopheles stephensi*. *Malar. J.* 22(1):104
94. Carlson CJ, Carleton TA, Odoulami RC, Molitor CD, Trisos CH. 2024. The historical fingerprint and future impact of climate change on childhood malaria in Africa. Preprint, medRxiv. <https://www.medrxiv.org/content/10.1101/2023.07.16.23292713v3>
95. MacDonald AJ, Mordecai EA. 2019. Amazon deforestation drives malaria transmission, and malaria burden reduces forest clearing. *PNAS* 116(44):22212–18
96. Parums DV. 2024. Climate change and the spread of vector-borne diseases, including dengue, malaria, Lyme disease, and West Nile virus infection. *Med. Sci. Monit.* 29:e943546
97. Keesing F, Belden LK, Daszak P, Dobson A, Harvell CD, et al. 2010. Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature* 468(7324):647–52
98. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). 2020. *Proceedings of the IPBES Workshop on Biodiversity and Pandemics*. IPBES. <https://www.ipbes.net/events/ipbes-workshop-biodiversity-and-pandemics>
99. Lau CL, Smythe LD, Craig SB, Weinstein P. 2010. Climate change, flooding, urbanisation and leptospirosis: fuelling the fire? *Trans. R. Soc. Trop. Med. Hyg.* 104(10):631–38
100. Swain CK. 2024. Environmental pollution indices: a review on concentration of heavy metals in air, water, and soil near industrialization and urbanisation. *Discov. Environ.* 2(1):5
101. Di Renzo L, Gualtieri P, Frank G, Cianci R, Caldarelli M, et al. 2024. Exploring the exposome spectrum: unveiling endogenous and exogenous factors in non-communicable chronic diseases. *Diseases* 12(8):176
102. Zhao Q, Guo Y, Ye T, Gasparrini A, Tong S, et al. 2021. Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *Lancet Planet. Health* 5(7):e415–25

103. Young R, Hsiang S. 2024. Mortality caused by tropical cyclones in the United States. *Nature* 635(8037):121–28
104. Stephens CQ, Newton C, Kappy B, Melhado CG, Fallat ME. 2024. Extreme weather injuries and fatalities, 2006 to 2021. *JAMA Netw. Open* 7(8):e2429826
105. Office of the United Nations High Commissioner for Refugees (UNHCR). 2024. *Climate action: focus area strategic plan for 2024–2030*. Rep., UNHCR. <https://reporting.unhcr.org/climate-action-focus-area-strategic-plan-2024-2030>
106. Internal Displacement Monitoring Centre (IDMC). 2024. *2024 global report on internal displacement (GRID)*. Rep., IDMC. <https://www.internal-displacement.org/global-report/grid2024>
107. Institute for Economics and Peace. 2024. *Ecological threat report*. Rep., Institute for Economics and Peace. <https://www.economicsandpeace.org/ecological-threat-report>
108. Women Deliver. 2021. *The link between climate change and sexual and reproductive health and rights: an evidence review*. Rep., Women Deliver. <https://womendeliver.org/wp-content/uploads/2021/02/Climate-Change-Report.pdf>
109. Sorensen C, Murray V, Lemery J, Balbus J. 2018. Climate change and women's health: impacts and policy directions. *PLOS Med.* 15(7):e1002603
110. Pinchoff J, Shamsudduha M, Hossain SMI, Shohag AAM, Warren CE. 2019. Spatio-temporal patterns of pre-eclampsia and eclampsia in relation to drinking water salinity at the district level in Bangladesh from 2016 to 2018. *Popul. Environ.* 41(2):235–51
111. Niedzwiecki MM, Rosa MJ, Solano-González M, Kloog I, Just AC, et al. 2020. Particulate air pollution exposure during pregnancy and postpartum depression symptoms in women in Mexico City. *Environ. Int.* 134:105325
112. Lawrance EL, Jennings N, Kioupi V, Thompson R, Diffey J, Vercammen A. 2022. Psychological responses, mental health, and sense of agency for the dual challenges of climate change and the COVID-19 pandemic in young people in the UK: an online survey study. *Lancet Planet. Health* 6(9):e726–38
113. Hayes K, Blashki G, Wiseman J, Burke S, Reifels L. 2018. Climate change and mental health: risks, impacts and priority actions. *Int. J. Ment. Health Syst.* 12:28
114. Whitmore-Williams SC, Manning M, Krygsman K, Speiser M. 2017. *Mental health and our changing climate: impacts, implications, and guidance*. Press Release, American Psychological Association/Climate for Health/ecoAmerica. <https://www.apa.org/news/press/releases/2017/03/mental-health-climate.pdf>
115. Hickel J, Slamersak A. 2022. Existing climate mitigation scenarios perpetuate colonial inequalities. *Lancet Planet. Health* 6(7):e628–31
116. Al-Faham H, Davis AM, Ernst R. 2019. Intersectionality: from theory to practice. *Annu. Rev. Law Soc. Sci.* 15:247–65
117. Faerron Guzmán CA, Zotova O. 2023. Acting on power and health inequities: an essential approach to global environmental challenges. *Int. Public Health J.* 15:371–90
118. Hagen I, Huggel C, Ramajo L, Chacón N, Ometto JP, et al. 2022. Climate change-related risks and adaptation potential in Central and South America during the 21st century. *Environ. Res. Lett.* 17:033002
119. Friel S, Collin J, Daube M, Depoux A, Freudenberg N, et al. 2023. Commercial determinants of health: future directions. *Lancet* 401(10383):1229–40
120. Rockström J, Gupta J, Qin D, Lade SJ, Abrams JF, et al. 2023. Safe and just Earth system boundaries. *Nature* 619(7968):102–11
121. Cuthbert MO, Gleeson T, Bierkens MFP, Ferguson G, Taylor RG. 2024. Concerns regarding proposed groundwater Earth system boundary. *Nature* 635(8039):E4–5
122. Rammelt CF, Gupta J, Liverman D, Scholtens J, Ciobanu D, et al. 2023. Impacts of meeting minimum access on critical earth systems amidst the Great Inequality. *Nat. Sustain.* 6(2):212–21
123. Redvers N, Poelina A, Schultz C, Kobei DM, Githaiga C, et al. 2020. Indigenous natural and first law in planetary health. *Challenges* 11(2):29
124. Redvers N, Celidwen Y, Schultz C, Horn O, Githaiga C, et al. 2022. The determinants of planetary health: an Indigenous consensus perspective. *Lancet Planet. Health* 6(2):e156–63
125. International Union for Health Promotion and Education (IUHPE). 2019. *Waiora: Indigenous Peoples' statement for Planetary Health and sustainable development*. Statement presented at 23rd

- IUHPE World Conference on Health Promotion. [https://www.healthpromotion.org.au/images/Indigenous\\_Statement\\_for\\_Plenary\\_Revised.pdf](https://www.healthpromotion.org.au/images/Indigenous_Statement_for_Plenary_Revised.pdf)
126. Ratima M, Martin D, Castleden H, Delormier T. 2019. Indigenous voices and knowledge systems—promoting planetary health, health equity, and sustainable development now and for future generations. *Glob. Health Promot.* 26(3):3–5
  127. Redvers N. 2018. The value of global Indigenous knowledge in Planetary Health. *Challenges* 9(2):30
  128. Redvers N, Lokugamage AU, Barreto JPL, Bajracharya MB, Harris M. 2024. Epistemicide, health systems, and Planetary Health: re-centering Indigenous knowledge systems. *PLOS Glob. Public Health* 4(8):e0003634
  129. Correa-Salazar C, Marín-Carvajal I, García MA. 2021. The role of violence in Planetary Health. *Lancet Planet. Health* 5(3):e113–14
  130. Orlove B, Dawson N, Sherpa P, Adelekan I, Alangui W, et al. 2022. *Intangible cultural heritage, diverse knowledge systems and climate change: contribution of Knowledge Systems Group I to the International Co-Sponsored Meeting on Culture, Heritage and Climate Change*. White Pap., ICOMOS and ICSM. <https://openarchive.icomos.org/id/eprint/2717>
  131. Raskin PD. 2006. *The Great Transition today: a report from the future*. Pap. 2, Great Transition Initiative. <https://greattransition.org/file/a-great-transition-today-a-report-from-the-future-2>
  132. Campbell E, Uppalapati SS, Kotcher J, Maibach E. 2023. Communication research to improve engagement with climate change and human health: a review. *Front. Public Health* 10:1086858
  133. Blühdorn I. 2016. Sustainability—post-sustainability—unsustainability. In *The Oxford Handbook of Environmental Political Theory*, ed. T Gabrielson, C Hall, JM Meyer, D Schlosberg. Oxford University Press
  134. United Nations Framework Convention on Climate Change (UNFCCC). 2022. *What is the triple planetary crisis?* Rep., UNFCCC. <https://unfccc.int/news/what-is-the-triple-planetary-crisis>
  135. Filho WL, Shiel C, do Paço A. 2015. Integrative approaches to environmental sustainability at universities: an overview of challenges and priorities. *J. Integr. Environ. Sci.* 12(1):1–14
  136. Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ. 2017. The circular economy—a new sustainability paradigm? *J. Clean. Prod.* 143:757–68
  137. Wellcome Trust. 2023. *COP 28 global review of research report*. Res. Rep., Wellcome Trust. <https://cms.wellcome.org/sites/default/files/2023-11/cop-28-global-review-of-research-report.pdf>
  138. Resources for the Future (RFF). 2021. *Global energy outlook 2021: pathways from Paris*. Rep., RFF. <https://www.rff.org/publications/reports/global-energy-outlook-2021-pathways-from-paris>
  139. International Renewable Energy Agency (IRENA). 2019. *Global energy transformation: a roadmap to 2050*. Rep., IRENA. <https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition>
  140. Hesse HC, Schimpe M, Kucevic D, Jossen A. 2017. Lithium-ion battery storage for the grid—a review of stationary battery storage system design tailored for applications in modern power grids. *Energies* 10(12):2107
  141. Hertwich E, Lifset R, Pauliuk S, Heeren N. 2020. *Resource efficiency and climate change: material efficiency strategies for a low-carbon future*. Rep., International Resource Panel. <https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change>
  142. Ruggeri Laderchi C, Lotze-Campen H, DeClerck F. 2024. *The economics of the food system transformation*. Glob. Policy Rep., Food System Economics Commission. <https://www.fao.org/family-farming/detail/en/c/1696203>
  143. Willett W, Rockström J, Loken B, Springmann M, Lang T, et al. 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* 393(10170):447–92
  144. Food and Agriculture Organization of the United Nations (FAO). 2019. *State of food and agriculture 2019: moving forward on food loss and waste reduction*. Rep., FAO. <https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1242090>
  145. Myers SS. 2020. Food and nutrition on a rapidly changing planet. In *Planetary Health: Protecting Nature to Protect Ourselves*, ed. S Myers, H Frumkin. Island Press
  146. Marrero A, Mattei J. 2022. Reclaiming traditional, plant-based, climate-resilient food systems in small islands. *Lancet Planet. Health* 6(2):e171–79

147. Alexander P, Brown C, Arneth A, Dias C, Finnigan J, et al. 2017. Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use? *Glob. Food Secur.*15:22–32
148. Smith MR, Stull VJ, Patz JA, Myers SS. 2021. Nutritional and environmental benefits of increasing insect consumption in Africa and Asia. *Environ. Res. Lett.* 16:065001
149. Myers SS, Pivor JJ, Saraiva AM. 2021. The São Paulo Declaration on Planetary Health. *Lancet* 398(10308):1299
150. World Bank. 2023. *Decarbonizing urban transport for development*. Rep., World Bank. <https://openknowledge.worldbank.org/handle/10986/40373>
151. Creutzig F, Roy J, Lamb WF, Azevedo IML, Bruine de Bruin W, et al. 2018. Towards demand-side solutions for mitigating climate change. *Nat. Clim. Change* 8(4):260–63
152. Ritchie H, Roser M. 2024. *Cars, planes, trains: Where do CO<sub>2</sub> emissions from transport come from?* Rep., Our World in Data. <https://ourworldindata.org/co2-emissions-from-transport>
153. Creutzig F, Agoston P, Minx JC, Canadell JG, Andrew RM, et al. 2016. Urban infrastructure choices structure climate solutions. *Nat. Clim. Change* 6(12):1054–56
154. Colding J, Barthel S. 2013. The potential of ‘urban green commons’ in the resilience building of cities. *Ecol. Econ.* 86:156–66
155. Cole HVS, Lamarca MG, Connolly JJT, Anguelovski I. 2017. Are green cities healthy and equitable? Unpacking the relationship between health, green space and gentrification. *J. Epidemiol. Community Health* 71(11):1118–21
156. García-Lamarca M, Anguelovski I, Venner K. 2022. Challenging the financial capture of urban greening. *Nat. Commun.* 13:7132
157. Anguelovski I, Corbera E. 2023. Integrating justice in nature-based solutions to avoid nature-enabled dispossession. *Ambio* 52(1):45–53
158. World Health Organization (WHO). 2023. *Health for all: transforming economies to deliver what matters*. Rep., WHO. <https://www.who.int/publications/i/item/9789240080973>
159. United Nations. 2024. *Pact for the future, global digital compact and declaration on future generations*. Summit of the Future Outcome Doc., United Nations. [https://www.un.org/sites/un2.un.org/files/sof-pact\\_for\\_the\\_future\\_adopted.pdf](https://www.un.org/sites/un2.un.org/files/sof-pact_for_the_future_adopted.pdf)
160. Dixon-Declève S, Gaffney O, Ghosh J. 2022. *Earth for All: A Survival Guide for Humanity*. Earth4All. <https://earth4all.life/the-book>
161. Raworth K. 2017. *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. Chelsea Green Publishing
162. Organisation for Economic Co-operation and Development (OECD). 2018. *Beyond GDP: measuring what counts for economic and social performance*. Rep., OECD. [https://www.oecd-ilibrary.org/economics/beyond-gdp\\_9789264307292-en](https://www.oecd-ilibrary.org/economics/beyond-gdp_9789264307292-en)
163. D’Alessandro S, Cieplinski A, Distefano T, Dittmer K. 2020. Feasible alternatives to green growth. *Nat. Sustain.* 3(4):329–35
164. O’Neill DW, Fanning AL, Lamb WF, Steinberger JK. 2018. A good life for all within planetary boundaries. *Nat. Sustain.* 1(2):88–95
165. Jungell-Michelsson J, Heikkurinen P. 2022. Sufficiency: a systematic literature review. *Ecol. Econ.* 195:107380
166. Vogel J, Steinberger JK, O’Neill DW, Lamb WF, Krishnakumar J. 2021. Socio-economic conditions for satisfying human needs at low energy use: an international analysis of social provisioning. *Glob. Environ. Change* 69:102287
167. Ghisellini P, Cialani C, Ulgiati S. 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* 114:11–32
168. Ellen MacArthur Foundation. 2019. *Completing the picture: how the circular economy tackles climate change*. Rep., Ellen MacArthur Foundation. <https://www.ellenmacarthurfoundation.org/completing-the-picture>
169. Calisto Friant M, Vermeulen WJV, Salomone R. 2020. A typology of circular economy discourses: navigating the diverse visions of a contested paradigm. *Resour. Conserv. Recycl.* 161:104917
170. Zhou X, Tang X, Zhang R. 2020. Impact of green finance on economic development and environmental quality: a study based on provincial panel data from China. *Environ. Sci. Pollut. Res.* 27(16):19915–32

171. Hepburn C, Adlen E, Beddington J, Carter EA, Fuss S, et al. 2019. The technological and economic prospects for CO<sub>2</sub> utilization and removal. *Nature* 575(7781):87–97
172. Rada E, Ragazzi M, Torretta V, Castagna G, Adami L, Cioca LI. 2018. Circular economy and waste to energy. *AIP Conf. Proc.* 1968:030050
173. Pope Francis. 2015. *Laudato si'*. Libreria Editrice Vaticana
174. Planetary Health Alliance. 2024. *São Paulo Declaration on Planetary Health*. Rep., Planetary Health Alliance. <https://planetaryhealthalliance.org/wp-content/uploads/2025/02/Sao-Paulo-Declaration-on-Planetary-Health-Updated.pdf>
175. Horton R, Lo S. 2015. Planetary Health: a new science for exceptional action. *Lancet* 386(10007):1921–22
176. Faerron Guzmán CA. 2022. Complexity in global health—bridging theory and practice. *Ann. Glob. Health* 88(1):49
177. United Nations Educational, Scientific and Cultural Organization (UNESCO). 2020. *Education for sustainable development: a roadmap*. Rep., UNESCO. <https://unesdoc.unesco.org/ark:/48223/pf0000374802>
178. Faerron Guzmán CA, Aguirre AA, Astle B, Barros E, Bayles B, et al. 2021. A framework to guide Planetary Health education. *Lancet Planet. Health* 5(5):e253–55
179. World Bank. 2022. *State and trends of carbon pricing 2022*. Rep., World Bank. <https://hdl.handle.net/10986/37455>
180. Swinburn B, Kraak V, Rutter H, Vandevijvere S, Lobstein T, et al. 2015. Strengthening of accountability systems to create healthy food environments and reduce global obesity. *Lancet* 385(9986):2534–45
181. García PJ. 2019. Corruption in global health: the open secret. *Lancet* 394(10214):2119–24
182. Prescott SL, Logan AC, Bristow J, Rozzi R, Moodie R, et al. 2022. Exiting the Anthropocene: achieving personal and planetary health in the 21st century. *Allergy* 77(12):3498–512
183. Phelan AL. 2020. The environment, a changing climate, and planetary health. In *Foundations of Global Health and Human Rights*, ed. LO Gostin, BM Meier. Oxford University Press
184. United Nations. 2024. *Summit of the future 2024*. Outcome Doc., United Nations. <https://www.un.org/en/summit-of-the-future>
185. United Nations Department of Economic and Social Affairs. 2015. *Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels*. Sustain. Dev. Goal 16, United Nations. [https://sdgs.un.org/goals/goal16#targets\\_and\\_indicators](https://sdgs.un.org/goals/goal16#targets_and_indicators)
186. Hallegatte S, Maruyama Rentschler J, Rozenberg J. 2020. *The adaptation principles: a guide for designing strategies for climate change adaptation and resilience*. Rep., World Bank. <https://documents.worldbank.org/en/publication/documents-reports/documentdetail/546611605298449211/The-Adaptation-Principles-A-Guide-for-Designing-Strategies-for-Climate-Change-Adaptation-and-Resilience>
187. Reckien D, Magnan AK, Singh C, Lukas-Sithole M, Orlove B, et al. 2023. Navigating the continuum between adaptation and maladaptation. *Nat. Clim. Change* 13(9):907–18
188. United Nations Office for Disaster Risk Reduction (UNDRR). 2022. *Global assessment report on disaster risk reduction (GAR). Our world at risk: transforming governance for a resilient future*. Rep., UNDRR. <https://www.undrr.org/gar/gar2022-our-world-risk-gar>
189. World Health Organization (WHO). 2021. *COP26 special report on climate change and health: the health argument for climate action*. Rep., WHO. <https://www.who.int/publications/i/item/9789240036727>
190. Schlosberg D, Collins LB. 2014. From environmental to climate justice: climate change and the discourse of environmental justice. *Wiley Interdiscip. Rev. Clim. Change* 5(3):359–74
191. Gupta J, Liverman D, Prodan K, Aldunce P, Bai X, et al. 2023. Earth system justice needed to identify and live within Earth system boundaries. *Nat. Sustain.* 6(6):630–38
192. State Council of the People's Republic of China. 2021. 让绿水青山造福人民泽被子孙—习近平总书记关于生态文明建 设重要论述综述\_滚动新闻\_中国政府网[Opinions on advancing Ecological Civilization in the new era]. News Release, State Council of the People's Republic of China. [https://www.gov.cn/xinwen/2021-06/03/content\\_5615092.htm](https://www.gov.cn/xinwen/2021-06/03/content_5615092.htm)

193. Ministry of Ecology and Environment of the People's Republic of China. 2017. *Report on China's environmental situation*. Rep., Ministry of Ecology and Environment of the People's Republic of China. <https://www.mee.gov.cn/gkml/hbb/bgt/201707/W020170728397753220005.pdf>
194. Ministry of Ecology and Environment of the People's Republic of China. 2021. *Environmental policy implementation and performance evaluation report*. Rep., Ministry of Ecology and Environment of the People's Republic of China. [https://www.mee.gov.cn/xxgk/xxgk03/202209/t20220919\\_994278.html](https://www.mee.gov.cn/xxgk/xxgk03/202209/t20220919_994278.html)
195. Peng DU, Tian-Tian LI, Xiao-Ming SHI. 2019. Establishment of surveillance, investigation and health risk assessment system with Chinese characteristics in the field of environmental health. *Chin. J. Dis. Control Prev.* 23(7):758–62
196. Goron C. 2018. Ecological civilisation and the political limits of a Chinese concept of sustainability. *China Perspect.* 2018(4):39–52