Climate change and global health: a call to more research and more action

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Angaben zur Veröffentlichung / Publication details:

Agache, Ioana, Vanitha Sampath, Juan Aguilera, Cezmi Akdis, Mubeccel Akdis, Michele Barry, Aude Bouagnon, et al. 2022. "Climate change and global health: a call to more research and more action." Allergy 77 (5): 1389–1407. https://doi.org/10.1111/all.15229.

Climate change and global health: A call to more research and more action

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Funding information
The study received funding from Sean N. Parker Center for Allergy and Asthma Research at Stanford University and grants NIAID P01HL152953 and NIEHS R01 ES032253. Susanne H. Sokolow was partly funded by Global Environmental Facility (GEF) Grant # 10230 (Strengthening Land Degradation Neutrality data and decision-making through free and open access platforms (Executing Agency: Conservation International)).

Abstract
There is increasing understanding, globally, that climate change and increased pollution will have a profound and mostly harmful effect on human health. This review brings together international experts to describe both the direct (such as heat waves) and indirect (such as vector-borne disease incidence) health impacts of climate change. These impacts vary depending on vulnerability (i.e., existing diseases) and the international, economic, political, and environmental context. This unique review also expands on these issues to address a third category of potential longer-term impacts on global health: famine, population dislocation, and environmental justice and education. This scholarly resource explores these issues fully, linking them to global health in urban and rural settings in developed and developing countries. The review finishes with a practical discussion of action that health professionals around the world in our field can yet take.

KEYWORDS
climate change, greenhouse gases, health, pollution

1 INTRODUCTION

Pollution caused by increased human activity is a major concern. The burning of fossil fuels, which include carbon dioxide (CO_2), methane, nitrous oxides, and other fluorinated gases, has increased greenhouse gas concentrations.[1] These gases, by trapping heat, have raised global temperatures and increased thermal pollution, the main driver of climate change. Further, deforestation, urbanization, and effluents released by mining, agriculture, and manufacturing pollute air, soil, and water and contribute to climate change. Deforestation reduces the Earth's ability to remove CO_2.

The 2021 Intergovernmental Panel on Climate Change (IPCC) reports that emissions of greenhouse gases from human activities are responsible for approximately 1.1°C of warming since 1850–1900.[2] In addition to increases in temperatures both on land and in the oceans, the pH of the oceans is also altered as they absorb the excess CO_2. Currently, the pH of the ocean is 25% higher than in preindustrial times.[3] Increased temperatures leading to thermal expansion of seawater and the melting of ice sheets and glaciers are increasing global sea levels.[2] These fundamental shifts in the environment are having impacts on weather patterns around the globe with increases in intensity and frequency of weather events such as heatwaves, hurricanes, heavy rain and flooding, drought, and wildfire.

Researchers have modeled different possible future climate change scenarios in order to assist with policy changes to mitigate these effects. To quantify future greenhouse gas concentrations and radiation (additional energy in watts/m^2 added by emissions caused by human activity by 2100) researchers use Representative Concentration Pathways (RCPs), which range from 1.9 to 8.5; the higher the RCP, the higher future global temperatures will rise. An RCP of 1.9 limits global warming to below 2.7°F (1.5°C) while an RCP of 8.5 projects global warming to 4.4°C by 2100.[4] The 2021 AR6 IPCC report combined RCPs with potential socioeconomic pathways (SSPs) to project five future climate scenarios (Table 1). SSPs use population, economic growth, education, urbanization, and the rate of technological development, all of which affect emissions and our ability to reduce them. SSP1 indicates the best-case scenario with sustainability-focused growth and equality while SSP5 indicates the worst-case scenario with rapid and unconstrained use of economic output, energy use, and global inequality.[5] In the most optimistic future climate change projected (SSP1-1.9) where global CO_2 emissions are cut to net zero around 2050, sea levels are projected to rise around 0.38m (15 inches). In the worst-case scenario (SSP5-8.5) of a doubling of current CO_2 emissions levels by 2050, sea levels are expected to increase to around 35 inches by the year 2100.[6] Similarly, global warming is very likely to be 1.0–1.8°C by 2081–2100 in the lowest emissions SSP1-1.9 scenario, 2.1–3.5°C in the intermediate SSP2-4.5 and 3.3–5.7°C under SSP5-8.5. It is the goal of the Paris Climate Accord to limit global temperature rise to well below 2°C above preindustrial levels by the end of the century and to pursue efforts to hinder temperature increase to below 1.5°C.[7] However,

TABLE 1 [172]SSP/RCP-based scenarios

SSP-RCP	This path allows for aggressive socioeconomic development and technological trajectories toward sustainable practices while reducing global inequity. Net-zero CO2 emissions are projected around the middle of the century. It is the only projection that meets the Paris Agreement's goal of keeping global warming to around 1.5°C above preindustrial temperatures.
SSP1-2.6	This path allows for moderate socioeconomic development and technological trajectories toward sustainable practices while reducing global inequity. Net-zero emissions are projected in the second half of the century On this path, temperatures are expected to stabilize around 1.8°C higher by the end of the century.
SSP2-4.5:	This path allows for slow progress toward sustainability with development and income growing unevenly. In this scenario, temperatures rise 2.7°C by the end of the century.
SSP3-7.0	This path allows for emissions to rise steadily. Global inequality continues and nationalism increases. On this path, temperatures are expected to stabilize around 3.6°C higher by the end of the century.
SSP5-8.5	This path allows for emissions to rise rapidly via increased use of fossil fuels. On this path, temperatures are expected to stabilize around 4.4°C higher by the end of the century.

meeting this goal requires global cooperation and it has been estimated that the probability of staying below 2°C of warming by 2100 is only 5% at the current time. To meet the target, country-based rate of emissions reductions should increase by 80% beyond current nationally determined contributions (NDCs).[8]

The science is clear and unequivocal that human activity is responsible for current and future climate change. These changes and increases in pollutants are affecting planetary health. Human health and well-being are consequences of overall planetary health. Even if we meet the Paris Accord goals, substantial health burdens and health risks due to climate change may be unavoidable. Much more aggressive policies combined with climate change action of each and every individual citizen is needed to mitigate and prepare for future climate events.

This review assembles international experts to describe both the direct (heat waves) and indirect (vector-borne diseases) health impacts of climate change and pollution on an international, economic, political, and environmental context. It also expands on these issues to address a third category of potential longer-term impacts on global health: famine, population dislocation, environmental justice, and education. Our purpose in writing the review is to provide a scholarly resource to define issues of climate change and link them to global health in urban and rural settings in developed and developing countries. The review finishes with a practical discussion of action that health professionals around the world in our field can take.

2 | EFFECTS OF CLIMATE CHANGE AND INCREASED EXPOSURE TO POLLUTANTS ON HUMAN HEALTH AND WELL BEING

2.1 | Increasing levels of CO_2

Preliminary evidence suggests that chronic CO_2 exposures as low as 1,000 ppm, a threshold exceeded in some indoor environments and equivalent to some estimates for urban outdoor air concentrations before 2100, are associated with potential health risks. Chronic atmospheric exposure has been associated with a diverse range of detrimental health effects, such as inflammation, bone demineralization, kidney calcification, respiratory acidosis, behavioral and physiological changes, and oxidative stress.[9] Rising atmospheric CO_2 levels have also been shown to decrease concentrations of plant carotenoids, antioxidants that are essential to human health.[10] Under conditions of elevated CO_2, increased photosynthesis and pollen production in plants as well as increased proliferation of spores from molds are observed. Both pollen and mold spores exacerbate respiratory allergy and asthma.[11,12]

2.2 | Increasing temperatures

The impact of climate change on heat-related health outcomes constitutes a substantial public health risk. Globally, in 2018, there was an increase of 220 million heatwave exposure events versus the average number of events in 1986–2005.[13] A study in France between 2015 and 2019 found that the economic impact of increased outpatient and emergency room visits and hospitalizations, mortality, and restricted activity days due to heat waves amounted to €25.5 billion, mainly in mortality (€23.2 billion), minor restricted activity days (€2.3 billion), and morbidity (€0.031 billion).[14]

Increased central body temperature causes vasodilatation, increased sweating, increased heart and respiratory rates, increases in oxidative stress, inflammation, muscle breakdown, and changes in coagulation. For example, a review of 57 studies found that heat exposure and air pollution were associated with adverse birth outcomes, including pre-term birth, low birth weight, and stillborn[15]

A comprehensive study by the Environmental Protection Agency (EPA) found that there are four socially vulnerable populations which are disproportionally impacted by increased heat-related illnesses and mortality associated with climate change:

(1) Those living below the 200% poverty line are more impacted from the heat because they are less likely to live in weatherized homes, have access to air conditioning and they tend to live in areas with the highest predicted increase in temperature-related mortality (2) Those with no high school diploma (e.g., more likely to be an outdoor worker) (3) The elderly >65 years old due to pre-existing conditions and increased susceptibility to cardiac stress from the heat and (4) Minority populations, especially Black and African Americans, who are more likely than others to live in areas with the highest projected increases in temperature-related mortality.[16] The lungs and the skin are more affected by the impacts of climate change. Therefore, increased protection is needed for vulnerable patient groups with asthma, COPD, and cardiovascular diseases.[17-20]

2.3 | Increasing levels of air pollutants

The World Health Organization (WHO) considers air pollution as the single largest environmental risk responsible for almost 7 million deaths per year of which almost 75% are due to respiratory diseases, such as lung cancer, chronic pulmonary obstructive disease, or cardiovascular diseases like ischemic heart disease and stroke.[21] Key air pollutants designated by WHO are particulate matter (PM), ozone, nitrogen dioxide, and sulfur dioxide.[22] Besides these, other air pollutants such as gases (benzene, toluene, and xylenes), liquid aerosols (perchloroethylene and methylene chloride), and inhalable particles (polycyclic aromatic hydrocarbons, cadmium, chromium, lead, and mercury) have been categorized as hazardous or toxic air pollutants.

PM pollution is of particular concern and particles 10μm or below (PM_{10}) are considered harmful to our health as they are inhaled; fine PM, those that are smaller than 2.5 microns ($PM_{2.5}$), can pass into the alveolae and enter the circulation, causing diffuse inflammation, and other effects.[23] The chemical composition of PM varies and can be made up of both man-made substances (sulfates, nitrates, ammonia, carbon, lead, organic compounds, etc.) as well as natural substances (soil, dust, and bioaerosols). A recent study found that long-term $PM_{2.5}$ exposure is associated with increased hospitalization for COVID-19[24,25] and increases risk for acute asthma exacerbation. Air pollution and climate change significantly contribute to the onset and aggravation of allergic rhinitis and asthma as well as other chronic respiratory diseases.[26,27] Similarly, short-term exposure to daily ozone, nitrogen dioxide, and sulfur dioxide was associated with an increased risk of asthma exacerbation in terms of asthma-associated emergency room visits and hospital admissions.[28] A study in Vienna, Austria, used crowd-sourced allergy symptom data in combination with pollen, weather, and air quality data and found that O_3, has an effect on the severity of symptoms of pollen allergy sufferers during the pollen season.[29] Lead is another serious environmental health hazard which can be found in air particulates. Reductions in children's executive function in the first four years of life were associated with their proximity to sources of airborne lead.[30]

2.4 | Increasing intensity and frequency of wildfires

Wildfires have become increasingly frequent and more intense with climate change. Wildfire smoke is a complex and continually changing mixture of gases and PM, including large amounts of fine ($PM_{2.5}$) and ultrafine particles ($PM_{0.1}$). Wildfires also often incinerate motor vehicles, homes, and commercial structures at the urban-wildlands interface, which may add toxic chemicals to the smoke from incineration of plastics and other manufactured materials. Likewise, ash and debris from burned homes and automobiles may contain toxic chemicals that can leach into the soil and contaminate rivers and downstream water sources. Little is yet known about the health hazards of toxic chemical contamination of soil and water from wildfires. Wildfires additionally damage vital community infrastructures (e.g., public water systems) of burned communities. Residents returning to two fire-stricken communities in northern California were exposed to very high levels of benzene and other volatile organic chemicals resulting from widespread chemical contamination of the public water system from pyrolyzed plastic water pipes.[31]

Both short- and long-term exposure to wildfire smoke harm health. These health harms include exacerbation of chronic respiratory and cardiovascular conditions; increased occurrence of acute cardiovascular events and metabolic, dermatologic, and mental health disorders; increased susceptibility to respiratory infections such as influenza and SARS-CoV-2; immune dysfunction; adverse pregnancy outcomes; sperm damage; infant developmental disorders; and dementia.[15,32-44] Increases in asthma attacks and asthma hospitalization are associated with wildfires. A study found that use of prescribed burns, which can decrease size and severity of wildfires, may be beneficial for immune health.[45] The many and varied health hazards of wildfires can be grouped into four broad categories based on when they occur and their precipitating circumstances (Table 2).

Extreme wildfires around the world have created a new form of public health emergency in so far as they typically last weeks to months, follow an unpredictable course, and their smoke and ash may be carried by winds and air currents for hundreds or thousands of miles away from the fire, exposing populations over large geographic areas to severe air pollution having a high content of fine and ultrafine particles.

2.5 | Increasing frequency and intensity of flooding

Climate change is increasing the likelihood and intensity of extreme precipitation events.[2,46] The type of extreme precipitation events that used to only occur once a decade are now occurring 30% more frequently, which can contribute to flash and urban flooding.[2] Tropical cyclones are stronger and contain more rainfall, and sea level rise is driving increased coastal flooding—especially during storms.[2] This will increasingly place more individuals at risk to the mortality and morbidity risks of flooding. Floods affect over 2.8

TABLE 2 Health hazards resulting from wildfire

Acute Health Effects—Injuries and illnesses due to direct exposure to flames, heat, or smoke and/or resulting from or responding to the fire	Delayed or Chronic Health Effects due to smoke exposure, deposition of toxicants in soil and/or water, and recovery activities	Acute or delayed health harms resulting from diminished access to or disrupted medical care resulting from	Acute or delayed health harms due to population displacement
Thermal burns and their complications (e.g., multi-organ failure)	Exacerbation of chronic respiratory conditions (e.g., asthma, COPD, or emphysema)	Local health service capacity overwhelmed by acute fire-related morbidity (e.g., burns and respiratory conditions) or loss of health workers (e.g., evacuated, injured)	Morbidity or mortality among patients resulting from evacuation from healthcare facilities
Heat illness (in all its forms)	Increased occurrence of respiratory infections[173] (e.g., influenza, COVID-19, other pneumonias, bronchitis, and bronchiolitis; sinusitis)	Local health facilities inaccessible due to road closures, road traffic congestion, or healthcare facility closure (e.g., destroyed by fire or evacuation of health workers)	Acute and delayed consequences of population relocation (e.g., populations relocated from burned areas to other communities) for both the displaced population and the population receiving them
Carbon monoxide or other toxic gas poisoning	Exacerbation of chronic cardiovascular conditions (e.g., congestive heart failure, ischemic heart disease, arrhythmias)	Impaired functioning of hospitals due to contamination of ventilation systems (e.g., with smoke and ash) or loss of electrical power or water supplies	
Upper airway irritation and other acute respiratory inflammatory conditions (e.g., nasal congestion, sinusitis, bronchitis)	Acute coronary events (e.g., myocardial infarction) from overexertion from recovery activities	Malfunction of personal medical equipment (e.g., oxygen concentrators, ventilators, or motorized vehicles) due to loss of electrical power or water supply	
Acute exacerbation of pre-existing respiratory conditions (e.g., asthma, chronic obstructive pulmonary disease, or emphysema)	Trauma from motor vehicle accidents, falls or falling debris or other causes and musculoskeletal overexertion injuries associated with clean-up and recovery activities	Loss of medications, medical supplies, or support systems	
Acute cardiovascular conditions such as angina or myocardial infarction (e.g., from over-exertion due to escaping from or fighting the fire) and stroke or atrial fibrillation (e.g., from inhalation of fine particulate matter) Exacerbation of pre-existing cardiac conditions such as congestive heart failure, ischemic heart disease, or arrhythmias from smoke exposure	Electrical burns and electrocution from exposed electrical wires or downed power lines		
Trauma from motor vehicle accidents, falls or falling debris, or other causes and overexertion injuries associated with escaping from or fighting the fire	Immune suppression and impaired immune response		

(Continues)

TABLE 2 (Continued)

Acute Health Effects—Injuries and illnesses due to direct exposure to flames, heat, or smoke and/or resulting from or responding to the fire	Delayed or Chronic Health Effects due to smoke exposure, deposition of toxicants in soil and/or water, and recovery activities	Acute or delayed health harms resulting from diminished access to or disrupted medical care resulting from	Acute or delayed health harms due to population displacement
Electrical burns or electrocution from exposed electrical wires or downed power lines	Adverse pregnancy outcomes such as pre-term delivery, low birth weight, or stillbirth		
Ophthalmic irritation or injuries such as corneal abrasions from airborne ash or flying debris	Possible transgenerational effects such as immune dysfunction, reduced respiratory capacity, or birth defects in offspring exposed during pregnancy		
Acute mental health conditions such as panic and anxiety disorders	Impaired male reproductive health from sperm damage		
Exacerbation of pre-existing mental health conditions such as depression	Acute mental health conditions such as panic attacks, anxiety disorders, depression, and post-traumatic stress disorder		
Adverse pregnancy outcomes such as pre-term birth	Exacerbation of mental health conditions such as depression		
	Ophthalmic irritation (e.g., from smoke) and injuries (e.g., corneal abrasions associated with clean-up operations)		
	Possible carcinogenic effects due to toxic chemical contamination of soil or water		

*Adapted from Kizer KW. Extreme wildfires—A growing population and planetary health problem. *JAMA*. 2020; 324(16):1605–1606.

billion people in the world and have caused over 200,000 deaths over the past three decades.[47]

Drowning is the leading cause of death during these events[48] with flash floods carrying a higher mortality risk.[49] Other immediate morbidity and mortality risks occur from, for example, trauma, musculoskeletal injuries, wounds, and carbon monoxide poisoning (e.g., exposure to unventilated generators).[48,49] Damage to and/or an inability to access health care also have indirect health implications.[48]

When flooding occurs, the population is exposed to numerous dangerous toxins, algal blooms, and other contaminants. Water contamination can lead to further acute effects including mortality and loss of potable water supplies[50] as well as the propagation of vector-borne diseases and waterborne pathogens, infection through exposure, poisoning via toxic chemical exposure, and mold in homes.[12,51] For example, in the aftermath of Hurricane Katrina, New Orleans residents were exposed to increased pollutants and pathogenic microbes including hydrocarbon fuel, aldrin, lead, arsenic, iron, chromium, pesticides, and fecal coliforms.[52]

The risk of outbreaks of gastrointestinal illness has been linked to extreme precipitation and flooding, often due to an overflow of combined sewage systems and/or a lack of access to clean water.[49] Mental health impacts can occur directly as a result of long-term losses; those who experience flooding events are more likely to report depression and anxiety, even years later.[48,53,54] Other long-term effects include chronic disease, disability, displacement, and poverty-related diseases including malnutrition.[55]

In the aftermath of flood events, existing evidence has found increased fungal growth and mold spores and higher indoor aeroallergen exposure.[12,56] Links have been documented with increased respiratory symptoms, though more evidence is needed to understand the true degree of health burdens that result—especially for those with pre-existing diseases like asthma.

2.6 | Climate change and thunderstorm asthma

Scientific uncertainty remains for how climate change impacts severe storms like thunderstorms, tornadoes, and hail.[57] Thunderstorms in the Southern Great Plains in the United States, for example, have been increasing in intensity and frequency, and emerging evidence has found links to climate change.[58] Thunderstorm asthma (TA) is a phenomenon characterized by a sudden increase in presentations of asthma in individuals following a thunderstorm. There has been over 23 reports worldwide since the 1980s[56] with the world's most severe TA event occurring in Melbourne, Australia, in November 2016, coinciding with the peak grass pollen season.[59] This catastrophic event resulted in 9,909 hospital emergency department presentations for severe asthma, 814 calls for ambulances and 10 deaths.[60] During the "perfect storm" of TA, extreme convergent environmental factors, wind, torrential rain, and high aeroallergen loads, trigger bronchospasm in susceptible individuals.[61] As the thunderstorm develops, warm updrafts of air rapidly ascend carrying concentrated whole pollens until they reach the cloud base. Due to the high humidity and wet conditions, the pollen bursts through osmotic rupture and each grain releases hundreds of small (<5μm) allergenic starch granules (capable of reaching the lower airways), returning to the ground by storm downdrafts.[56] The major risk factor for hospitalization in the Melbourne event was allergic rhinitis (87%).[61]

Recent studies have shown increased duration of pollen season, peak pollen concentration, total season pollen load,[62] and pollen allergenicity with climate change.[56] A recent study has found that climate change in North America contributes to about 50% of the lengthening pollen season.[63] A systemic review and meta-analysis found a statistically significant increase in children and adolescents the percentage change in the mean number of asthma emergency department presentations for an increase in 10 grass pollen grains per cubic meter of exposure.[64] While the links between climate change and thunderstorms remain uncertain, the links to pollen are clear—thus possibly increasing the frequency of TA events. Increased pollen concentrations have also been correlated with increased SARS-CoV-2 infection rates, as evidenced from 31 countries across the globe. Pollen exposure has also been shown to weaken innate immunity against respiratory viruses.[65,66] To mitigate the health consequences of TA, it is essential to monitor and forecast atmospheric pollen levels[67] as well as other meteorological factors.

2.7 | Increasing land degradation, desertification, and drought

Land degradation is defined by the United Nations Convention to Combat Desertification as a reduction or loss in the biological or economic productive capacity of land,[68] affects 20% of the Earth's vegetated surface and over 1.3 billion people.[69] It is generally caused by human activities, but it is exacerbated by natural processes and is intertwined with climate change and biodiversity loss. Drought (a reduction in water availability) along with desertification (a gradual transformation of previously productive ecological regimes to more xeric ones) combine with the anthropogenic phenomenon known as land degradation to impact human health through a variety of pathways.[70]

As water sources dry up, soils aerosolize, increasing airborne pollution and dust storms, and pose risks for respiratory health and mortality.[71,72] Some estimates have suggested as much as 50% of tropospheric aerosols are made up of desert dust. Other potential human health impacts from desertification, land degradation, and drought include malnutrition from dwindling crop yields,[73,74] water and hygiene-related diseases due to household water scarcity,[75-78] and vector-borne and parasitic diseases that expand with changing water resources and migrating human populations.[79-81] For example, coccidioidomycosis (Valley fever) prevalence has increased. It is caused by inhalation of Coccidioides spp. spores, which are found in the soil. From 1995 to 2009, annual incidence rates in California ranged from 1.9 to 8.4 per 100,000, followed by a substantial increase to 11.9 per 100,000 in 2010 and a peak of 13.8 per 100,000 in 2011.[82] Due to increasing temperatures and shifting precipitation patterns due to climate change, it is projected that the number of cases will increase by 50% by 2100 and that the disease will spread north of California into other dry western states.[83]

2.8 | Decreases in environmental greenness and biodiversity

Exposure to and interacting with green spaces and biodiverse environments are associated with numerous physical and mental health benefits, including immune health.[84-87] Several hypotheses also support the relationship between biodiversity and human health.[84] It was proposed by Dubos et al. that allergy may be an important sentinel measure of planetary health—altered immune reactivity, which might reflect the state of the world around us.[88] Biophilia shows that humans have an innate drive to interact with different species of vegetation and animals because this interaction drove the evolution of humans, and thus, mental health benefits may be derived from interacting with biologically diverse environments. Biodiversity (i.e., exposure to a variety of biodiverse environments and microbes) regulates the human gut microbiome and promotes healthy immune system development. Biodiversity hypothesis states that contact with natural environments enriches the human microbiome, promotes immune balance, and protects from allergy and inflammatory disorders.[89] Finally, the dilution effect proposes that in environments with many vertebrate species, transmission of infectious diseases may be lower in species-rich environments because of a lower prevalence of infected vectors.[84,90] Therefore, the loss of biodiversity and decreased proximity to nature, soil, and greenery as a consequence of modern urban development and life style is another factor that ultimately contributes to the development of diseases in humans and animals.[87,91] More greenery and vegetation in the neighborhood and prolonged contact with a green environment showed a protective effect against allergic sensitization in 10-year-old children,[92] and living in close proximity to a greener environment at birth had a protective effect on the development of allergic diseases and asthma at the age of 7.[93] Additionally, in areas of lower biodiversity, invasive species (such as ragweed) can introduce new allergens to populations increasing the incidence of allergies and asthma.[94]A summary of selected systematic reviews that relate to biodiversity, greenness, and human health is presented in Table 3.

2.9 | Increasing plastic pollution

The global plastic pollution crisis is a growing threat to human and planetary health and is directly linked to and exacerbated by the current climate crisis. First and foremost plastics are created from fossil fuels and therefore a direct contributor to climate change: 4%–8% of global oil consumption is associated with plastic production and this percentage is projected to increase to 20% by 2050, with continued trends of increasing plastic use.[95] With lack of proper disposal in most regions of the world and the harsh reality that only a scant amount of the world's plastic is actually recycled (less than 10%),[96] much of plastic waste is burned, leading to air pollution, airborne toxins, and the release of more greenhouse gasses.[97] Plastic that is not incinerated ends up in landfills, leaching pollutants into our soils and water sources, or in our oceans, which leads to threatened marine ecosystems, food insecurity, and the ubiquitous ingestion of microplastics.[98] In addition to direct human health harms, plastic pollution also leads to indirect impacts such as the increased abundance of disease-laden mosquitoes that breed in plastic waste and contribute to outbreaks of deadly infections.[99-101] These outbreaks will only worsen as the climate warms.[102] In every phase of its life cycle, plastics contribute to climate change and exacerbate the harmful impacts on human health; therefore, alternatives to plastic and novel solutions to combat the plastic already poisoning our planet and its peoples are desperately needed.

2.10 | Increases in vector-borne infections

Snails and arthropods, including mosquitoes, ticks, flies, and fleas, are vectors for infectious diseases transmissible to humans and non-human hosts. Common vector-borne diseases include Malaria, Dengue, Zika, Chikungunya, Lyme disease, Chagas, Leishmaniasis, Schistosomiasis, Japanese encephalitis, lymphatic filariasis, West Nile Virus, Yellow Fever, and the Plague (Table 4), though the science linking them to climate change is still growing. The WHO estimates the global mortality of vector-borne diseases to be greater than 700,000 deaths annually.[103] Climate change is expected to directly and indirectly impact the prevalence, incidence, and mortality of some vector-borne diseases by altering their geographic distribution. Extreme weather events, changes in precipitation, and extremes of high and low temperatures are expected to likely increase the incidence and abundance of certain vector-borne diseases by lengthening the season of transmission,[104] pressuring vectors to expand northward secondary to global warming,[105] altering ecosystems to increase habitat availability in non-endemic regions,[106] and increasing vector and pathogen reproduction rates.[107] In addition, climate-induced migration and forced displacement of human hosts may promote the spread of vector-borne diseases to non-endemic areas.[13] These changes will likely increase human and non-human host exposure to vectors and possibly trigger the emergence of new pathogens and vector-borne diseases.

2.11 | Increases in harmful algal blooms

With climate change, scientists expect harmful algal blooms (HABs) to become more frequent, wide-ranging, and severe.[108] HABs pose risks to ecosystem health because of the toxins that they can produce. They contaminate shellfish, the consumption of which seriously threatens human health and life. The five most commonly recognized HAB-related illnesses include ciguatera poisoning, paralytic shellfish poisoning, neurotoxin shellfish poisoning, diarrheic shellfish poisoning, and amnesic shellfish poisoning.[109] In 2014, a HAB on Lake Erie containing microcystin (a liver toxin) contaminated the municipal water supply in Toledo, Ohio, providing non-potable water to 400,000 people.[110] A number of strategies are now proposed for mitigation such as control of nutrient loads, chemical treatment, biological manipulation, and cyanotoxin removal.[111]

2.12 | Decreased food security

According to the Food and Agriculture Organization of the United Nations, global malnutrition rates have been steadily increasing since 2015 and exacerbated by the COVID-19 pandemic. This trend is attributed to an interconnected combination of domestic and international conflicts, economic downturns in otherwise peaceful nations, and climate disturbances.[112] Severe climate events are predicted to increase in frequency and severity, and threaten to destabilize all aspects of global food systems, with negative impacts disproportionately burdening vulnerable communities.[2,113] These stressors are predicted to multiply the risk of further geopolitical instability, economic inequities, and adverse global health outcomes.[114]

The global food system, including its production, manufacturing, and transportation, is responsible for nearly one third of anthropogenic greenhouse gas emissions.[115] There is a pressing need to reduce carbon emissions, strengthen local food and social systems, redistribute power to indigenous and historically marginalized communities, and mitigate the impacts of climate change.[116] Community-centered livelihood interventions such as Shamba Maisha in the Nyanza province of Eastern Kenya have demonstrated the feasibility and cost-effectiveness of climate change adapting strategies on food security and associated health outcomes and can serve as a model for pragmatic action.[117-119]

2.13 | Increased displacement

Extreme storms, floods, wildfires, droughts, melting permafrost, sea level rise, and heat—that will render nearly a fifth of the planet too hot for humans by 2070[120]—threaten the food security, livelihoods, homes, and resource access of billions around the world. These climate change-related factors, described as "threat multiplier[s],"[121] often exacerbate political instability, economic concerns, and conflict—resulting in the displacement of millions (Figure 1). Refugees, internally displaced people, and stateless persons are on the frontlines of the climate emergency. Many are living in climate "hotspots" where they typically lack the resources to adapt to an increasingly inhospitable environment. Researchers highlight four

TABLE 3 Selection of recent systematic reviews that have assessed associations between greenness, biodiversity, and human health

Study	No. of studies	Key findings
Lambert et al 2018[174]	11	Four studies found increased greenness reduced risk of atopic sensitization and 2 studies found increased greenness increased risk of atopic sensitization; 5 studies found no association,
Rojas-Rueda et al 2019[175]	9	Seven studies found increased greenness was associated with a reduced risk of all-cause mortality; two studies found no association.
Shin et al 2020[176]	13	Eleven studies found that increased green space exposure was associated with better sleep quality and quantity; two studies found no association.
Islam et al 2020[86]	23	Increase exposure to green space during pregnancy was associated with increased birth weight. Increased exposure to greenness during childhood was associated with increased physical activity and lower risk of obesity and neurodevelopmental problems. Increase exposure to green space was associated with a reduced risk of wheezing, although some plant species increased risk of asthmatic symptoms.
Hartley et al 2020[177]	7	One study found increased greenness was associated with a reduced risk of asthma; six studies found no association
De la Fuente et al 2020[178]	19	Increased exposure to green spaces is associated with a reduced risk of Type 2 diabetes mellitus and obesity, and increased likelihood of physical activity.
Flies et al 2020[179]	19	Two studies found rural aerobiomes (airborne fungal and bacterial communities) shifted immune function away from Th2-dependent allergic phenotype.
Li et al 2021[180]	29	Overall beneficial role of early-life nature and green space exposure on mental health, although some inconsistencies are reported.
Hu et al 2021[181]	29	Moderate evidence that increased residential greenness is associated with higher birthweights. Little evidence that greenness was associated with pre-term birth and weight for gestational age.
Anderson et al 2021[19]	20	Nature exposure was associated with anti-inflammatory effects, anti-asthmatic effects, and enhanced cytotoxicity from NK cells.

regions of critical concern for climate impacts and consequent displacement: the African Sahel, the Middle East and North Africa, the "Dry Corridor" in Central America, and South Asia—which together "host the world's most vulnerable billions."[121] Estimates range from 150 million to over one billion displaced by 2050.[122] About 200 million people, a year need international humanitarian aid due to climate-related impacts, representing an annual cost of $20 billion.[123] Critical adaptation measures include recognizing climate refugees under international law to afford them more protections,[124] improving national immigration policies,[125] supporting community mobilization,[126] and developing infrastructure and emergency preparedness in vulnerable countries,[123] along with health system resilience.

2.14 | Stress and psychological issues

Climate change affects the mental health of populations through multiple pathways. Population group vulnerability is shaped by geographic location, access to resources, information and protection, rendering mental health in a changing climate an environmental justice issue.[127] Acute events such as hurricanes, wildfires, and floods can lead to well-understood psychopathologies, including post-traumatic stress disorder and mood disorders.[2] Experiences of evacuation and isolation during a disaster, as well as repeated exposure to adverse environmental changes, can negatively impact emotional well-being[53] and have been linked to maladaptive coping (i.e., substance abuse, suicide[128]). High ambient temperatures and heatwaves may lead to increased suicide, self-harm, aggressive behaviors, as well as psychological morbidity and mortality among people with pre-existing mental disorders.[129] The knock-on effects of rising temperatures, such as migration, economic instability, and resource scarcity are also urgent threats to mental health.[130] Meanwhile, a growing body of research shows existence of chronic worrying about the current and future state of the environment ("eco-anxiety",[131] "climate anxiety"[132]) and felt environmental losses.[133]

TABLE 4 A representative, but not exhaustive, list of vector-borne diseases

Vector	Disease(s) Caused
Aedes Mosquito	Chikungunya Dengue Lymphatic Filariasis Yellow Fever Zika
Anopheles Mosquito	Lymphatic Filariasis Malaria
Culex Mosquito	Japanese encephalitis Lymphatic filariasis West Nile fever
Aquatic Snails	Schistosomiasis
Blackflies	Onchocericiasis
Fleas	Plague Tungiasis
Sandflies	Leishmaniasis Sandfly Fever
Ticks	Lyme disease Rickettsial Diseases Q Fever Tick-Borne Encephalitis Tularaemia
Triatome Bugs	Chagas Disease
Tsetse Flies	African Sleeping Sickness

3 | CLIMATE CHANGE: TRACKING AND MITIGATION

3.1 | Mitigating climate change: Health systems solutions

The effects of climate change, including extreme weather and climate events of increasing frequency, duration, and intensity, increasingly threaten the service provision of health systems.[48] Climate-resilient adaptations to health system infrastructure are necessary to preserve service delivery and mitigate climate-sensitive health outcomes such as illness and death, especially in disadvantaged communities that struggle with access to healthcare services.[48,134] Key health system vulnerabilities that must be addressed include supply chain disruptions, healthcare workforce shortages, loss of access to medical records, and damage to and loss of healthcare facilities.[134-137] Table 5 addresses some of the ways the healthcare sector can prepare for resilience in the face of climate change.

In addition to preparing for extreme weather events and other climate-related stressors, health systems must also take steps to mitigate their sizeable environmental impact. Globally, the healthcare sector is responsible for 4.4% of greenhouse gas emissions.[48,138] The U.S. healthcare sector accounts for 8.5% of total domestic greenhouse gas emissions—the highest in the world.[138,139] Emissions arise from the carbon-intensive operation of healthcare facilities, as well as the health care supply chain through the production of goods and services.[138-140]Significant reductions in healthcare-associated

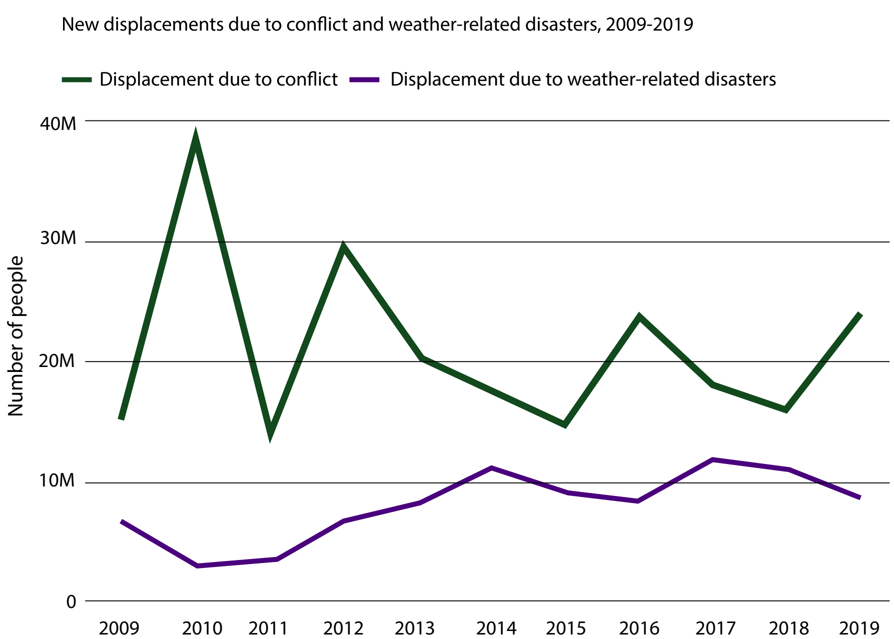

FIGURE 1 Displaced on the frontlines of the climate emergency. UNHCR. Accessed August 20, 2021. https://storymaps.arcgis.com/stories/065d18218b654c798ae9f360a626d903

greenhouse gas emissions can be achieved through a commitment to decarbonizing healthcare facilities and the healthcare supply chain.[48,140]

3.2 | Mitigating climate change: Education

Education is essential to catalyze and sustain climate action. As the IPCC released the first part of the Sixth Assessment Report in August 2021 on the physical science basis for climate change,[2] the message needs to be disseminated and digested by children and adults alike. Understanding how climate change affects personal health through infographics (Figure 2) can motivate individuals to find solutions as individuals and as a community. Disseminating health information online promotes health literacy and helps users make data-driven decisions.[141,142]

Several professional societies have released statements in support of climate change and health education for preclinical, clinical, and continuing medical education.[143] Despite these calls for new curricula (with the greatest pressure coming from medical students), medical schools offer little to no education on the health impacts of climate change.[144-146]

Studies show that most students and physicians in practice lack the necessary knowledge and skills to recognize, treat, and prevent climate-related health conditions in their patients, or to understand health inequities and climate injustice.[147,148] As highly trusted figures in the community, healthcare workers and aspiring healthcare workers should also be trained to work on mitigation, adaptation, and policy making around climate change, as well as to prepare and "green" their healthcare systems. Climate change and health should be infused throughout medical education, as it affects all aspects of human health and every medical specialty.[149] To prepare faculty members to teach on this topic, faculty development, grand rounds presentations, and continuing medical education need to be implemented.[150] Ligozat et al. detail ten simple rules that researchers can follow to make their research more sustainable.[151]

3.3 | Mitigating climate change: Individual solutions

Stanisław Jerzy Lec's quote, "No snowflake in an avalanche ever feels responsible," likely echoes the sentiments of most of humanity, each and every one of whom are responsible for the profound effects of climate change. Individual action is an important component in combatting climate change.[152] The concept of "reduce, reuse, recycle" is an excellent framework to help prioritize individuals' and households' climate mitigation strategies. These can be implemented in many different domains, including transportation (living car free and avoiding airline travel), energy (conserve and reduce energy at home, purchase decarbonized electricity), food (eating meatless and reducing waste), and other purchases (such as furniture, clothing, and consumables).[153]

Of course, these activities may not be feasible for some individuals and households, depending on their available wealth and community resources (such as public transportation). As such, the most important individual action may be in advocacy and political engagement. Large-scale behavioral changes require social pressures (policy, nudges, incentives, peer pressure) and are only possible when enough individuals demand action from businesses, non-profits, and government.[152,154] Therefore, becoming educated about climate change; sharing information with friends, families, and neighbors; and voting for leaders or policies that support climate action have a multiplying effect above and beyond any individual mitigation activities.

4 | MONITORING CLIMATE CHANGE AND POLICY-DRIVEN EFFECTS ON HEALTH

4.1 | Global exposure monitoring

There are a number of large public databases (Table 6) that can be accessed to follow climate change as well as data made available by private companies to assess confounders such as mobility away from climate events. Advances in remote patient monitoring, wearables, and bluetooth devices have the potential for us to better track objective measures of health in real time and longitudinally for persons proximate to climate events. Such advances will promote objective measures of health and clinical outcomes that can be closely tracked and linked as a direct consequence of climate change.

4.2 | Personal exposomic tracking

Technologies for monitoring of the exposome, which comprises the totality of nongenetic factors that affect human health, have made significant and continuous improvements in recent years. Wearable sensor technologies are becoming a promising way to measure personal exposure continuously: indoors, outdoors, and even on the move. Participants in the biomarkers for Air Pollutants Exposure (China BAPE) used wearable passive samplers (The FreshAir wristband) coupled with high-resolution mass spectrometry (HR-MS) chemical analysis to enable comprehensive characterization of personal exposures. Out of the 70 airborne compounds of potential concern screened, 26 compounds from 10 chemical classes were found to be above detection thresholds across >70% of the study population.[155] The Biomedical REAl-Time Health Evaluation (BREATHE) is another platform for personal exposome monitoring. BREATHE uses a smartwatch to enable data stream integration from local sensors and a smartphone for data transmission. Additional data collection to create a complete picture of an individual's health and real-time environment is made possible by accessing various online resources.[156] GeoAir is another novel portable, GPS-enabled, low-cost air-pollution sensor for assessments of personal exposure. There is rapid growth in this field with exciting possibilities for the future of personal exposome monitoring.

TABLE 5 Climate resilient health systems

Developing climate resilient health systems	Actionable items
Adaptation[134,140] Preparing for and managing the risks and impacts of climate change	Healthcare facilities.[48,134-137,140] • Implement infrastructure adaptations such as sustainable land use and building design, and emergency power generation to minimize facility and utility loss during extreme weather events • Establish back-up data systems to ensure continued access to patient medical records • Partnerships with public health agencies to enhance surveillance and early warning systems for climate-related threats Healthcare workforce.[48,134-137,140] • Integrate climate change education into all stages of preclinical and clinical training • Ensure access to healthcare and financial resources to support healthcare personnel working through emergencies
Mitigation[134,140] Reducing emissions that contribute to climate change	Decarbonization strategies include[134,140] • Low-carbon or net zero healthcare facility design • Investment in renewable energy and energy efficient technologies • Use of telemedicine and other low-carbon technologies for care • Sustainable waste, water, and transport management • Sustainable procurement of goods and services

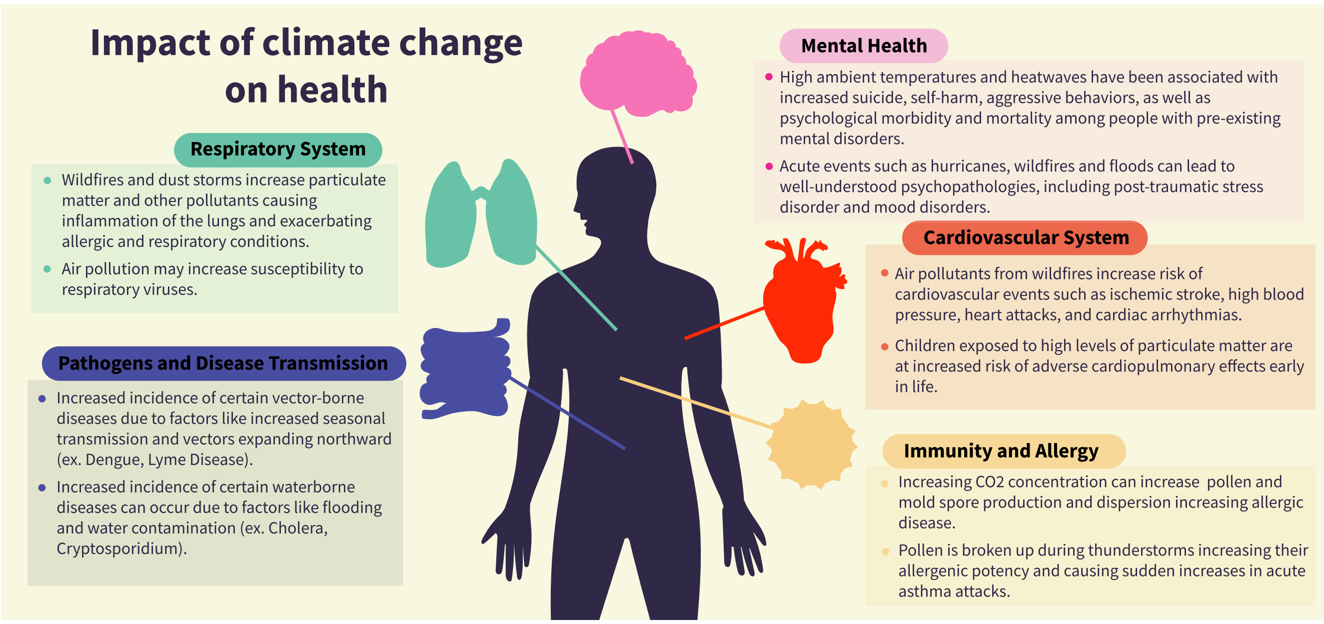

FIGURE 2 Health effects associated with climate change

4.3 | Biomarkers

As one might expect, epigenetics—the manner in which genes differentially express themselves in response to environmental changes—are greatly influenced by many of the environmental impacts of climate change. Increased exposure to heat stress, wildfire smoke, and microbial and chemical toxins from flooding all produce a cascade of epigenetic responses. A number of recent studies shed light on some key epigenetic markers that can be used to both assess population-based needs as well as mark the impact of public health policies. C-reactive protein (CRP) is often used as an unspecific marker of inflammation. A recent meta-analysis identified 218 potential DNA methylation (DNAm) markers associated with circulating levels of the inflammatory marker CRP.[157] Exposure to $PM_{2.5}$, carbon monoxide, and ozone was linked to altered methylation of most CpG sites for immunoregulatory genes Foxp3, IL-4, IL-10, and IFN-g.[158] A nasal epigenome-wide association analyses of 503 children from Project Viva found 362 CpGs associated with 1-year $PM_{2.5}$ and 10 Differentially Methylated Regions. The study found differential DNAm at/near genes implicated in cell cycle, immune, and inflammatory responses.[159]

4.4 | Summary and solutions

Climate change, increasing temperatures, wildfires, urbanization, increased pollution, loss of biodiversity, and lifestyle changes heavily impact human, animal, and plant health in many ways. The distortion of the exposome is directly responsible for the epidemic increase in the prevalence and severity of allergies, asthma, and infectious diseases.[160] Collective action at all level of organization, from international climate change agreements to actions by individuals are needed to meet the challenge of mitigating the effects of climate change (Figure 3).

Several holistic and interdisciplinary approaches, like One Health, Eco Health, or Planetary Health, exist to safeguard health.[161] Such an integrated approach is needed to tackle environmental risks, based on high-quality evidence, in order to implement appropriate measures. To this end, an excellent framework delivered by the Academia in the format of evidence-based guidelines is required (Box 1). The One Health concept is thus intended to involve all responsible parties—human and veterinary medicine, environmental scientists, consumers and patients, climate activists, landscape and urban planning, media, policy makers and health insurances, planning—and ultimately help to achieve "health for all."

Countries are taking measures against climate change. Over the past few decades, national-level climate-focused laws and policies have expanded to include more than 2,300 laws and policies across 164 countries worldwide (Figure 4), covering both mitigation and adaptation[162] and account for 95% of global greenhouse gas emissions. However, this international response on climate change has been not sufficient so far.[163] In spite of 40 years of global climate negotiations, with few concessions, we have mostly conducted business as usual and have mostly failed to address this situation.[164] According to Roelfsema et al.,[165] the implementation of current policies will leave us an average emission gap of 22.4 to 28.2 $GtCO_2eq$ by 2030 with the optimal ways to implement the Paris targets well below 2°C and 1.5°C. Nevertheless, a new climate law is associated with a reduction in the intensity of emissions, which highlight the importance of a solid legal framework to address climate change.[166,167] Protecting our health from the effects of emerging infectious disease and climate change will require national and regional policies focused on cumulative health effects experienced by overburdened communities,[168] a common interest in the quality of life for present and future

TABLE 6 Tracking climate change and population health

Websites and Mobile apps for tracking climate change and population health
https://www.airnow.gov
https://www.ncdc.noaa.gov/climate-information
https://www.climate.gov
https://www.ospo.noaa.gov/Products/land/hms.html
https://www.cdc.gov/nceh/tracking/Topics.htm
www.usafacts.org
http://www.climatologylab.org/gridmet.html
Earth now (mobile app)

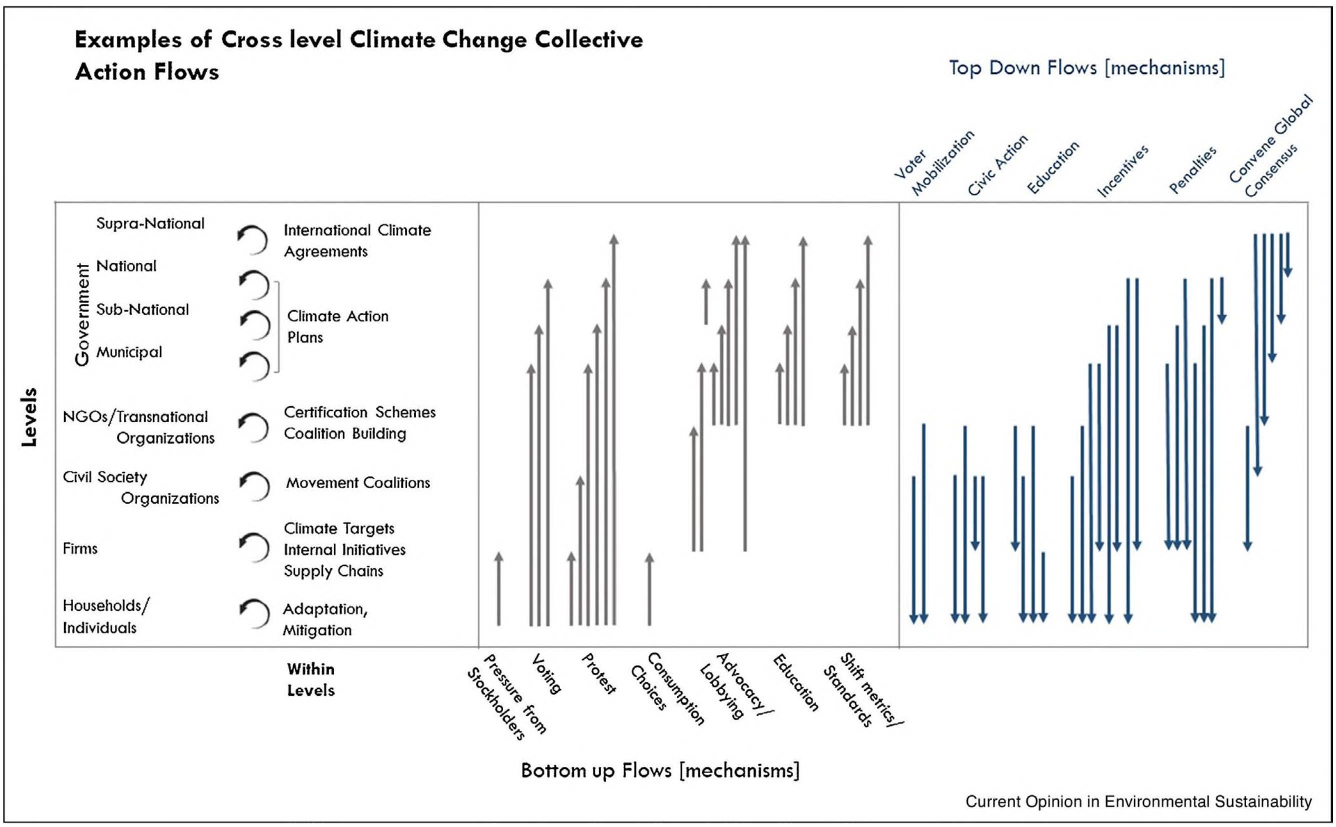

FIGURE 3 Climate change collective action (Reproduced from York AM et al. Integrating institutional approaches and decision science to address climate change: a multi-level collective action research agenda. Current Opinion in Environmental Sustainability 2021;52:19–26)

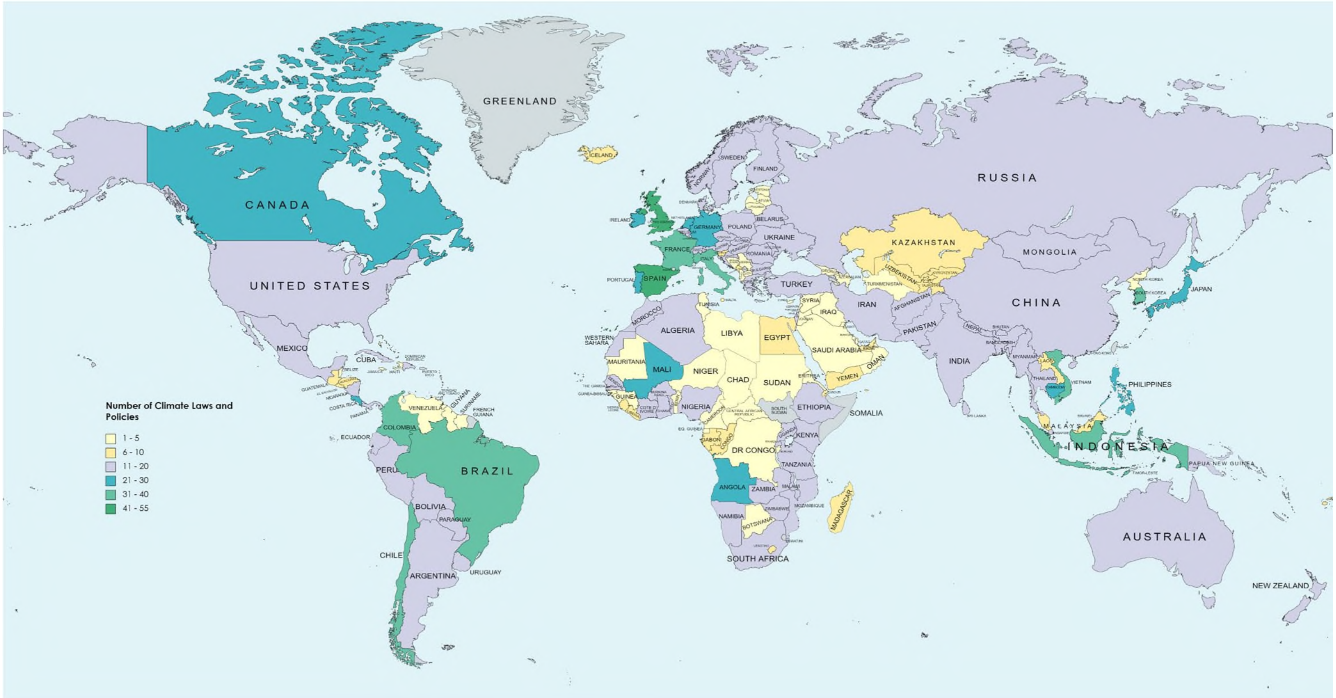

FIGURE 4 Climate change regulations around the world. Countries shaded gray are not yet covered by the database. Source: Grantham Research Institute on Climate Change and the Environment at the London School of Economics and Political Science and the Sabin Center on Climate Change Law at the Columbia Law School (https://climate-laws.org/)

BOX 1 Key messages

1. The health sector should reinforce holistic prevention measures following the One Health or Planetary Health model.
2. Academia must deliver guiding frameworks, such as high-quality evidence-based guidelines.
3. Asthma and allergic diseases, as environment-driven entities with life-long impacts, are very suitable for One Health policy implementation.
4. The environment can support health through key pillars of resilience like diet, microbiome, and the epithelial barrier.

generations, justice and equity in the allocation of resources and life within ecological limits.[169] Meeting the targets would require fast and far-reaching transitions in energy, land, urban, and infrastructure (including transportation and buildings), and industrial systems,[2] and health professionals have a leadership role to play on that. They can support in the development of effective adaptation to reduce the health risks of climate change,[170] endorse healthy behaviors and strategies with low environmental impact, support intersectoral activity to reduce the environmental footprint of society in general, and the health system in particular.[171]

ACKNOWLEDGMENTS

The authors thank Sara Minelli, Alex Zvoleff, David Lopez-Carr, Narcisa Principe, Kevin Mwenda, and Kerry Mapes for input on land degradation and health.

CONFLICT OF INTEREST

Dr. Jutel has received grants or contracts from Stallergenesm Allergopharma, GSK, Genentech, Takeda, and Chiesi; consulting fees from Stallergenesm Allergopharma, and Chiesi; Payment or honoraria from Stallergenesm Allergopharma, and ALK; Participated on DSMB or Advisory board for Stallergenesm and Allergopharma; president of EAACI; Unrelated to this publication, Dr. Thiel is a paid consultant for Becton Dickenson, a paid advisor to The Sean N. Parker Center for Allergy and Asthma Research at Stanford University, an unpaid member of the Mass General Center for Climate and Health advisory board, a member of the advisory board for Zabble, Inc. for which she has received stock options and a paid consultant for the Stryker Corporation and received honoraria for lectures hosted by 3 M. All other authors indicate no conflict of interest. Dr Cezmi Akdis reports research grants from Allergopharma, Idorsia, Swiss National Science Foundation, Christine Kühne-Center for Allergy Research and Education, European Commission's Horison's 2020 Framework Programme "Cure," Novartis Research Institutes, Astra Zeneca, research grants and advisory board from Glaxo Smith-Kline, Sanofi/Regeneron, Scibase, Novartis, and is Editor-in-Chief of Allergy. Dr. Agache is Associate Editor of Allergy. All other authors report no COI.

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