ANNUAL REVIEWS

Annual Review of Nutrition

Climate Change, Extreme Weather Events, Food Security, and Nutrition: Evolving Relationships and Critical Challenges

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Annu. Rev. Nutr. 2025. 45:2.1–2.26

The *Annual Review of Nutrition* is online at nutr.annualreviews.org

https://doi.org/10.1146/annurev-nutr-111324-111252

Keywords

climate change, climate variability, extreme weather events, food security, nutrition, equity

Abstract

Climate change, also known as global warming, poses significant challenges for both the planet and humanity. With further warming, every region across the world is projected to increasingly experience concurrent and multiple changes in climate, compounding overall risk. Long-term climate change and near-term extreme weather events have multiple negative effects on food security, diets, and nutrition via complex, multidirectional pathways through food, health, water, and social protection systems. However, measuring climate-attributable malnutrition impacts, especially among the most vulnerable populations, remains challenging. Changes in climate across a range of geographies have been modeled, projected, and observed showing detrimental associations with dietary and nutrition outcomes, particularly undernutrition. Many of these undernourished populations are climate vulnerable due to a variety of determinants challenging their ability to adapt to impending risks. While nutrition integration within climate adaptation

plans have lagged, there is momentum for robust collaboration between climate and nutrition communities to fill data gaps that are critical for joint decision-making.

Contents

1. THE PATHWAYS OF CLIMATE CHANGE ON FOOD, WATER, AND HEALTH SYSTEMS

1.1. Introduction

Throughout the past 100 years, the global rise in greenhouse gas (GHG) emissions can be primarily attributed to human activities. These activities include increased consumption of energy, food, and water; greater demand for transportation and infrastructure; changes in land-use patterns and deforestation; and a heavy reliance on fossil fuel combustion (120). Atmospheric concentrations of these heat-trapping gasses have caused the planet's average surface temperature to increase 1.1°C since the late 1800s (59, 92) and expedited changes in earth systems, including ocean and biosphere alterations (79).

Human-induced climate change also alters weather patterns and increases the risk of extreme events, causing widespread adverse risks, impacts, losses, and damages to both human society and nature (79). While climate variability and extreme weather events have been a historical constant and more extreme in some places than others, the unpredictability, frequency, and severity of these events have significantly increased (67). The motivation for this review is that climate change and variability is causing threatening and devastating effects on human food security and adverse nutrition and health outcomes that we are now only beginning to understand (29, 63, 74, 89, 105, 122).

If we remain on a high-emissions, business-as-usual trajectory, climate extremes and long-term climate change impacts, such as irreversible changes to crucial earth systems, will continue to be steered by human activity, resulting in devastating outcomes for humans and the planet (96, 120). While the scenario is not optimistic, the United Nations Framework Convention on Climate Change, also known as the Paris Agreement, signed by all countries in 2015, aims to keep global temperatures below 2°C above preindustrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C by the end of the century. Despite global efforts, current trends indicate that the world is falling short of meeting the Paris Agreement's goals (120).

In this review, we delve into the relationship between climate variability and change and extreme weather events and their associations with diet and nutrition outcomes. We provide some grounding in the pathways in which climate impacts these outcomes, the current state of malnutrition, and the differences and measurement of climate variability and change. We elucidate the relationship between climate and diet and nutrition outcomes, the challenges for poorly nourished populations to adapt, and the ways to ensure populations can be more resilient. We end with research gaps and other challenges related to climate and nutrition relationships.

1.2. The Influence of Climate Change and Climate-Related Extreme Events on Food, Water, and Health Systems

Due to rising GHG emissions, climate change and climate-related extreme events influence food security, diets, and nutrition outcomes through various pathways, mainly food, water, health, and social protection systems (**Figure 1**). Malnutrition is multicausal, and these systems, at minimum, must function effectively and consistently to ensure optimal nutrition (37). There is potential for climate-related shocks to alter these systems (as well as other systems such as educational and economic/financial), which could have devastating consequences for dietary and nutrition outcomes (41). The world has witnessed simultaneous impacts to systems with other nonclimate-related shocks, such as the COVID-19 pandemic (18).

Increased atmospheric concentrations of GHGs, warming temperatures, rising sea levels, and increased extreme weather events all have both direct and indirect ramifications on food systems, altering the quantity, quality, transport, and loss of food (39, 56, 93, 116, 122). Some crops and animals may benefit or be less altered or harmed by warmer temperatures, depending on the optimal latitudes of where crops are grown, as well as the CO_2 fertilization effects on different plants species—C3 (95% of all plants such as rice, wheat, and potato) and C4 (the other 5% such as corn, sorghum, sugarcane, and millet) crops (13, 71, 94). Over the long term, however, the effects of climate change on agriculture are likely to have a deleterious effect on certain crops

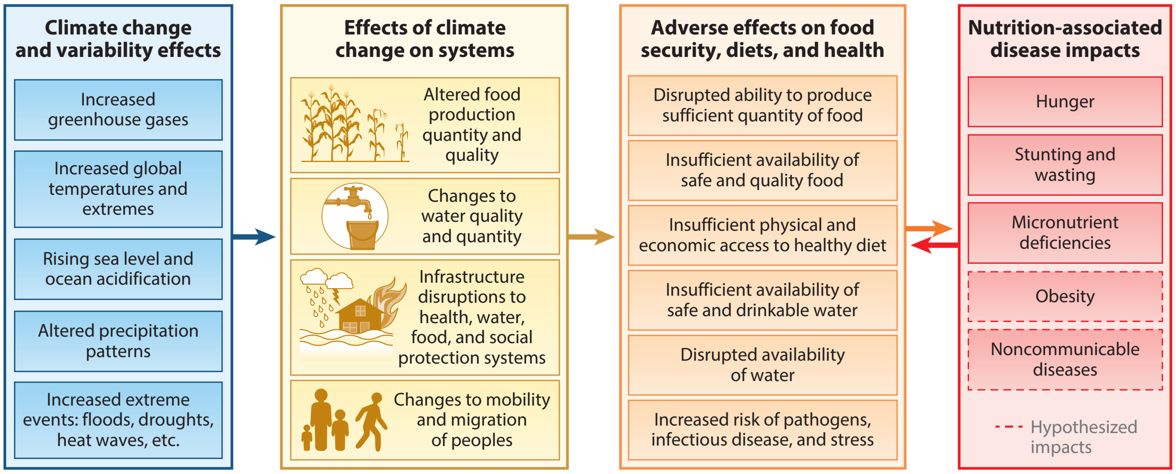

Figure 1

Effects of climate change and extreme weather events on various systems that influence nutrition outcomes. Figure adapted from Reference 41.

(e.g., maize) and the availability of a diverse set of food crops across food supplies (62, 98). These larger changes in climate, along with extreme weather events, impact the yields of food harvested from farms and across supply chains, as well as increase food loss (particularly of perishable foods such as fruits, vegetables, and animal-sourced foods), which can exacerbate food inflation and prices, as well as reduce the access and affordability of healthy diets, particularly for low-income and vulnerable populations (60, 61). These disruptions to food systems can worsen food insecurity, diet, and nutrition outcomes (38, 40).

Climate change also affects water systems and has knock-on effects for the functioning of both food and health systems, resulting in adverse nutrition outcomes. As temperatures rise, extreme weather events, such as storms, typhoons, and droughts, change water accessibility, availability, and quality, impacting the ability to grow food and ensure safe drinking water (25). Extreme water-related weather events—such as continuous droughts and severe floods—can spur significant water scarcity and affect water quality, as pollutants such as sediments are mixed with water sources during floods (162). Regarding food production, water scarcity can strain the ability to irrigate water-intensive crops (85). As sea levels rise, there is a risk of increased salinization of freshwater supplies (137). In regions struggling with water storage capacity and the continued demand for water, forced constraints or the use of unsuitable water could have deleterious outcomes for human health and health systems (12). Warmer water also creates a more hospitable environment for the growth of bacteria, increasing waterborne diseases such as diarrhea, giardiasis, dysentery, typhoid fever, *Escherichia coli* infection, and salmonellosis (99, 109).

Increased exposure to infectious disease burden exacerbates the consequences and severity of malnutrition, putting additional strain on health systems and care (108). In addition, with destructive extreme events and disasters, health facility infrastructure, staff, supplies, and operations can be damaged or decimated, making it all the more challenging to prevent, treat, and care for those who are malnourished or ill from infectious diseases, compounding the impacts (34). Already, malnutrition is the underlying cause of 45% of infectious disease burden among young children (36). If social protection systems—safety nets that provide food assistance and aid, school meals, cash, etc.—are impaired, they have significant impacts through food, water, and health system pathways, further exacerbating poor nutrition outcomes.

2. THE STATE OF THE WORLD'S FOOD SECURITY, NUTRITION OUTCOMES, AND DIETS

2.1. Food Insecurity, Hunger, and Undernutrition

While various factors influence food security, according to the Food and Agriculture Organization (FAO), climate change is one of the leading factors responsible for 733 million people (9%) who are considered undernourished or hungry (141). After a decade of decline, over the last several years, hunger has increased, mainly due to climate change, wars, and the economic downturn following the COVID-19 pandemic (44). Some hotspots of deep hunger and famine still exist, particularly in places of protracted crisis and conflict, exacerbating vulnerability to climate change. For example, in Africa, undernourishment has increased by 22.4% over the last 5 years, with 300 million people suffering from hunger (141).

In addition, many children continue to suffer from undernutrition, with 148 million children (23%) under the age of 5 classified as stunted or chronically undernourished and 45 million children (7%) under the age of 5 classified as wasted or acutely undernourished (156). While these prevalences have declined alongside increasing levels of exclusive breastfeeding in the last decade, progress in ending childhood undernutrition has been slow to achieve the Sustainable Development Goal (SDG) 2 to end undernutrition by 2030. Almost every country in the world is considered off track in reaching the SDG to end anemia in women of reproductive age, with a global prevalence of 29.9%. Currently, the least developed countries suffer from the highest prevalence (40%) of anemia among women (141). An estimated two billion people, or approximately 30% of the global population, lack one or more essential micronutrients. More than half of children under the age of 5 are deficient in at least one micronutrient such as iron, zinc, or vitamin A. Additionally, more than two-thirds of nonpregnant women of reproductive age lack at least one micronutrient, such as iron, zinc, or folate (133).

2.2. Overweight, Obesity, and Noncommunicable Diseases

Opposite, but sometimes related, to these states of undernutrition, 37 million children (5.5%) under the age of 5 are overweight (156). As populations age, the situation has worsened. Currently, 2.5 billion adults are overweight and obese (154). Overweight and obesity are risk factors for numerous noncommunicable diseases (NCDs), including cardiovascular diseases (heart disease and stroke), diabetes, chronic respiratory diseases, and some forms of cancer (48, 102). NCDs now disproportionately impact people living in low- and middle-income countries (LMICs). Modeled estimates suggest that 75% of global NCD deaths (31.4 million) occur in LMICs (48).

2.3. Multiple Burdens of Malnutrition

Many regions, countries, and communities suffer from what has been coined a double (or triple) burden of malnutrition (DBM)—in which individuals and societies have more than one form of malnutrition. A child can be stunted, overweight, and have multiple micronutrient deficiencies at the same time. There is an accumulation of evidence of co-occurrence of stunting and overweight in children in countries such as Peru, Ethiopia, and Ghana (42, 126, 150, 160), as well as co-occurrence of stunting and wasting with anemia (32) and stunting and wasting in children (78).

Several studies show that many countries are struggling with a DBM characterized by the simultaneous presence of childhood undernutrition (e.g., stunting, wasting, and micronutrient deficiencies) alongside adult overweight, obesity, or diet-related NCDs (113). This phenomenon can occur at the population, household, or individual level. The DBM has shifted more prominently into LMICs over the past few decades. This shift has occurred primarily since the 1990s and has accelerated in the 2000s and 2010s. Indonesia has emerged as the largest country experiencing severe levels of the DBM. There are several reasons for this rise in burden, including early life undernutrition that predisposes obesity and NCD burdens into adulthood (152), poverty and food insecurity coexisting in obesogenic environments, and rapid demographic and nutrition transitions due to changes in physical activity and dietary changes that come with economic and technology growth, urbanization, globalization, modernization, and industrialization (112).

2.4. Dietary Quality and Its Impacts on Nutrition and Health

The diversity and quality of diets that people can physically, economically, and socially access contribute to optimal nutrition, and, often, this access is inequitable and challenging for many people around the world (129). Currently, 2.8 billion (35%) of the world's population cannot afford a healthy diet—defined as a diet that meets basic nutrient needs and is health protective (53). In addition, many populations cannot access diverse foods—82% (34 out of 41 countries that account for two-thirds of the world's population) do not consume the five healthy food groups (fruits, vegetables, nuts, legumes, and whole grains) daily (53). While it is known that the low availability of diverse diets has deleterious effects on micronutrient intake and their associated outcomes (14), the evidence of dietary diversity, using existing measures/indicators, on other health outcomes is less clear with mixed results (151). Yet even with the wide range of dietary patterns consumed around the world, some evidence suggests that certain principles of healthy diets (low processing, wide variety, and high proportion of plant-based foods) can be health protective (72).

Instead, most of the world can afford what are called ultraprocessed foods. These foods are high in added sugars, sodium, and unhealthy fats and contain industrialized additives and chemicals (91). These foods—which are cheap, easily traded, can be stored for long periods, and are highly palatable (8, 33)—have been associated with harmful health outcomes, including all-cause mortality, heart disease–related mortality, diabetes, and risk of overweight and obesity (77, 107). Modeling estimates suggest that 11 million deaths (20%) annually are attributed to poor diets around the world (1).

3. DEFINING AND UNDERSTANDING NEAR- AND LONG-TERM CHANGES IN CLIMATE

3.1. Different Changes, Different Measures

The changing climate can be measured and described in various ways, from near-term weather predictions (days, weeks, and months) to seasonal interannual predictions (seasons, years) to long-term climate change projections (decades, centuries) (143). Near-term weather and seasonal predictions are measured and projected using weather stations, satellites, and buoy data to provide information on temperature, precipitation, wind, currents, humidity, and other factors that are used to identify trends, patterns, and near-term and seasonal extremes. These data types are critical to enabling multiyear to decadal climate predictions and regionally specific information. They are utilized by a broad range of communities and decision-makers engaged in near-term planning activities across sectors (e.g., agriculture, urban planning, health).

To understand how the climate has changed over longer periods of time, such as centuries, scientists rely on measuring atmospheric GHG concentrations of carbon dioxide (CO_2) and surface temperature averages and changes and deviations (anomalies from the norm) over time. They also use other measures as indicators of climate change, such as sea-level rise, arctic sea ice extent, and glacial retreat. Future climate change is projected through global climate models (GCMs) that simulate interactions between the atmosphere, oceans, land surface, and ice; these models run scenarios to project how the climate may change under various societal pathways.

The studies presented in this review (in Section 4) on the relationship of near-term events are not modeled or projected and instead are events that have occurred with an understanding of how they relate to diet and nutrition outcomes, whereas the studies presented on the relationship of long-term events are modeled with projections looking into the future—often, from 2050 to 2100—of how climate change could impact diet and nutrition outcomes.

3.2. Long-Term Climate Change

The long-term climate change that the world is witnessing is mainly due to a rise in GHG emissions—the major forms being CO_2, methane (CH_4), and nitrous oxide (N_2O)—in the atmosphere. CO_2 accumulates, whereas CH_4 and N_2O, while potent, are relatively short-lived gasses, but their heating potential is more significant than that of CO_2. Put simply, these GHGs warm up the planet. The increases in GHG emissions—starting around the industrial revolution at a time when people's incomes and consumption increased—have not evaporated and do not diminish easily and instead have accumulated in the atmosphere and the permafrost.

This accumulation and concentration of GHGs can have direct and indirect spillover and knock-on effects, causing massive declines in biodiversity survival, accelerating coral reef bleaching and ocean acidification, and increasing environmental pollution. Some of these systems—coral reefs, thawing of the permafrost, collapse and breakups of Greenland and Antarctic ice masses, and loss of rainforests—are reaching tipping points, which could signal a point of no return and direct humanity down a perilous path (5). Many of these tipping points are interrelated, and some are likely to trigger others, potentially leading to cascades of irreversible changes to our climate.

Some of these shifts involve what has been termed planetary boundaries—nine critical processes that could destabilize the processes that make our world livable. The boundaries are climate change, biodiversity loss and extinction, stratospheric ozone depletion, ocean acidification, altered phosphorus and nitrogen biogeochemical flows that pollute air and water, land-use changes such as deforestation, depletion of freshwater use, atmospheric aerosol loading, and toxic substance introductions (119). If these boundaries are crossed, it is less likely that the world's population will be able to live in what is termed a safe operating space, with irreversible environmental changes that are detrimental to human nutrition, health, and well-being (121). To date, six of the nine boundaries have been transgressed, and climate change is a central driver in crossing several of these boundaries, creating complex feedback loops and reinforcing consequences for earth systems. Crossing the planetary boundaries could also increase the risk of reaching tipping points (76).

3.3. Near-Term Extreme Weather Events and Climate Variability

Extreme weather events are considered the outliers of natural weather or climate variability and fluctuation. While natural climate variability still occurs, advances in extreme event attribution science allow researchers to link specific extreme events more confidently to human-caused climate change (96). For example, 71% of 504 extreme weather events studied were found to be made more likely or more severe by human-caused climate change (111). Climate change significantly amplifies the frequency, intensity, duration, and spatial extent patterns of extreme weather events (26), magnifying its impact on these events (115). Climate change also increases the likelihood of compound extreme events, where multiple hazards co-occur or occur in close succession, amplifying feedback effects (34).

These patterns of climate-related events—including heat waves, hurricanes, storm surges, flooding, mud- and landslides, prolonged droughts, wildfires, and rising sea levels—result in an increased severity of disasters that economically and physically impact communities across wide-ranging geographies around the world (70). For example, the summer of 2023 was the hottest summer on record since 1880, with June, July, and August averaging 0.23°C warmer than any other summer, intensifying heat-related human morbidity and mortality (95). Other disasters are becoming more normalized. In 2023, the 10 countries most affected by floods and droughts experienced a dramatic increase in the number of disasters, from 24 in 2013 to 656 in 2023 (139). Global mean sea levels have risen 5 in. over the past 50 years, exacerbating coastal flooding (84).

Despite instances of extreme events, climate variability affects food security and food systems (143). For rain-fed agriculture, not knowing when the rains are coming for planting crops, whether it will rain enough, or whether excessive rains will spoil the harvest is becoming increasingly common. Similarly, grazers and pastoralists living in places with inherent climate variability face greater struggles to manage their livestock and experience significant animal losses or income, in detriment to their livelihoods (66). No geographic areas are immune to climate extremes, particularly those considered large breadbasket countries. For example, the western part of the United States, where horticulture and livestock are significant industries, has been experiencing a megadrought, with climate change estimated to be responsible for 42% of soil moisture deficits in the region since 2000, causing more severe droughts (153). Another significant food producer, Brazil, has suffered a significant drought causing the Amazon Basin to reach its lowest levels on record.

Recent research suggests that climate change is leading to more frequent and intense El Niño and La Niña events, which are naturally occurring phases driven by sea-surface temperatures in the tropical Pacific Ocean, known as the El Niño–Southern Oscillation (ENSO) (21). Intense ENSO episodes have occurred more frequently (10% increase) than average since 1965, the postindustrial anthropogenic period (158). The increased severity of ENSO events can lead to drier or wetter regions, increase the severity and likelihood of hurricanes and atmospheric rivers, and exacerbate droughts, floods, and heat waves. These events can, in turn, create unpredictable cropping seasons and alter transmission patterns of diseases such as malaria (20, 23, 24), which have downstream impacts on nutrition outcomes.

4. THE EFFECTS OF CLIMATE CHANGE AND EXTREME WEATHER EVENTS ON FOOD SECURITY, DIETS, AND NUTRITION OUTCOMES

4.1. Measuring the Connections Between Climate, Food Security, Diets, and Nutrition

Many types of empirical methods and models are used to understand how climate change and extreme weather events are impacting and will impact food security, diet, and nutrition outcomes. First, diverse sets of data demonstrate how the climate is changing and becoming both more severe and less predictable. Weather forecasting data (rainfall, temperature, etc.) describe a more detailed picture of expected daily, weekly, or subseasonal conditions. Longer-term GCMs use probabilistic projections to understand how climate will change under different pathways and scenarios (see the sidebar titled Scenarios of the Future: Making Sense of the Shared Socioeconomic and Representative Concentration Pathways for Nutrition Outcomes). Dozens of scientific institutions develop climate models, and the Coupled Model Intercomparison Project (28) brings these models together to align, validate, and improve their interpretations.

Second, the data and indicators used to capture food security and nutrition outcomes are often collected and analyzed at different temporal and spatial scales, geographic heterogeneity, and statistical power. There are specific measures of hunger (frequently equated with food insecurity) and undernutrition (such as the prevalence of undernourishment and food insecurity experience scales) (80), dietary intake (such as consumption recall surveys), and nutritional outcome measures [such as low birth weight, stunting and wasting in early childhood, anemia, micronutrient

SCENARIOS OF THE FUTURE: MAKING SENSE OF THE SHARED SOCIOECONOMIC AND REPRESENTATIVE CONCENTRATION PATHWAYS FOR NUTRITION OUTCOMES

Climate and energy modelers and economists developed two sets of complementary pathways—the Representative Concentration Pathways (RCPs) and the Shared Socioeconomic Pathways (SSPs)—to explore and explain how the world might change over the rest of the 21st century. Grasping SSPs and RCPs is essential for comprehending the intricate connections between climate change and nutrition outcomes. By recognizing how different SSPs and RCPs can lead to varying outcomes in food security and health, targeted interventions can be designed that promote sustainable agricultural practices and equitable access to nutritious foods.

The RCPs describe different levels of GHG emissions and radiative forcings (the difference between incoming and outgoing energy in the earth's climate). There are four RCPs: 2.6, 4.5, 6.0, and 8.5 W/m^2, in which an RCP of 2.6 corresponds to lower GHG emission concentrations with less severe climate change and an RCP of 8.5 corresponds to higher GHG emission concentrations and more severe climate change. The RCPs set pathways for GHG concentrations and, effectively, the warming that could occur by the end of the century.

The SSPs (103) were developed as a way of proposing feasible global futures with lower or greater economic growth and mitigation ambition. They included a world of sustainability-focused growth and equality (SSP1); a middle-of-the-road world where trends broadly follow their historical patterns (SSP2); a fragmented world of resurgent nationalism (SSP3); a world of ever-increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5). These five pathways feature multiple baselines in which the world may evolve in the absence of climate policy and how different levels of climate change mitigation could be achieved when the mitigation targets of RCPs are combined with the SSPs.

deficiencies, and body mass index (BMI)] that are all collected differently. While bringing together vastly different types of data, variables, statistical methods, and models to understand the relationship between climate and food security, diets, and nutritional outcomes is complex, many studies vary in quality, validity, interpretations, and assumptions of associations, causalities, and impacts (64).

4.2. Long-Term Climate Change Projections on Hunger, Diet, and Nutrition Outcomes

Long-term climate change will continue to influence hunger, diets, and malnutrition in the immediate future; however, results vary in their pathways and impacts, depending on the model used, the input variables, and the outcome(s) measured. Below is a summary of some studies examining the long-term projections on hunger and food insecurity, diets, and nutrition outcomes.

Using a middle-of-the-road SSP2 projection to 2050 (46), the International Food Policy Research Institute's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) shows that the share of the population at risk of hunger (equivalent to FAO's prevalence of undernourishment) will decrease in most regions, except the Middle East and North Africa. Much of this reduction is attributed to improvements in agriculture such as increasing yields of cereal crops and income growth across the world (97, 122, 135). Using an RCP projection of 8.5 that corresponds to higher GHG emissions, another study found that 440 million more people are projected to be at risk of hunger by 2050 (61). The authors attributed this increase to food production losses. Using various pathways of RCP4.5–SSP2, RCP8.5–SPP2, and RCP8.5–SSP3, an additional research group showed that there could be a 6%, 10%, and 14% decrease, respectively, in global food production by 2050, resulting in an increased number of people suffering

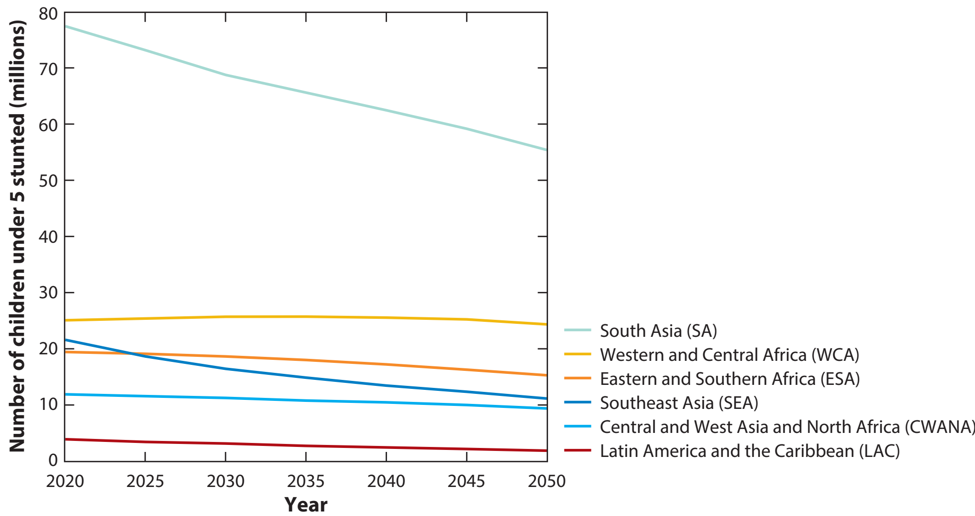

Figure 2

Projections of the number of stunted children by region for the years 2020–2050 using a reference scenario. The reference scenario is based on middle-of-the-road assumptions about changes in population and income along with rapid climate change. The population and income assumptions are based on the Intergovernmental Panel on Climate Change (IPCC)'s Shared Socioeconomic Pathway 2 (SSP2), in which the global population will reach 9.2 billion in 2050 and the average income will reach \$25,000 per person. The climate change assumptions are based on the IPCC's Representative Concentration Pathway 8.5 (RCP8.5) and the Hadley Centre Global Environmental Model (HadGEM) general circulation model. Investments in the reference scenario are based on historical trends and expert opinions about future changes. Extended data from International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) version 3.4 (122).

from severe food insecurity by 556 million, 935 million, and 1.36 billion, respectively, as compared to the 2020 model baseline (74). These production losses will not always be geographically isolated. Simultaneous breadbasket failures could increase local and global food prices and undermine food security, particularly in import-dependent low-income regions (63). Using the Food Insecurity Experience Scale (FIES) as the outcome measure of food security, one model suggests that for every 1°C of temperature anomaly, moderate and severe FIES increases by 2.14%, with the highest impacts in Africa (30).

While most modeling studies have examined food insecurity and longer-term hunger, several modeling exercises have examined nutrition outcomes including stunting, micronutrient deficiencies, and anemia. The IMPACT study, using the SSP2 projection to 2050, found that undernutrition (measured as stunting) among children under the age of 5 could vary depending on the timing and region (**Figure 2**). An additional study created two scenarios: one of increasing poverty and climate change and another of increasing prosperity and lower climate change. They found that in the absence of climate change, 110 million children aged under 5 could be stunted in 2030 under the poverty scenario in comparison with 83 million under the prosperity scenario. They attributed climate change to >1 million stunting under the poverty/high climate change scenario and 570,000 under the prosperity/low climate change scenario (87).

Another modeling exercise, using the SSP2 pathway, examined how climate change would modify disability-adjusted life years (DALYs) attributed to micronutrient deficiencies (measured as iodine, iron, zinc, and vitamin A deficiencies, associated with the same per-person kilocalorie availability of major food types) to 2050. The total burden of DALYs due to micronutrient deficiencies is projected to increase globally by 30 million, or a 10% increase by 2050 relative to 2010 (135). A complementary paper shows that climate change will continue to slow projected reductions in hunger in Africa specifically—increasing the number of people at risk of hunger in 2030 by 16 million compared to a scenario without climate change (88). Modeled research also shows an association between ambient temperature and childhood anemia (not specifically iron-deficient anemia) prevalence across 26 sub-Saharan African countries. Under a high-emission climate scenario (SSP5–8.5), excess childhood anemia cases attributable to climate change could increase by 7,597 per 100,000 person-years by the 2090s compared to the 1985–2014 baseline, with considerable regional disparities observed (161).

In addition to examining nutrition outcomes, a model comparing 2010 to 2050 estimated that more than 500,000 additional deaths would occur in 2050 due to climate-related changes to dietary patterns. Most of the deaths are attributed to decreases in food intake and decreases in fruits and vegetable intake (132). This modeling exercise provides some potential mechanisms for the other modeling studies mentioned, indicating that micronutrient and nutritional deficiencies could rise with more climate change. All these models and projections suggest that if no action is taken on climate change in the present time, and if agriculture technologies and income growth do not keep up with dietary demands, food insecurity and child malnutrition could worsen with global warming over the next 50 years.

4.3. Near-Term Extreme Temperature Effects on Food Security, Diets, and Nutrition Outcomes

An emerging area of research on temperature extremes—temperature variations above (extreme heat) or below (extreme cold) normal conditions (see the sidebar titled What Are Heat and Cold Waves and How Do They Affect Food Security and Nutrition?)—suggests a relationship with food security, diets, nutrition, and NCD outcomes. The evidence on how these shorter-lived temperature extremes affect these outcomes are mainly associations with less evidence of causality.

One study, using household surveys spanning 150 countries to assess moderate and severe food insecurity experiences, found an association between episodic hot weeks and a higher risk of food insecurity experience as measured by FIES. The households most affected were those of lower socioeconomic status and those working in agriculture (75). Thus, while longer-term projections show potential risks to food insecurity out to 2050, current extreme heat–related events that last a few days to a week can also put households and individuals at risk due to heat-related strain, limiting the ability for people to earn income.

WHAT ARE HEAT AND COLD WAVES AND HOW DO THEY AFFECT FOOD SECURITY AND NUTRITION?

Recognizing the connection between temperature extremes and nutrition can inform adaptive strategies to improve outcomes. It is thought that heat and cold waves impact crop yields and quality, dietary intake, and physiological stress responses, as well as create implications for public health (i.e., increased mortality rates during heat waves can be higher for nutritionally vulnerable populations).

Extreme heat waves are considered "marked warming of the air, or the invasion of very warm air, over a large area; it usually lasts from a few days to a few weeks" (157, p. 5), whereas extreme cold waves are considered "a meteorological event generally characterized by a sharp drop in air temperature near the Earth's surface, leading to extremely low values that can be associated with hazardous weather, such as frost and icing" (157, p. 5).

Several studies have begun to understand how heat is associated with child growth starting at conception. A longitudinal study in The Gambia observed that with each 1°C increase in mean daily temperature exposure to pregnant mothers during their first trimester, there was a reduction in weight-for-gestational age z-score at birth. When tracking these children up to the first 2 years of life, the authors found that heat stress affected infants aged 6–18 months, with reductions in weight-for-height z-scores (wasting) and a marginal increase in height-for-age z-scores (HAZ) (stunting) (17). There is also evidence to suggest a negative association between maximal daily temperature in the first trimester and z-scores of birth length and head circumference of neonates, as studied in Pakistan (130).

Several studies to varying degrees of quality have shown associations between postnatal child growth (as measured by stunting and wasting) and extreme heat. One such study showed that extreme heat exposure in West Africa increases the prevalence of both chronic (stunting) and acute (wasting) undernutrition. A 2°C rise in temperature increases the prevalence of stunting by 7.4% (16). Another global review found a strong correlation between stunting and extreme heat looking across many countries and geographies (19).

Further research used Demographic and Health Survey (DHS) anthropometric data of 192,000 children surveyed between 1993 and 2012 from 30 countries in sub-Saharan Africa and paired with historical spatiotemporal-varying climate data. The authors found a strong negative relationship between child wasting and average temperature across regions and multiple timescales, with rural areas being the most impacted as compared to urban areas (9). It is thought that physical isolation, higher poverty rates, and dependence on limited geographic and economic diversity are underlying drivers. An additional study found an association between high ambient temperatures and wasting over timescales in sub-Saharan Africa. These associations were more pronounced in rural areas, driven by agriculture productivity losses as compared to urban areas (9). An additional investigation in sub-Saharan Africa used anthropometric DHS data of children aged 0–5 years from 52 countries ($n = 656{,}107$ children) over the time span of 2003–2016 and linked these survey data with remotely sensed monthly mean daytime land surface temperature from 2000–2016. The researchers found that monthly mean daytime land surface temperatures above 35°C were associated with increases in the odds of wasting and of concurrent stunting with wasting (148).

Examining the relationship between near-term climate events and diets has been less studied, and empirical evidence on how temperature changes affect dietary quality and diversity is limited. A scoping study found that 89% of published studies exploring climate shocks (what they termed environmental variability) across food supplies were biased toward production, and only 15% of studies focused on dietary intake (31). That said, some studies are emerging to understand the relationship related to heat and dietary diversity.

In a study conducted by Niles et al. (100), the investigators linked DHS data from 107,000 children under the age of 5 in 19 LMICs across six regions with 30 years of geocoded temperature and precipitation data. They found that reductions in dietary diversity were associated with higher long-term average temperatures. In five out of six regions, higher temperature (either long-term averages or short-term anomalies) had a consistent negative relationship with child dietary diversity. Further research in India, specifically, used DHS surveys from 2015–2016 and 2019–2020 combined with geospatial data. The investigators found that high temperatures, particularly larger shifts in temperature, were associated with decreased dietary diversity among children from 6 months to 2 years of life. Their analysis suggests that some of the pathways that lead to this decrease in dietary diversity include low road density and poor market access; however, more empirical validation is necessary to understand the mechanisms and drivers (114).

As for NCD outcomes, there is less research published. An important study found that a 1°C temperature rise has been associated with a significant increase in morbidity due to arrhythmias, cardiac arrest, and coronary heart disease. More specifically, this heat exposure leads to an elevated risk of morbidity and mortality for women, people 65 years and older, individuals living in tropical climates, and those in LMICs (86).

Very little information exists on how cold waves associate with or affect nutrition outcomes. One meta-analysis showed that cold spells are associated with increased all-cause mortality and cardiovascular disease, and associations are more substantial for the elderly (125).

4.4. Near-Term Precipitation Pattern Effects (Droughts and Flooding) on Food Security, Diets, and Nutrition Outcomes

Due to increases in GHG emissions and global temperatures over the past century, precipitation patterns are changing and leading to water scarcity and hazard weather events such as droughts and floods. These events are becoming more frequent and more intense (68). Droughts are defined as a deficiency of precipitation over an extended period of time resulting in hydrological imbalances and water shortages. Some examples include climate change altering evaporation patterns, snowpack accumulation, and soil moisture. Extreme heavy precipitation events occur when the amount of snow or rain substantially exceeds what is normal and can result in flooding—the overflowing of the normal confines of a body of water over areas not normally submerged. These outlier phenomena work through multiple pathways and systems, including food, water, environment, and health, ultimately impacting nutrition outcomes (57).

While a significant amount of work has synthesized evidence examining the associations of drought on malnutrition piecing different datasets together, particularly in Africa (6, 7, 35, 69) and in LMIC contexts (15), a recent systematic review and meta-analysis evaluated the effects of droughts and floods on malnutrition outcomes of children and adults. They found that there was a strong positive relationship between climate-related precipitation events and some form of malnutrition depending on the location, age, gender, event, and timing of the study. The comprehensive meta-analysis found that drought was significantly associated with childhood wasting (83).

An additional study used 580,000 observations of children from 53 countries starting in 1990 using DHS and a derived Standardized Precipitation–Evapotranspiration Index (SPEI) from climatological data to understand better how precipitation anomalies are related to increased child stunting. After controlling for the effects of individual, household, annual, and population factors, they found that precipitation deviations from long-term norms such as minor to severe droughts or severely wet periods were associated with worse child malnutrition, as measured by child HAZ. Across a 24-month SPEI, the researchers discovered the points at which low and high rainfall levels—the extremes—are associated with worsened child nutrition outcomes. Higher-than-average rainfall was not related to lower HAZ unless it was extreme, while lower-than-average rainfall was related to lower HAZ even at minor levels, yielding a large number of children in a wide variety of geographical contexts more impacted by drought than excessively wet periods. They also established that droughts appeared to be associated with child malnutrition where the drought occurred, whereas excess rainfall, such as flooding and landslides, can be caused by rainfall far from the location of a child nutrition observation (27).

Flooding is thought to influence food security, diets, and nutrition through food, water, and health pathways, potentially impacting both food availability and access and increasing infectious disease burden through contaminated water systems. Modeling studies suggest that flooding can degrade food security over time in sub-Saharan Africa (118). Interestingly, the Niles et al. (100) study, referred to earlier in this review, found that higher precipitation correlates with improved dietary diversity across 19 LMICs. This makes some sense in that drier conditions could negatively impact agriculture productivity across a range of crops, making food access more challenging, but it conflicts with other study findings on floods and overall food security. Other studies have suggested that flooding may have some weak associations with stunting in LMICs (2) and, more specifically, sub-Saharan Africa (35, 134), with an increased risk of infectious disease burden, which could be associated with poor malnutrition outcomes. However, much more research needs to be done. According to Belesova and colleagues (15), the evidence base attributing drought to child malnutrition outcomes (i.e., wasting and stunting) is less clear due to the design quality of epidemiological research, bias, heterogeneity of geographic contexts, lack of compatibility, and quality control.

ENSO is a contributor to climate variability impacting many sectors (49, 159), particularly agriculture (123), due to its influence in the tropics shifting to higher temperatures and precipitation changes in which some areas get drier and others wetter (55). One study examined ENSO variation and its association with childhood underweight (not the optimal proxy for measuring child malnutrition). Capturing countries with local climates teleconnected to ENSO, where DHS surveys exist, the investigators analyzed this association in 1.3 million children aged 0–4 years, representing 48% of the world's under-age-5 population, from 1986 to 2018. They found that a warmer ENSO was correlated with an increase in the prevalence of underweight but no statistically significant associations with wasting and stunting (4). Thus, these data are less conclusive, as underweight as an indicator is influenced by various factors and does not capture the full impact of early-life nutrition on long-term health outcomes as does stunting or wasting.

4.5. Compounding and Cascading Risks for Food Security and Nutrition Outcomes

"Extreme weather and climate events and their impacts can occur in complex combinations, an interaction shaped by physical drivers and societal forces" (117, p. 611). Often termed compounded events, such occurrences comprise multiple events, risks, and hazards that can be temporal, spatial, and concurring. They can also be nonlinear, interacting, and cascading, influencing many forms of vulnerability, adaptation, and potential migration (110, 140). Very little has been researched on understanding the temporal and spatial nature of compounding events on nutrition outcomes, and to do so is complex. One study using linear regression analysis found that high temperatures in sub-Saharan Africa compounded with low precipitation were associated with reduced child weight and wasting (142). What is less clear in the literature is how compounded events impact the pathways that influence nutrition outcomes. For example, compounded events likely influence the functioning and efficiency of food systems (90). Compound climate risks have been shown to have detrimental consequences for aquatic food systems, putting people at increased risk of micronutrient and nutritional deficiencies (145).

4.6. The Challenges of Linking Climate Change with Overweight and Obesity

The links between obesity and climate change are still highly unexplored. A seminal *Lancet* Commission report published in 2019 (136) explored the concept of a global syndemic involving obesity, undernutrition, and climate change. In this paper, the Commissioners argue that obesity and climate change share similar systemic and institutional drivers, including food and transportation systems, urban design, and land use change. These drivers are altered by both obesity and climate change. They also argue that obesity and climate change have a bidirectional relationship in that climate change affects obesity by reducing food security and crop yields, increasing reliance on processed foods; extreme weather events disrupt food supplies and physical activity patterns; and rising temperatures may reduce physical activity outdoors. The authors posit that obesity contributes to furthering climate change by increasing food consumption, especially energy-dense ultraprocessed foods and animal products; increasing transportation-related emissions due to greater body mass; and increasing the energy requirements for heating/cooling spaces (144). However, the mechanisms of the bidirectional relationship between climate change and obesity need to be further studied and elucidated.

While some of these relationships remain hypotheses, some studies are emerging to understand this connection better. For example, one study modeled different diet scenarios (current diets, diets that followed national dietary guidelines, vegetarian diets, and vegan diets). The authors demonstrated that transitioning to more plant-based diets could prevent 5.1 million deaths worldwide by 2050, and most of those prevented deaths were due to reduced obesity and NCD rates, with benefits increasing progressively from the current diet scenario to the vegan scenario, with the vegan diet offering the most substantial reductions in obesity-related mortality. They also found that high-income countries would see the most significant per-capita reductions in obesity-related mortality (132).

Some limited data suggest that heat waves pose greater health risks for obese individuals with a reduced ability to dissipate heat (73). A recent study examined the effects of interannual variations of average temperature and precipitation on children's and adults' BMI in 134 countries over 40 years. They found a U-shaped (and direct and independent) relationship between temperature and BMI across all ages and gender groups—in which BMI increases at colder and warmer temperatures. They also found that this relationship is more robust in LMICs in that a 1°C increase in temperature increases the BMI of girls and women by 5% and 2%, respectively (147).

Some studies argue that those with obesity create a more significant burden on the environment (45). This is a highly underinvestigated and sensitive area of research, in that messaging and interpretation of results could lead to increased stigma and blame for those with increased body size and potentially more discrimination toward those populations in public spaces and workspaces.

5. WHY POORLY NOURISHED POPULATIONS STRUGGLE TO ADAPT TO CLIMATE CHANGE

The degree to which people or communities are at risk of being negatively impacted by climate change and variability (also known as vulnerability) is strongly associated with the social determinants of health, as well as the other systems critical for well-being (e.g., food, water, social protection, and education). The social determinants of health are conditions in which people are born, grow, work, live, and age, and the broader set of forces and systems shaping daily life includes economic policies and systems, development agendas, social norms, social policies, and political systems (155). Importantly, these determinants are influential on health and, consequently, nutrition inequities, or the unfair and avoidable differences in nutritional status seen within and between countries. For example, a bidirectional relationship exists between poverty and malnutrition, whereby those living in poverty often cannot afford safe, nutritious food, leading to food insecurity and insufficient calorie intake (131). Additionally, while the quantity of food is important, the quality and nutrient content are crucial, as poverty often results in diets rich in cheap carbohydrates and fats, leading to micronutrient deficiencies. The issue of obesity has also emerged in developing countries, further complicating the relationship between poverty and nutrition.

Climate variability and changing trends are becoming more concerning, likely worsening the vulnerability of impoverished households and intensifying poverty around the world, particularly in LMICs (58). The impacts of climate change will be felt differently by communities and households, with some populations, usually those with the lowest GHG footprint, less capable of adapting to those impacts (81). Those different experiences of adaptation often have to do with factors such as social status, race, ethnicity, gender, caste, and disability (104). Climate change vulnerability is also significantly affected by poverty, which is increasingly seen as a complex and evolving issue shaped by historical factors; individual and community traits; and broader social, economic, political, and environmental influences.

Individuals in low-income, informal, or hourly jobs who cannot get access to social protection interventions (e.g., cash, food, subsidies, welfare benefits) are particularly affected by climate-related disruptions and often reside in areas more prone to climate extremes and compounding shocks (138). As a result, those without sufficient financial, educational, and technological resources to cope with and adapt to increasing climate risks bear the brunt of these impacts, and inequities mediate this relationship between climate change and nutrition outcomes (127). Populations already reeling from food insecurity and poor access to healthy diets, as well as coexisting burdens of malnutrition (113), will disproportionately suffer from increased climate change risks, making it all the more challenging to adapt to a warmer world.

6. THE POTENTIAL FOR CLIMATE AND NUTRITION RESILIENCE

To ensure that nutritionally vulnerable populations can adapt to climate change and move toward greater resilience, implementing actions that have co-benefits for nutrition and climate adaptation should be prioritized. These nutrition-specific actions are well known and cited, have a high impact, and can save lives. Interventions include promoting exclusive breastfeeding and nutrient-rich complementary foods for young children; providing adequate nutrition for women during pregnancy and lactation; ensuring vitamin A, zinc, and micronutrient supplements are available; managing acute malnutrition; providing deworming medications; diversifying agriculture systems to grow a diverse set of foods: ensuring access to healthy diets: and fortifying essential staple foods (65, 124). Mobilizing the education system and social protection systems are also critical to scale up school- and community-based food safety nets and food assistance for the most nutritionally vulnerable. Doing these actions well, at scale and with full coverage, is critical to ensure the global population is well-nourished and resilient enough to adapt to a changing climate (51).

Yet, in practice, the processes of designing, implementing, monitoring, and adapting policies, programs, and interventions that are most effective to ensure both climate resilience and optimal nutrition outcomes (50) require a collective understanding of the climate problem and how it is impacting nutrition outcomes of people and communities. Much of the current empirical research has focused on mitigation and adaptation within specific systems such as food (11) and health (106) and to a lesser extent on water, education, and humanitarian response for both climate and nutrition resilience. Importantly, while various frameworks, visions, pathways, and tools have offered a plethora of viable mitigation and adaptation options to policymakers, their real-world, long-term evaluation on nutrition outcomes has been limited (47).

Given the multifactorial nature of food insecurity, poor diets, and malnutrition and the many factors operating within any complex system, transforming toward systems that are climate- and nutrition-resilient necessitates collaborative engagement and coherence (horizontally and vertically) (10) across several systems, sectors, and stakeholders including food, health, water, social protection, education, and humanitarian responses (**Figure 3**). In the design of tailored solutions that are effective, contextually appropriate, and locally led, it is also critical to consider and avoid potential maladaptation—when any policy, program, or intervention inadvertently increases vulnerability to climate, causing further harms and inequities (101)—and to be aware of climate risk and uncertainty, address structural inequalities, and invest in local capabilities (52).

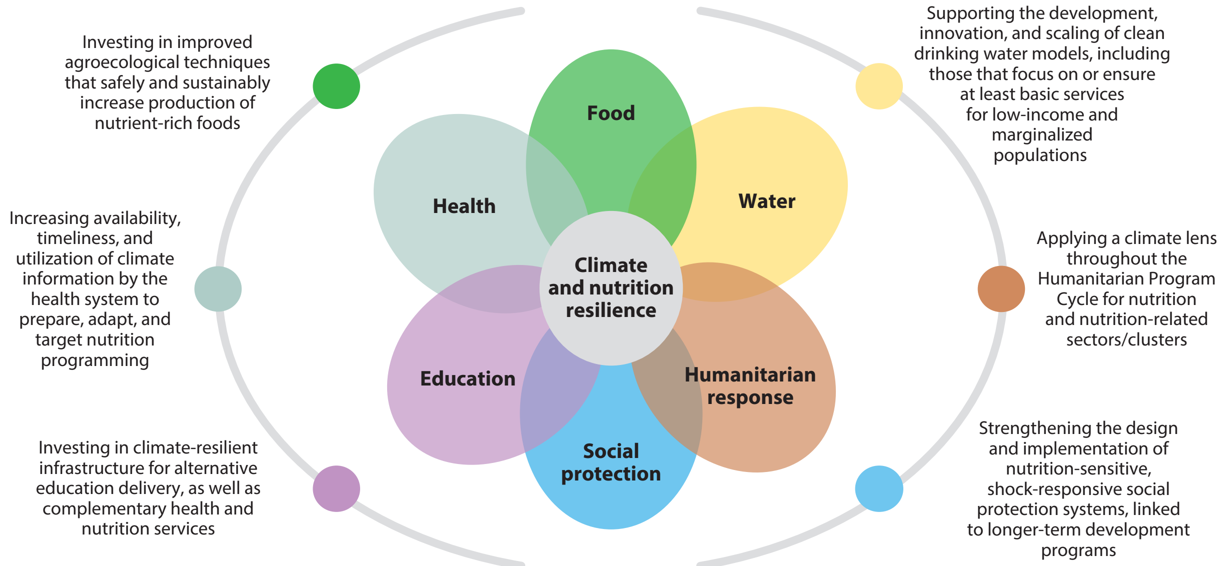

Figure 3

Integrated adaptation options for climate and nutrition resilience using a systems and multisectoral approach. Author's own interpretation. For more information, see References 43, 54, and 149.

7. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

Long-term climate change projections suggest that scenarios that de-emphasize mitigation and continue generating GHGs will worsen food security and nutrition outcomes for many populations around the world. At the same time, near-term climate-related extreme weather events will have adverse effects on undernutrition, particularly wasting. While stunting is harder to measure and interpret in these studies, increased episodic periods of wasting can amplify and have concurrent stunting outcomes. The growing literature on consistent hotter days and heat waves is correlated with poor birth outcomes and both stunting and wasting. As this review suggests, the quantity and quality of research in this area is ripe for growth and improvement with several paths of exploration.

First, more research is needed to understand the long-term implications of heat on child malnutrition and the mechanisms of this association (adaptive response to heat, reduced appetite, and the energetic cost of thermoregulation), as well as NCD risk. As part of this research, there is a need for more sophisticated data, methods, and analysis to monitor and track climate change's causal impacts on nutrition outcomes of individuals over longer timescales who are consistently exposed to extreme, prolonged events. For example, as we saw in the set of papers analyzed for this review, while drought is likely a factor contributing to the burden of malnutrition in children and other vulnerable populations, research methods need to become much more sophisticated.

The research to date highlights associations and focuses less on causality (64) of both long-term climate change and short-term climate variability impacts. To improve the methods to better understand these temporal and spatial relationships, we need more longitudinal panel data that track the nutrition of populations (who are not migrating) and the effects of shocks, compound events, and long-term climate change over time. There is also a need to conduct more location-specific studies to understand regional variations in these relationships, as well as consistent comparative analysis across regions, with models that can better predict nutrition outcomes based on climate projections. Perhaps advanced statistical analysis and machine learning could be used to identify patterns and analyze and merge these large complex datasets. Natural experiments and quasi-experimental designs could be utilized to study the effects of climate events on nutrition.

Second, there are significant topical gaps. The effects of compound and cascading episodes of climate change and extreme events (including nonclimate drivers such as conflict) on nutrition are understudied and require more complex analysis. Also, the relationship between climate change and obesity is less understood, and there is a need for much more thoughtful (and non-stigmatizing) research in this area. Finally, understanding how climate information and services (developed by national and regional meteorological offices) are used by nutrition practitioners in public health settings (beyond food security and food aid)—and whether the information is fit for the purpose of better preparing, preventing, and treating cases of malnutrition—needs more exploration. Addressing these data and research gaps is crucial for developing effective policies and interventions to mitigate the adverse effects of climate change on nutrition and food security. Improved data collection, standardization of metrics, and convergence research approaches are needed to bridge these gaps and inform evidence-based decision-making.

Third, while this review suggests that long-term climate projections and near-term extreme events will have and are having adverse impacts on food security, diets, and nutrition through various factors and mechanisms (which are beyond the scope of this article), it is also important to posit and better understand if there are any potential benefits in certain circumstances. Ebi and colleagues (34, p. 153) suggest that "while climate change may benefit some health outcomes in certain regions, the overall balance will be detrimental for health and well-being, especially in LMICs that experience higher burdens of climate-sensitive health outcomes." This review agrees that the cumulative impacts of climate change will largely strain the systems critical for improved malnutrition and instead put many populations at risk for malnutrition. However, some early modeling evidence suggests that climate change may increase the growing seasons for certain crops grown in certain regions and latitudes (depending on soil management and resources) and improve the nutritional content of certain crops (related to water availability and precipitation) (3, 128). Furthermore, if the world stays on a business-as-usual climate change trajectory, there may be an opportunity to redirect research and development resources toward the use of traditional crops that are better adapted to environmental stressors and provide nutritional benefits (22). Such changes to crop production may have downstream positive effects on the quality of diets and nutrition outcomes; however, much more empirical investigation is needed to make these causal links under different sets of scenarios and projections.

Fourth, it is essential to understand the distribution of inequities—in terms of who will be most impacted by climate change, how, and why—to identify and prioritize adaptation and mitigation interventions for those who need them the most, particularly children, pregnant women, the elderly, Indigenous peoples, and those living in remote geographic poverty traps (127). This means better data disaggregation of nutrition data by age, geography, sex, disability, and ethnicity, as well as more ethnographic qualitative methods and participatory research methods that incorporate local knowledge and perspectives to understand the lived experiences of those who disproportionately suffer.

Last, there is a need for more interaction between climate and nutrition research and global policy communities. These two communities rarely engage except for those who more specifically investigate the impacts of climate on agricultural productivity, food security, and diet pathways. However, this dysconnectivity is changing. At the time of the writing of this review in late 2024, three Conference of Parties meetings were occurring, including the Rio Convention Conference of Parties to the United Nations Convention on Biological Diversity, the United Nations Framework Convention on Climate Change, and the United Nations Convention to Combat

Desertification, as well as the attention on nutrition with the Nutrition for Growth Summit and the stocktake of the United Nations Food Systems Summit in 2025. These global agendas and efforts are important moments to merge and promote the nexus of climate, food systems, and nutrition. This collaborative nexus should broaden to communities engaged in other sectors critical for climate and nutrition including health, water and sanitation, income, women's empowerment, and care capacity—all major drivers of nutrition outcomes that provide a more comprehensive picture of the climate and nutrition relationships (82). At the highest level, it is of critical importance to integrate nutrition-sensitive solutions into climate action, including within Nationally Determined Contributions and National Adaptation Plans, to protect the lives of the most vulnerable (146).

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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