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Climate Change and Variability

What are the Risks for Nutrition, Diets, and Food Systems?

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ABSTRACT

The intersection of climate change, food security, and nutrition is critical given growing adverse climate change impacts that threaten food security and nutrition outcomes, especially for the most vulnerable in the global South. A better understanding of the pathways linking climate change and nutrition is critical for developing effective interventions to ensure that the world's population has access to sufficient, safe, and nutritious food. Undernutrition can be exacerbated by the effects of climate change at all stages of the food value chain. In addition, disease is affected by climate and can, in turn, increase nutrient demands and reduce nutrient absorption. Dietary diversity and animal-source foods can be important tools for improving nutrition and health in nutritionally deficient populations.

The paper uses a food systems approach to analyze the bidirectional relationships between climate change and food and nutrition along the entire food value chain. It then identifies adaptation and mitigation interventions for each step of the food value chain to move toward a more climate-smart, nutrition-sensitive food system. The study focuses on poor rural farmers, a population especially vulnerable to the adverse effects of climate change on nutrition, although we recognize that there are other vulnerable populations, including urban poor and rural populations working outside of agriculture. Although this report does not explicitly exclude overweight and obesity, it focuses primarily on undernutrition because this nutritional status is currently more prevalent than overnutrition among our target population.

The study identifies seven focal areas for interventions to reduce nutrition risks under climate change along the food value chain. Under the first focal area, relating to the input side in the food value chain, we find that crop and livestock diversity, soil quality, and water access increase crop production and nutrition, and that crop and livestock diversity also have the potential to increase dietary diversity. Under the second area, focusing on the agricultural production side, we find that mitigation and adaptation strategies are needed to offset adverse impacts of climate change on food production. Mixed crop and livestock systems improve the nutritional quality of food and minimize the impacts of livestock on climate. Services and financing can also reduce nutrition risks under climate change. The third focal area relates to food storage and processing practices that reduce climate-related food safety concerns, such as aflatoxins, while also preserving the nutritional value of foods and minimizing, where possible, the need for fossil fuel–intensive cold storage. These strategies can also support reducing food waste in low- and middle-income countries. The fourth area focuses on distribution, marketing, and retail. Climate change is expected to reduce market access for smallholder farmers, thus adversely affecting nutrition outcomes. Climate-proofed infrastructure and transportation can reduce these adverse impacts, protect nutritional value, and reduce food waste through improved connections between farmers and consumers and through increased access of retailers to cold storage. Public health campaigns around the world can promote an understanding of the need to incorporate sustainability into dietary guidelines. The fifth area focuses on food consumption and utilization. Here, climate-smart interventions include social protection services to protect the most vulnerable from long-term stresses and short-term shocks that threaten food security, judicious consumption of animal-source foods, and energy-efficient methods of food preparation. The sixth area addresses the many dimensions of undernutrition. Increasing the number of healthcare facilities and staff can improve access to healthcare for vulnerable populations, especially the rural poor. Access to fortified and animal-source foods can improve nutrition for vulnerable populations. Under the seventh and final area, to reduce nutrition risks along the entire value chain, early warning systems are needed so that farmers can produce sufficient food and traders can adequately store food in the face of extreme weather events, and policies are needed to ensure that droughts and floods do not lead to unhealthy food consumption patterns. Although work has been done on the food production stage, research needs to be expanded to address all stages in the food value chain.

Keywords: nutrition, climate change, food security, diets, food systems, adaptation, mitigation, food value chain

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1. INTRODUCTION

Key Points

1. Climate change is already happening, and its future effects will be most pronounced in the global South, especially Africa south of the Sahara and Southeast Asia.
2. The rural poor are the least able to adapt; thus, climate change increases inequity.
3. The global food system both drives and is impacted by climate change.
4. Without action, climate change will impact nutrition through decreased food quantity and access, decreased dietary diversity, and decreased food nutritional content.
5. We need a climate-smart and nutrition-sensitive food system in order to ensure that mitigation and adaptation strategies take nutrition into account.

Motivation

Humanity is witnessing the repercussions of climate change. Though some of us may have opportunities to make choices in how we adapt across multiple aspects of our lives, others do not. In much of the southern hemisphere, where most of the world's poverty remains, many are living in real time with a changing climate that is affecting their livelihoods, mobility, and many of the systems they engage with, be they health, education, or food systems. The agriculture-food system is highly sensitive to climate, being both a victim and an instigator of the effects of climate variability.

In many regions of the world, particularly in Africa south of the Sahara and in South Asia (although variation within countries and regions is certain), agriculture will have greater difficulty in producing enough food that is of good quality (diverse, high in nutrient density, and safe) (GLOPAN 2015). Food systems and the ability to move food from production to markets will be affected, which will further limit consumers' access to diverse, high-quality diets in their local food environments. In the "business-as-usual" and worst-case models and scenarios, nutrition and health outcomes are guaranteed to worsen due to multiple drivers (FAO 2016a; Whitmee et al. 2014; Springmann, Godfray, et al. 2016).

Climate-smart agriculture is one such approach that has promise, but we need more *evidence and action* that links climate-smart agricultural approaches to diets and nutrition, particularly for women and children, who suffer the most significant burdens of poor nutrition. Additional research presents an opportunity to understand these links. We argue for agriculture to be smarter in the context of climate change but also nutrition smart at the same time.

The purpose of this paper is to examine the relationships between climate change, climate-smart agriculture, and nutrition through a food system lens. The paper begins with an overview of current climate change and variability projections. It then describes the impacts of climate change on nutrition outcomes and burdens, and on health overall. Next it uses a food chain model to analyze how climate change is disrupting and will continue to disrupt food systems, food environments, and diets. Thereafter, the paper describes promising mitigation and adaptation strategies to improve the food system, diets, and nutrition impacts.

Climate- and Nutrition-Smart Agriculture: Through a Food Systems Lens

More research that seeks to understand how climate change will affect food systems, food environments, diets, and nutritional outcomes is urgently needed to better design producer choices and policy approaches that are both climate smart and nutrition sensitive. As cropping patterns, productivity, and the timing of seasons of "lean" and "plenty" continue to change, and as these patterns become increasingly unpredictable, disruptions in value chains that result in food insecurity in local markets and across landscapes are likely. These changes have implications both for undernutrition and for overweight and obesity, both of which pose risks for maternal and child mortality and diseases. Some analysis has been done to predict how climate change may influence crop production and calorie availability in the future, but studies rarely examine the entirety of the food system beyond production and its impacts on diets and nutrition outcomes, such as micronutrient deficiencies, protein availability, and child stunting.

Because modern food production and consumption are also major users of energy and contribute to greenhouse gas production, those concerned with global nutrition in the context of sustainable development must increasingly factor in the climate as both a potential driver and an outcome of changes in nutritional status. That being said, in general, more intensive production systems have lower emissions levels per unit of output. A further area of concern is the unintended nutritional consequences of some adaptation and mitigation strategies. The future is not what it was. Forecasts of the future climate—whether short-term seasonal anomalies or long-term climate change scenarios—may also impact production and consumption patterns, price hikes of food staples, and social stability.

Both the Sustainable Development Goals adopted in 2015 and the Paris Climate Agreement of 2015 under the United Nations Framework Convention on Climate Change call for significant action on climate change. The global targets include limiting global temperature rise to less than 2.0°C, pursuing efforts to limit it to 1.5°C above preindustrial levels, and achieving net zero emissions (that is, keeping greenhouse gas emissions within what the world's carbon sinks can absorb) by the second half of this century. According to the Food and Agriculture Organization of the United Nations (FAO), 94 percent of all countries include the agriculture sector in their mitigation or adaptation strategies (2016a).

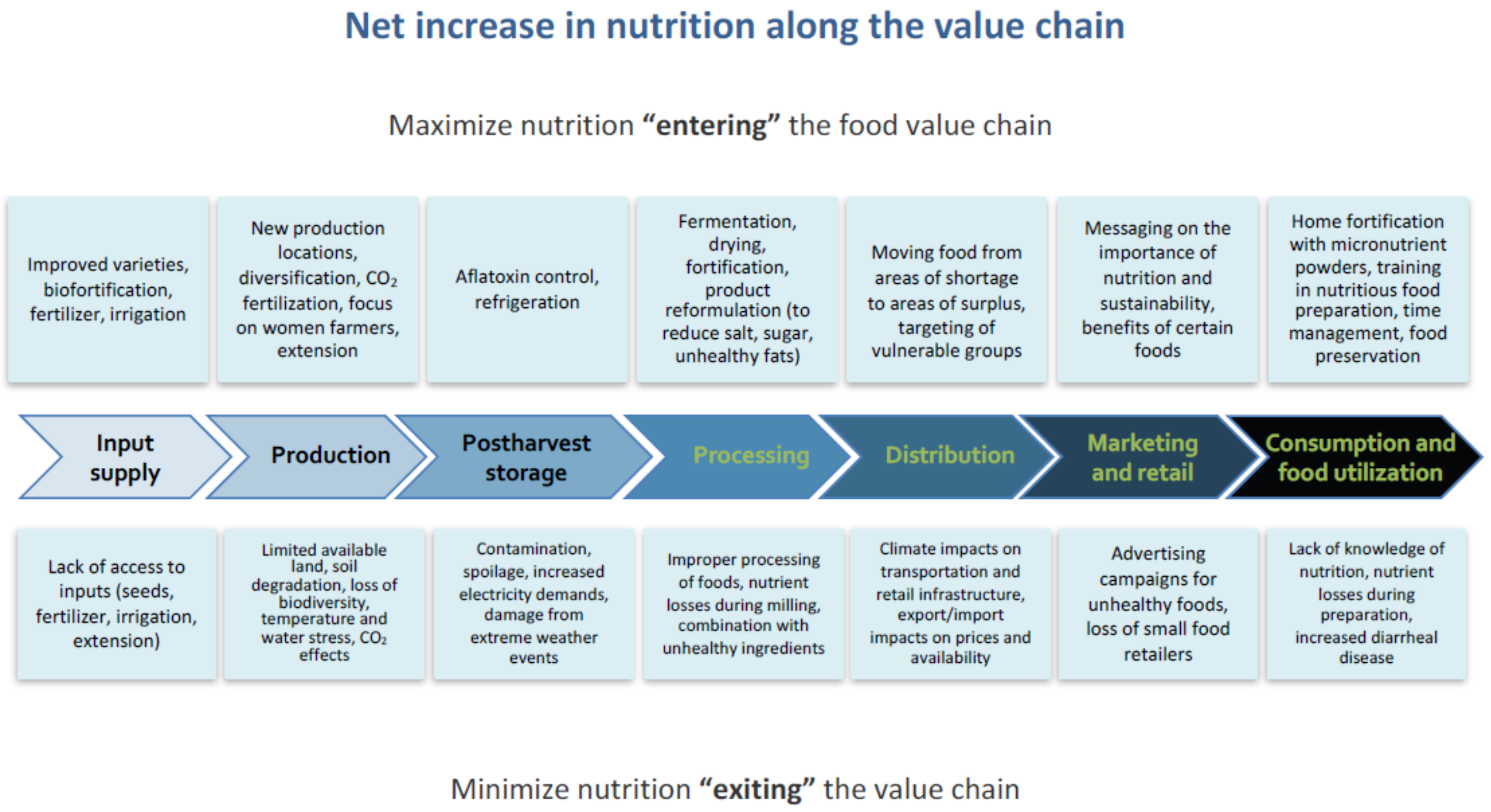
A Framework of Climate Change and Nutrition

Researchers have evaluated where nutrition can enter and exit the value chain at all stages, from agricultural inputs and food production to food consumption and utilization (Fanzo et al. 2017). Our adapted framework (Figure 1.1) adds the effects of climate change on the food value chain and elucidates their effects on nutrition.

The first step in the food value chain is the agricultural input supply, which includes seeds, fertilizer, irrigation, and extension services. At this point in the chain, the seeds impact what crops and varieties are grown, which is key for crop diversity as well as for choosing varieties that are heat and drought resistant in the face of climate change. Fertilizer and other methods of improving soil quality affect how productive and nutritious crops are. Irrigation also affects crop productivity and provides increased stability amid changing precipitation patterns due to climate change. The second step is food production. Changing temperatures and precipitation patters affect where food can be grown. Increased carbon dioxide levels increase some crop growth to a certain extent but also decrease crops' nutritional quality. The third step is food storage. Again, increasing temperatures and changes in precipitation cause new food safety risks, especially with aflatoxins. It is critical to address these risks in storage to keep food safe. Rising temperatures will also increase demand for cold storage in order to maintain food safety and quality, and to prevent food waste. Extreme weather events also pose a risk for food storage and can lead to food waste.

The fourth step is processing, which provides an opportunity to add nutrition through fortification or to increase the quality and stability of nutritious vegetables, fruits, and animal-source foods through fermentation, drying, and other methods. However, some processing, such as milling, causes a loss of nutrition. The fifth step is distribution, which allows food to be moved from areas of surplus to areas of shortage and can be used to target vulnerable populations. However, climate change will impact methods of transportation, from roads to rail lines, through both long-term changes in climate and short-term extreme weather events. Transportation disturbances can impact food availability and prices. The sixth step is marketing and retail. At this stage, it is critical that sustainability, as well as nutrition, be incorporated into food marketing and dietary guidelines. The same long-term changes in climate and short-term extreme weather events discussed above can also impact food availability and prices by affecting retail infrastructure. The seventh and final step is food consumption and utilization. It is important for people to have the knowledge and skills to prepare nutritious foods and to minimize nutrient losses during preparation. Climate change also threatens to increase infectious diseases, including diarrheal diseases, which can decrease nutrient absorption and increase individuals' nutritional needs. All of these steps of the food value chain will be discussed in greater detail below and will be used to formulate the recommendations in this paper.

Figure 1.1 Climate change and nutrition entry and exit points in the food value chain



Net increase in nutrition along the value chain

Maximize nutrition **“entering”** the food value chain

Improved varieties, biofortification, fertilizer, irrigation	New production locations, diversification, CO_2 fertilization, focus on women farmers, extension	Aflatoxin control, refrigeration	Fermentation, drying, fortification, product reformulation (to reduce salt, sugar, unhealthy fats)	Moving food from areas of shortage to areas of surplus, targeting of vulnerable groups	Messaging on the importance of nutrition and sustainability, benefits of certain foods	Home fortification with micronutrient powders, training in nutritious food preparation, time management, food preservation
Input supply	**Production**	**Postharvest storage**	**Processing**	**Distribution**	**Marketing and retail**	**Consumption and food utilization**
Lack of access to inputs (seeds, fertilizer, irrigation, extension)	Limited available land, soil degradation, loss of biodiversity, temperature and water stress, CO_2 effects	Contamination, spoilage, increased electricity demands, damage from extreme weather events	Improper processing of foods, nutrient losses during milling, combination with unhealthy ingredients	Climate impacts on transportation and retail infrastructure, export/import impacts on prices and availability	Advertising campaigns for unhealthy foods, loss of small food retailers	Lack of knowledge of nutrition, nutrient losses during preparation, increased diarrheal disease

Minimize nutrition **“exiting”** the value chain

Source: Adapted with permission from Fanzo et al. (2017).

2. CLIMATE CHANGE AND VARIABILITY

Key Points

1. Greenhouse gas emissions are retained in the atmosphere, where they absorb and re-emit solar radiation, leading to planetary warming, changes in precipitation, increases in extreme weather events, ocean acidification, glacier melting, and sea level rise.
2. The net result of climate change negatively impacts terrestrial, freshwater, and marine plant and animal species, some of which are key food sources.
3. Climate change causes an increase in infectious diseases through increased vector and pathogen survival and virulence.
4. Climate change decreases water and food availability where they are needed, risks that disproportionately fall on the global poor and have the potential to result in forced migrations, increased numbers of internally displaced people and refugees, and violent conflict over resources.
5. In order to limit the global temperature increase to less than 2°C, we need to decrease greenhouse gas emissions by 25 to 50 percent between 2010 and 2050. Currently, however, emissions have been increasing, by 2.2 percent every year from 2000 to 2010.

Introduction

There is overwhelming evidence that the planet is warming due to the actions of humans. Although natural variability in the climate shapes individual weather events, many recent events correspond to climate change projections (ASC 2016). These projections, which incorporate natural and human factors, are also in line with the amplitude and spatial pattern of warming that has occurred over the 20th century (ASC 2016). Between 1880 and 2012, the average surface temperature of the Earth, including both land and ocean, increased by 0.85°C. Of the 16 warmest years on record, 14 have occurred since 2000. The El Niño year 2015 was more than 1.0°C higher than preindustrial temperatures and 0.2°C higher than 2014, the previous warmest year. The level of carbon dioxide, methane, and nitrous oxide in the atmosphere is the highest it has been in more than 800,000 years (ASC 2016). Changes observed since the 1950s are unprecedented over decades to millennia (IPCC 2014b). If current trends continue under a business-as-usual scenario, we could see a 4°C rise in global mean surface temperatures by the end of the next century (WHO 2009a).

Anthropogenic Influences on Climate

Scientific evidence shows that the climate system has been affected by human activity. Greenhouse gases in the atmosphere absorb and re-emit solar radiation that warms the surface of the earth. Fossil fuel use and human agriculture generate greenhouse gases, which include carbon dioxide, methane, and nitrous oxide. Of these, carbon dioxide may well be the longest lasting. Although the atmospheric lifetime of carbon dioxide is difficult to determine, the Intergovernmental Panel on Climate Change (IPCC) and others agree that a significant percentage of carbon dioxide released into the air, 20 percent or more, can remain in the atmosphere for thousands of years or longer (IPCC 2007; Archer et al. 2009). Greenhouse gas emissions have incrementally grown since the Industrial Revolution, leading to an all-time-high concentration of atmospheric greenhouse gases of more than 400 parts per million in 2014 (Watts et al. 2015; Whitmee et al. 2014).

Humans have made other changes to the environment that have a negative impact on natural ecosystems, though these changes do not definitively cause climate change. Humans have converted approximately one-third of all ice- and desert-free land into cropland or pasture and use about half of all the world’s accessible freshwater each year. Since 2000, 2.3 million square kilometers of primary forest have been cut down. Roughly 90 percent of monitored fisheries are harvested at or above maximum sustainable yields. More than 60 percent of the world’s rivers have been dammed to control water resources and produce energy. Human activity has led to species extinction at rates that are more than 100 times those observed in the fossil record. The 2005 Millennium Ecosystem Assessment found that 60 percent of ecosystem services are being degraded or used unsustainably (cited in Whitmee et al. 2014).

Current Impacts of Climate Change

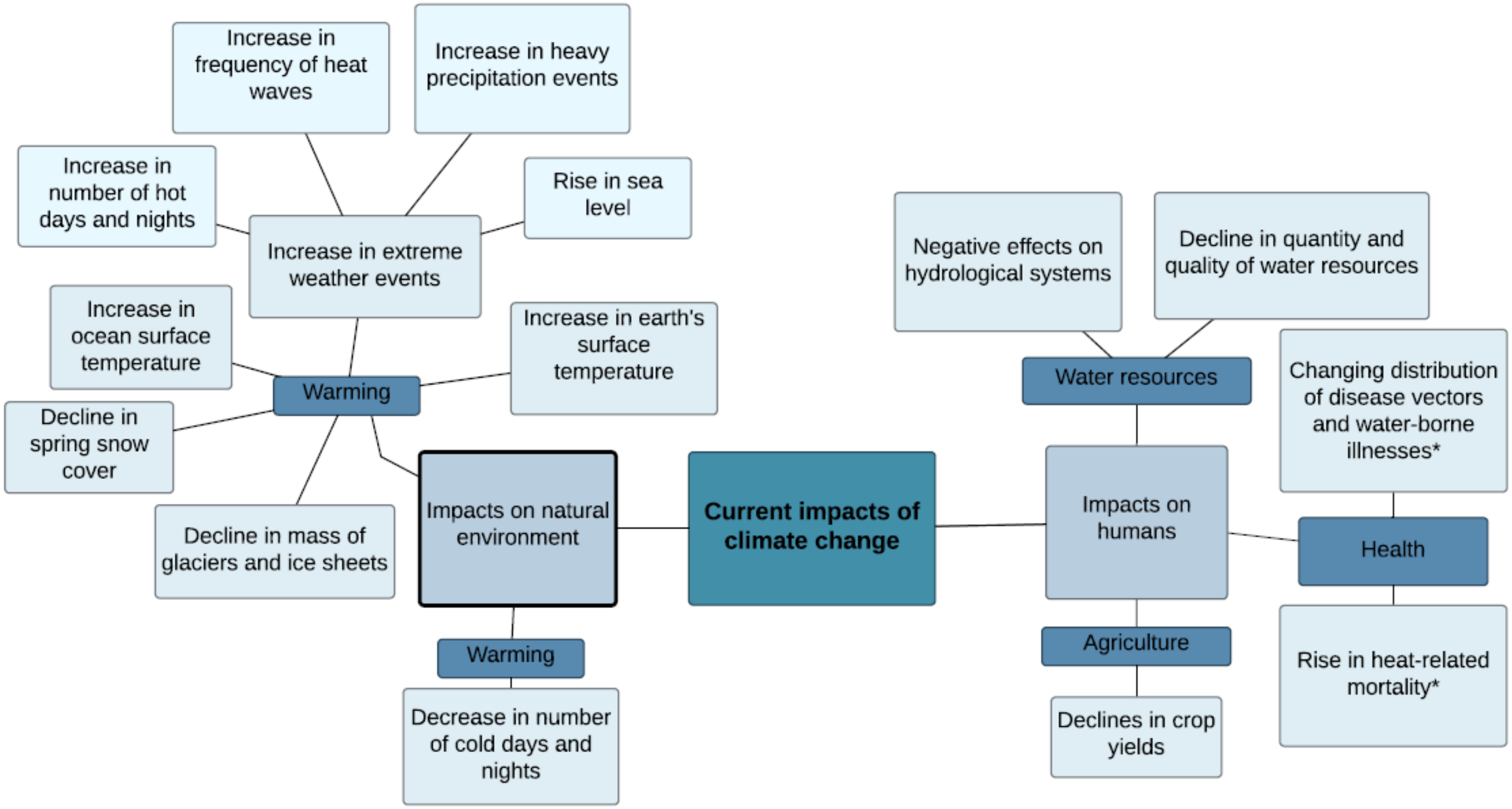
Major changes in the planet's climate system have been observed in the atmosphere, oceans, cryosphere, and sea level. What we are now witnessing is a warming planet, rising seas, and melting glaciers.

Changes in the climate system have numerous effects on the planet's natural systems (Figure 2.1). The Earth's surface temperature has warmed more over the last three decades than during any other time since 1850 (IPCC 2014b). Ocean warming accounts for the primary increase in energy stored in the climate system. This type of warming represents more than 90 percent of the energy accumulated between 1971 and 2010; in contrast, approximately 1 percent of energy is stored in the atmosphere (ASC 2016; IPCC 2014b). Globally, ocean warming is greatest near the surface: the upper 75 meters warmed by 0.11°C per decade from 1971 to 2010. In the cryosphere, glaciers have shrunk over the last two decades almost everywhere in the world. The Greenland and Antarctic ice sheets have lost mass over the same period. Spring snow cover in the northern hemisphere has continued to decrease in extent (IPCC 2014b). Between 1901 and 2010, the global mean sea level rose by 0.19 meters (ASC 2016; IPCC 2014b). Since the mid-19th century, the rate of sea level rise has been greater than the mean rate during the previous two millennia (IPCC 2014b). The rate of sea level rise has grown to more than 3 millimeters per year since the 1990s, though this change cannot be entirely attributed to climate change (ASC 2016).

Changes in the climate system have serious implications for human systems (Figure 2.1). Many regions have experienced changing precipitation that alters hydrological systems and, subsequently, impinges upon the quality and quantity of water resources (IPCC 2014b; Whitmee et al. 2014). Crop yields have also been adversely influenced by climate change. Though the global burden of ill health caused by climate change has not yet been extensively quantified, there are indications that heat-related mortality has risen and the distribution of disease vectors and waterborne illnesses has shifted due to changing temperature and rainfall (IPCC 2014b).

Extreme climate and weather events have also changed in association with a warming planet. Globally, the number of warm days and nights has increased while the number of cold days and nights has decreased (ASC 2016; IPCC 2014b). The frequency of heat waves has grown in large parts of the world (ASC 2016). Heavy precipitation events have risen in many land regions (ASC 2016; IPCC 2014b). Extreme sea levels have likely been heightened as a result of mean sea level rise since 1970. However, it remains difficult to causally link anthropogenic climate change to the frequency and magnitude of fluvial floods, drought trends, or tropical cyclone activity. Weather-related disasters have led to a sharp increase in direct and insured losses in recent decades. Climate variability has resulted in significant vulnerability to some ecosystems and many human systems, a fact that has been made especially clear by the impacts of extreme climate-related events globally and regionally (IPCC 2014b).

Figure 2.1 Current impacts of climate change on human and natural systems



Source: Created by authors and based on ASC (2016), IPCC (2014b), and Whitemee et al. (2014).
Note: * Indicates impacts that are likely, though not definitively, linked to climate change. This figure depicts some, though not all, of the current impacts in a thematic, not causal, manner.

Climate Change Impacts in the Future

The continuation of greenhouse gas emissions will further perpetuate long-lasting changes to the climate system. In turn, these changes will intensify the possibility of severe, irreversible effects on people and ecosystems. Emission projections vary, depending in part on socioeconomic development and climate policy. Representative Concentration Pathways (RCPs) are the standard set of scenarios used for climate change projections: based upon climate models, which are mathematical simulations of processes inherent in the climate system, these scenarios are generated through a range of approaches and in consideration of key driving factors (IPCC 2014b). RCPs project that the world's average temperature will increase within a range from 1.4°C to 5.8°C by 2100 (McMichael, Woodruff, and Hales 2006). Current greenhouse gas emissions are consistent with the higher end of these RCP scenarios (WHO 2015). Risks from climate change depend upon the intersection between climate-related hazards and the vulnerability of human and natural systems. Continuing climate change will amplify existing risks and create new ones for humans and ecosystems (IPCC 2014b). To limit global warming, greenhouse gas emissions would need to decrease by 25 to 50 percent over the 2010 to 2050 period, a reduction that would facilitate achievement of a less than 2.0°C increase from preindustrial times by a 50 percent probability or more. Instead, however, emissions grew by nearly 2.2 percent per year from 2000 until 2010 (WHO 2009a).

Changes in the climate system are projected to impact air temperature, the water cycle, the oceans, the cryosphere, sea level, the carbon cycle, and biogeochemistry. By the end of the 21st century, global surface temperature change will likely exceed 1.5°C regardless of whether we take significant mitigation action now. Atmospheric concentrations of greenhouse gases are projected to be almost four times preindustrial levels by the end of this century (WHO 2015). As this change occurs, it is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas. Precipitation changes will vary globally as the world warms, with some regions projected to experience significant declines in precipitation while others may undergo increased, more severe precipitation. Throughout the 21st century, the oceans will continue to warm and mean sea level will continue to rise, although sea level rise will differ around the world. Further reductions in arctic sea ice are also projected. Oceans will continue to absorb carbon dioxide, and feedback between climate change and the carbon cycle is predicted to amplify global warming. The dissolved oxygen content of ocean water will likely decrease (IPCC 2014b). Ocean acidification will grow, with a potential increase of 170 percent by 2100 (IPCC 2014b; Whitmee et al. 2014).

Human systems will face increased risks from global warming. These risks will be unevenly distributed and generally higher for disadvantaged populations. More people will likely experience water scarcity and issues of food security related to food production, access, use, and price stability, relative to no climate change. In some parts of the world, it is likely that competition for water resources will increase as renewable surface water and groundwater resources diminish (IPCC 2014b; Whitmee et al. 2014). Water demand is expected to increase by 55 percent globally between 2000 and 2050. Groundwater currently supplies about 50 percent of the freshwater used domestically around the world, 40 percent of nonpiped water for industry, and approximately 40 percent of the water used for irrigation (Siebert et al. 2010). In many areas, groundwater is extracted faster than it can be replenished (Watts et al. 2015). Throughout the 21st century, climate change is projected to exacerbate existing human health problems and ultimately increase ill health in many areas, especially developing countries (IPCC 2014b). Urban areas are expected to experience increased risks to people, assets, economies, and ecosystems, largely as a result of heat stress, storms, flooding, landslides, air pollution, drought, water scarcity, sea level rise, and storm surges. Many regions will be increasingly affected by major river flooding (IPCC 2014b; Whitmee et al. 2014). Rural areas are projected to undergo impacts on water availability and supply, food security, infrastructure, and agricultural incomes (IPCC 2014b; Whitmee et al. 2014). The impacts of climate change will likely impede economic growth, thereby prolonging poverty, making poverty reduction more difficult to achieve, and intensifying food insecurity. These impacts are also projected to escalate displacement and increase the risks of violent conflict through conflict drivers such as poverty and economic shocks (IPCC 2014b).

3. CLIMATE CHANGE IMPACTS ON OVERALL HEALTH

Key Points

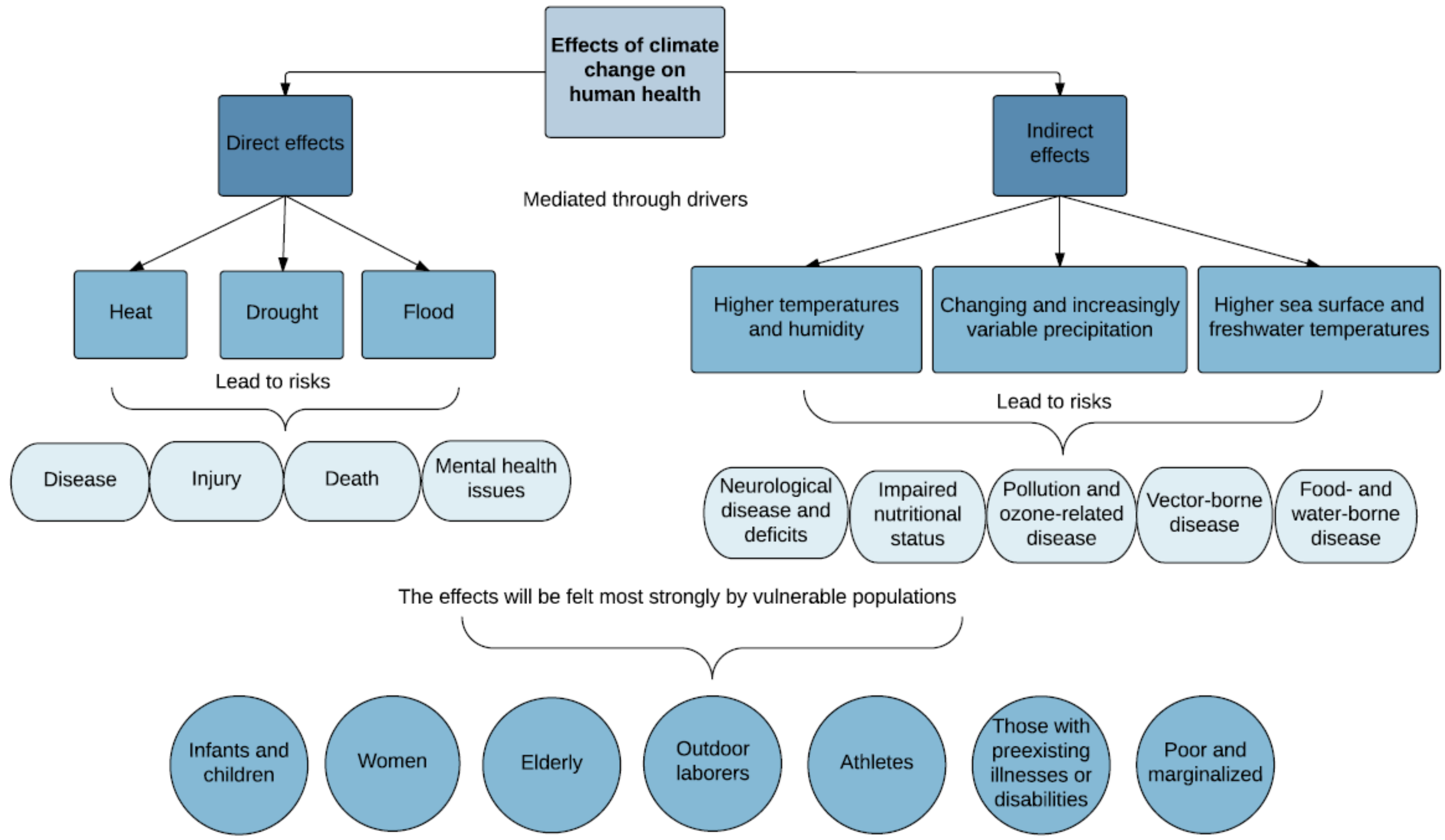
1. Climate change has direct impacts on human health through extreme weather events, especially through direct injuries and deaths from storms and an increased incidence of heat exhaustion, heat stroke, and heat-related mortality from increasing temperatures.
2. Climate change will cause increases in pollution, most importantly air pollution, which already causes 3.7 million premature deaths every year.
3. Climate change has indirect impacts on human health through water and food availability,

Introduction

This report aims to investigate the impacts of climate change on nutrition through the food system and diet lenses. However, it is important to understand its impacts on health overall before focusing more specifically on nutrition. In recognition that the environment has long been the foundation for human well-being, climate change has been called “the biggest global health threat of the 21st century” (cited in Watts et al. 2015, 6). The overall combination and interaction of risks from climate change will create negative health effects worldwide that will outweigh any positive health impacts. As a result of the changing climate, humans will experience both direct health effects, defined as risks from changes in extreme weather, and indirect effects, which are those mediated by changes in the biosphere and social processes. A selection of these health impacts is depicted in Figure 3.1. Negative impacts will be greater in regions where climate change combines with factors that increase vulnerability. Examples of these impacts include malaria, diarrhea, and health impacts from malnutrition, all of which are strongly affected by both climate conditions and poverty. These effects will most strongly affect low- and middle-income populations, especially in Africa south of the Sahara, South Asia, and small island developing states (WHO 2009a). Vulnerable groups, including children, women, elderly people, those with existing health problems and disabilities, and the poor and marginalized, will be disproportionately affected (Watts et al.

2015; WHO 2009a). The impacts of climate change on health have special implications for women. As noted above, women are a part of the population that is expected to disproportionately affected and potentially experience greater health burdens. Yet women face greater difficulties in accessing healthcare and protecting their health than men, obstacles that in many cases result from gender-based inequalities related to income, education, employment, and social status. It is also notable that healthcare costs are generally higher for women than men (WHO 2009b). In addition to their own health concerns, women will also be disproportionately affected by the health of their family members. Especially in low-income settings, women are primarily responsible for taking care of children, the elderly, and other family members (WHO 2009b; Ferrant, Pesando, and Nowacka 2014). Because they carry the greatest burden of time for care work, women will have less time and ability to engage in other types of productive work, either paid or unpaid.

Figure 3.1 Effects of climate change on human health



Source: Created by authors, based on WHO 2009a; WHO 2009b; Watts et al. 2015; McMichael, Woodruff, and Hales 2006; and IWGCCH 2010.

The complexity of causal pathways makes it hard to definitively link climate change to impacts on human health (McMichael, Woodruff, and Hales 2006; Watts et al. 2015; Whitmee et al. 2014). Though not all effects can be directly observed, estimates can be made of the ill-health burden that is attributable to climate change. Through the WHO's Global Burden of Disease project, researchers estimated that impacts from climate change caused about 160,000 deaths and the loss of 5.5 million disability-adjusted life years globally in the year 2000 (cited in McMichael, Woodruff, and Hales 2006). Another WHO report found that an estimated one-quarter of the global disease burden and one-third of the burden in children could be attributed to modifiable environmental factors (cited in Whitmee et al. 2014). The WHO has also estimated that an additional 250,000 deaths will potentially occur annually between 2030 and 2050 as a result of the well-understood impacts of climate change. These include deaths from malaria, malnutrition, heat stress, and diarrhea (WHO 2016). However, this estimate of the global health burden is quite limited, and it is well acknowledged that the health effects of climate change will become amplified over time (Watts et al. 2015).

Direct Health Effects

Direct health effects are expected to occur through changes in extreme weather and resulting storms, floods, droughts, or heat waves (Watts et al. 2015). An increase in the number of warm days and nights will lead to an increase in the frequency and intensity of heat waves. This change will also increase the risk of fire in low-rainfall conditions. The resulting health risks include excess heat-related mortality; increased incidence of heat exhaustion and heat stroke; and exacerbated circulatory, cardiovascular, respiratory, and kidney diseases. Ozone and air pollution resulting from fire, two issues that are discussed in greater depth later in this section, will also lead to increased premature mortality. Other impacts include greater risk of injury, disease, and death due to more intense heat waves and fire. Outdoor laborers, athletes, and the elderly are at greater risk for these health impacts (McMichael, Woodruff, and Hales 2006; Watts et al. 2015; WHO 2009a). Upward trends in population, urbanization, and migration indicate that the proportion of people exposed to hot weather will increase (Watts et al. 2015).

Heat waves have an especially negative impact on health (Watts et al. 2015). One example of such an impact was the 2010 heat wave in Russia, which was the most severe heat wave recorded globally in recent decades, according to the Heat Wave Magnitude Index. More than 250,000 fires over a region of 1.1 million hectares raised levels of carbon monoxide, nitrogen oxides, aerosols, and particulate matter in European Russia. A smoke plume covered Moscow in August 2010, doubling the normal level of particulate matter. The heat wave and consequent air pollution caused 110,000 additional deaths, as compared with the previous summer (Watts et al. 2015).

It has also been posited that the decreased number of cold days and nights may lead to lower cold-related mortality and reduced cardiovascular and respiratory disease. This change is especially salient for the elderly in cold and temperate environments. The health impact could potentially lead to an improvement in cold-related mortality and morbidity, but the likelihood of this change as compared with that of negative health impacts from increased heat is not completely clear. Though the WHO states that extreme heat has a more negative effect on health than cold weather, and thus the benefits from fewer cold days and nights are less likely, other research indicates that nonoptimum ambient temperature is responsible for excess mortality, with most attributable deaths caused by cold rather than heat (Gasparrini et al. 2015; WHO 2009a).

The increased frequency of extreme weather events will have substantial immediate, short-term, and long-term effects on human health (McMichael, Woodruff, and Hales 2006). These events, which include floods, hurricanes, and storm surges, have immediate risks, exemplified by the 6,000 fatalities that resulted from 2013's Typhoon Haiyan in the Philippines. In the short and long term, flooding also negatively affects well-being through disease outbreaks, mental health issues, and displacement (IWGCCH 2010; Watts et al. 2015). The risks related to extreme precipitation affect large swaths of people (Watts et al. 2015).

Indirect Health Effects

In addition to direct health impacts from climate change, humans will also experience indirect effects mediated through natural systems. Higher temperatures and humidity, changing and increasingly variable precipitation, and higher sea surface and freshwater temperatures are all drivers of negative health impacts. These changes lead to risks of accelerated microbial growth; persistence, transmission, and virulence of pathogens; and shifting geographic and seasonal distributions of diseases such as cholera and schistosomiasis. Additionally, changes in climate will result in a lack of water for hygiene, flood damage to water and sanitation infrastructure, and contamination of water sources through overflow, the latter especially true of human and animal waste entering waterways (McMichael, Woodruff, and Hales 2006). Resulting health impacts include increased risks of food- and waterborne diseases. For example, cholera is transmitted through tainted water sources and often occurs in conjunction with seasonal algal blooms. Cholera outbreaks sometimes occur after extreme weather and in association with El Niño through drinking water that is contaminated by wastewater (Watts et al. 2015). The likelihood of these health risks' occurring is considered to be very high (IWGCCH 2010; McMichael, Woodruff, and Hales 2006; WHO 2009a).

Higher temperatures and humidity, and changing and increasingly variable precipitation also lead to risks of vector-borne disease. These risks include accelerated parasite replication and biting rates, prolonged transmission seasons, reemergence of previously prevalent diseases, changing distribution and abundance of disease vectors, and reduced effectiveness of vector-control interventions (IWGCCH 2010; McMichael, Woodruff, and Hales 2006; WHO 2009a). One example of a vector-borne disease influenced by climate change is malaria. Climate affects the reproductive rates and range of malarial mosquitoes, as well as the life cycle of the parasitic protozoan that is responsible for malaria. Malaria incidence has already been linked to higher air temperatures in some highland areas (Watts et al. 2015). The WHO estimates that malaria is responsible for 2.9 percent of the world's total disability-adjusted life years (cited in IWGCCH 2010). Another example is the Zika virus, which is considered to have spread explosively throughout Brazil in part because of climate conditions caused by the 2015 El Niño season. Brazil's record warm temperatures were accompanied by a severe drought that led to an increase in water storage in household containers, a practice that is correlated with a range expansion for Aedes aegypti mosquitoes (Paz and Semenza 2016). The temperature and precipitation range in the southeastern region of the United States presents an environment that is highly suitable for transmission of vector-borne diseases; although the majority of reported Zika and malaria cases in the United States are associated with travel, both Texas and Florida have experienced locally acquired cases of Zika, and the number of malaria cases reported in the country in 2013 was the third-highest annual total since 1973, with a small percentage of cases attributable to local transmission in southern states (Messina et al. 2016; CDC 2016; Cullen, Mace, and Arguin 2016). Equally significant climate-related risks are associated with dengue fever, cholera, and food safety (Watts et al. 2015).

The effects on health can also be mediated by human systems. Higher temperatures and changes in precipitation lead to risks such as lower food production in the tropics and lower access to food due to reduced supply and higher prices. Other risks include the combined effects of undernutrition and infectious diseases, and the chronic effects of stunting and wasting in children. Ultimately, these effects lead to a greatly increased risk of undernutrition resulting from diminished food production in poor regions (Watts et al. 2015; WHO 2009a). Higher temperatures and humidity also lead to risks for outdoor and unprotected workers who work in unsafe conditions. The health effects of these conditions can lead to lost work capacity, lost income and livelihood opportunities, and reduced labor productivity in vulnerable populations (WHO 2009a).

There is also evidence that factors affected by climate influence the prevalence of neurological diseases and deficits. These factors include malnutrition; exposure to hazardous chemicals, biotoxins, and metals in food, air, and water; and changes in pest management. Though the relationship between environmental factors and neurological disease is not yet fully understood, these factors are suspected to play a role in the development of learning disabilities, Alzheimer’s disease, and Parkinson’s disease (IWGCCH 2010).

Drivers of climate change, such as air pollution and ground-level ozone, also influence human health. Through fine particulate matter, air pollution causes cancer, cardiovascular disease, and respiratory diseases. Each year, 4.3 million deaths occur because of household air pollution, which is largely produced by the combustion of solid fuels on cookstoves in poorly ventilated buildings in the world's poorest communities. Outdoor air pollution is estimated to cause 3.7 million premature deaths annually. Almost 90 percent of the global urban population is exposed to air that does not meet WHO air quality standards. Black carbon makes up a large proportion of particulate pollution in many areas worldwide. This particulate matter is a short-lived climate pollution, like ozone and methane, that contributes significantly to warming and damages health. There is also a significant intersection between carbon dioxide, the main driver of long-term climate change, and health-damaging pollution (WHO 2009a). Ground-level ozone and particulate air pollutants are projected to experience significant increases as a result of climate change (Watts et al. 2015).

Though many of the health impacts of climate change will be felt most strongly in vulnerable, low-income countries, these impacts also hold special implications for those in the United States. As is true around the globe, the health impacts of climate change will most severely affect vulnerable populations in the United States. Those with preexisting health conditions, children, some communities of color, and low-income groups already experience a greater burden of ill health due to climate change and are at a higher risk of dying (The White House 2014). As noted previously, women will also experience a disproportionate burden of caring for family members, especially in areas where the healthcare system functions poorly.

Climate change is predicted to elevate ground-level ozone levels over large portions of the United States, especially in the Northeast and Midwest, over the coming century. Ozone-related acute mortality in the country will rise by an estimated 4.5 percent from 1990 to 2050 (Watts et al. 2015). Ozone is associated with increased risk of diminished lung functioning, particularly for children, and premature adult mortality (The White House 2014).

The frequency and severity of wildfires in the American West and Southwest are also projected to increase as a result of climate change. Wildfire smoke contains particulate matter, carbon monoxide, nitrogen oxides, and other pollutants. Smoke exposure, both directly and in areas downwind of fires, can lead to greater incidence of bronchitis, asthma, chest pain, and other cardiovascular and respiratory issues (The White House 2014).

Vector- and waterborne diseases are expected to increase, as are direct health risks from heavy precipitation. Different parts of the country will experience increases in vector-borne infectious diseases including Lyme disease, dengue fever, West Nile virus, and Rocky Mountain spotted fever. Floods, one of the deadliest weather-related hazards in the United States, are expected to continue increasing in frequency and severity in conjunction with the rise in heavy precipitation events. In addition to the immediate health hazards of heavy precipitation, elevated reports of waterborne disease outbreaks often occur in the weeks following a heavy precipitation event. In addition, warmer air temperatures lead to increased production of plant-based allergens, which are expected to cause more pollen-related allergies and asthma episodes (The White House 2014).

4. CLIMATE CHANGE IMPACTS ON THE MULTIPLE BURDENS OF MALNUTRITION

Key Points

1. Climate change affects maternal and child health through an increase in infectious diseases and a decrease in food intake due to decreased food availability and increased food prices.
2. Girls in low-income countries, including those in Africa south of the Sahara and South Asia, are often the most impacted by decreased food intake due to preferential feeding of boys.
3. Extreme weather events have been shown to increase child wasting and stunting, and

Introduction

Determinants of maternal nutrition and optimal child growth and development range from underlying factors, such as socioeconomic status and environmental conditions, to more direct determinants, such as food and nutrient intake and disease (Black et al. 2013). To further complicate matters, the implications of climate change extend across all determinants of malnutrition. By some projections, medium-high climate change is expected to result in an additional 4.8 million undernourished children by 2050 (IFPRI 2017) (Table 4.1). Our emphasis on malnutrition as a consequence of climate change is supported by a plethora of evidence linking the dire effects of malnutrition with productivity and health at different scales, be they the individual, household, national, or global levels (Victora et al. 2008).

Table 4.1 Number (in millions) of undernourished children younger than five in 2000 and 2050 using the National Center for Atmospheric Research climate model and the A2 scenario

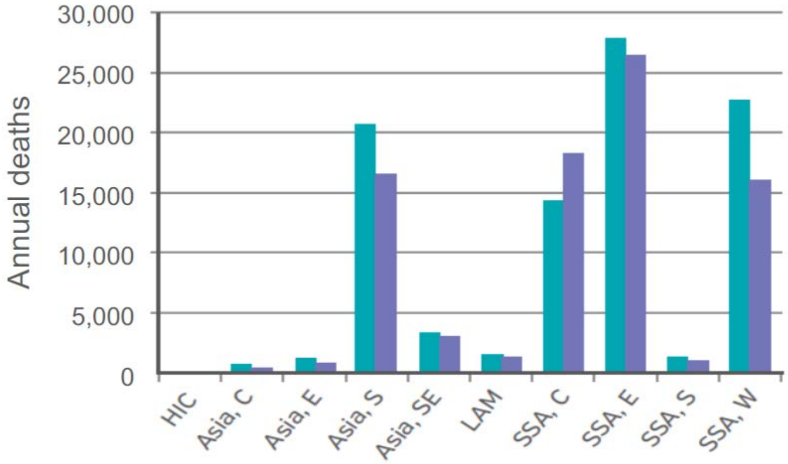
	No. of undernourished children younger than five, in millions			
		2050		
Region	**2010, base climate**	**Without climate change**	**With climate change**	**Additional no. of children undernourished because of climate change 2010–2050**
Africa south of the Sahara	40.9	37.0	39.3	2.4
South Asia	77.1	50.4	51.9	1.4
East Asia / Pacific	21.9	7.8	8.2	0.4
Latin America & Caribbean	4.3	1.5	1.8	0.3
Middle East / North Africa	4.0	1.7	1.9	0.2
Europe and former Soviet Union	1.8	1.5	1.6	0.1
WORLD	150.0	99.9	104.8	4.8

Source: IFPRI (2017).

In 2004, childhood undernutrition (stunting, wasting, and low birth weight due to intrauterine growth restriction) was responsible for 2.1 million deaths and 91.0 million disability-adjusted life years in children younger than five, with the highest burden in South-Central Asia (Black et al. 2008). Childhood stunting (height-for-age *z*-score < -2) affects approximately 162 million children five years old and younger, and has long-term implications at the individual, household, and community levels (Victora et al. 2008). Stunting in the first two years of life can lead to shorter adult height, lowered cognitive functioning, and reduced adult income (Briend, Khara, and Dolan 2015; Victora et al. 2008). Childhood wasting (weight-for-height *z*-score < -2) is estimated to be at 10 percent globally, with 52 million children affected (Black et al. 2013). Child wasting is associated with reduced lean mass, increased risk of infection, and mortality (Briend et al. 2015). Low birth weight (< 2,500 g) is associated with high adult body mass index (Black et al. 2008) and increased risk of cardiovascular and metabolic disease in later life if followed by rapid weight gain (Barker et al. 2005; Prentice and Moore 2005).

Figure 4.1 shows the estimated future undernutrition all-cause mortality of children younger than five due to climate change in 2030 (light blue bars) and 2050 (purple bars), distributed by world region. Results are shown for the A1B emissions scenario, assuming only weak action to mitigate climate change (that is, most similar to the RCP8.5 pathway) and continued economic growth. These estimates do not include indirect effects such as those due to conflict; migration; reduced labor productivity; or interactions with other environmental changes, such as ocean acidification and biodiversity loss. The most significant mortality will be in Central, East, and West Africa south of the Sahara and in South Asia (WHO 2015).

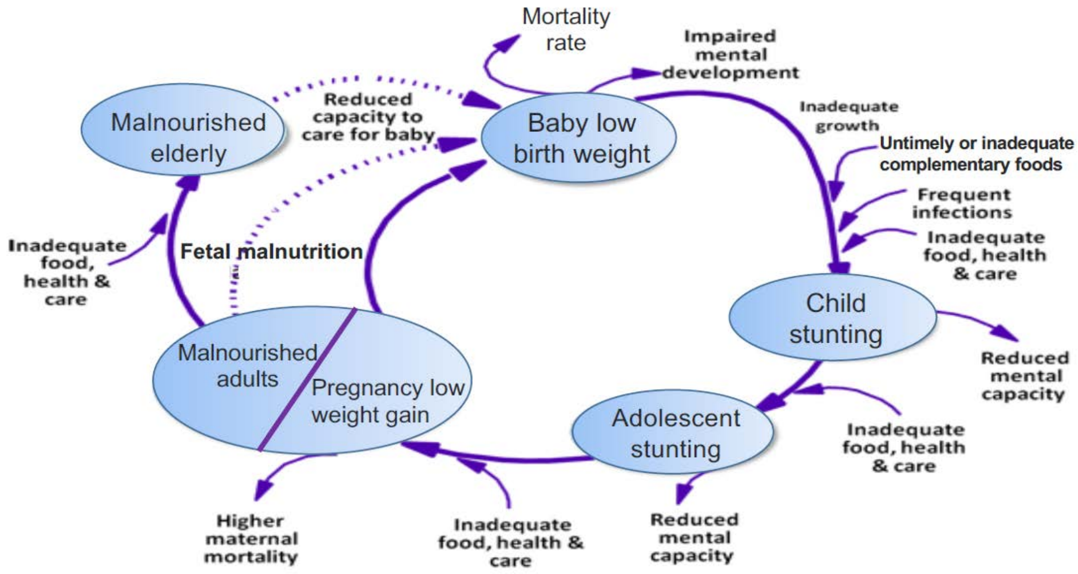
Figure 4.1 Undernutrition mortality of children younger than five due to climate change, by world region, 2030 and 2050



Source: Adapted with permission from WHO (2015).
Note: Estimated future mortality due to climate change in 2030 (light blue bars) and 2050 (purple bars). Region codes: HIC = high-income countries (includes Asia Pacific, high income; Australasia; Europe, Central; Europe, western; North America, high income; and Oceania); Asia, C = Asia, Central; Asia, E = Asia, East; Asia, S = Asia, South; Asia, SE = Asia, Southeast; LAM = Latin America (includes Latin America, Andean; Latin America, central; Latin America, southern; Latin America, tropical; and Caribbean); SSA, C = Africa south of the Sahara, central; SSA, E = Africa south of the Sahara, eastern; SSA, S = Africa south of the Sahara, southern; SSA, W = Africa south of the Sahara, western. Estimates for North Africa / Middle East are not included.

Because rapid growth faltering typically occurs before the age of two years (Victora et al. 2010), interventions aimed to prevent malnutrition are often targeted at infants and young children. However, there are other potential windows of opportunity to improve nutrition status, such as the first 1,000 days, which includes pregnancy and infancy, as well as later childhood and adolescence (Prentice et al. 2013). The intergenerational effects of malnutrition have a proven impact on child growth: beginning with pregnancy, short maternal stature (a consequence of poor nutrition in childhood) is associated with low birth weight and child stunting, which has implications on adolescent nutritional status and, in turn, leads to a repetition of the cycle (Martorell and Zongrone 2012) (Figure 4.2). Because climate change results in short-term shocks and long-term stressors, it will have an impact across the entire life cycle.

Figure 4.2 Chronic undernutrition through the life cycle



Source: Reprinted with permission from ACC/SCN (2000).

Climate change can exacerbate undernutrition through three main pathways: impacts on household food security (access to safe, affordable, and sufficient food), impacts on child feeding and care practices, and impacts on environmental health and access to health services (Met Office and WFP 2012). Calorie insufficiency resulting from inadequate food intake is currently the leading cause of child undernutrition (Black et al. 2008). Climate change is expected to lead to an increased risk of stunting and micronutrient deficiencies due to reduced food availability (measured as calories available) as well reduced availability of fruits, vegetables, and red meat, with large regional variations in the extent of this reduction (Springmann, Mason-D'Croz, Robinson, Garnett, et al. 2016).

Climate change has a significant impact on maternal and childhood nutrition but also affects nutrition in all populations. Climate change affects what food is available and at what price, impacting overall calorie consumption as well as consumption of healthful foods such as vegetables, fruits, and animal-source foods. Springmann, Mason-D'Croz, Robinson, Garnett, and colleagues (2016) estimated the increased mortality due to climate change–mediated changes in diets in 2050 and found that these changes were associated with 529,000 deaths. These deaths were due to decreased food intake overall, but more importantly, from decreased vegetable and fruit consumption. These dietary changes were projected to result in changes in weight and noncommunicable diseases, including cancer and cardiovascular disease (Springmann, Mason-D'Croz, Robinson, Garnett, et al. 2016).

Undernutrition is also closely linked with socioeconomic factors, many of which have a gendered dimension that contributes to the vulnerability of women. Though not the focus of this section, these factors constitute underlying determinants of malnutrition and underpin the heightened risk of malnutrition for women, and thus for their children. As discussed earlier, women in low- and middle-income countries are often the primary caregivers for children and sick family members. Additionally, they are often responsible for producing and acquiring food (Smith and Haddad 2000). Women's education and their status relative to men's are strongly associated with child malnutrition. Smith and Haddad (2000) found that in low- and middle-income countries from 1970 to 1995, improvements in female secondary school enrollment rates were responsible for an estimated 43.0 percent of the total 15.5 percent reduction in child underweight rates. Water cleanliness, sanitation, and access to health services are other socioeconomic factors strongly associated with malnutrition.

This section of the paper will discuss the literature available on the effects of and pathways from the different manifestations of climate change to nutrition (Phalkey et al. 2015), with a focus on the most vulnerable populations, including children and women.

Effects of Changes in Rainfall on Nutritional Status

Globally, more than 80 percent of agriculture is rainfed: 95 percent of croplands in Africa south of the Sahara, 90 percent in Latin America, 65 percent in East Asia, and 75 percent in the Middle East and North Africa (FAOSTAT 2005). The importance of rainfall is evident in terms of food supply and availability, which have direct implications for nutritional status. The effects of changes in rainfall vary across regions and subpopulations. For example, in Rwanda, girls—but not boys—who were born in years with large positive rainfall shocks (increased rainfall) but normal rainfall on average had higher height-for-age *z*-scores (HAZs), which measure a child's height for his or her age, compared with those born in years with large negative rainfall shocks (decreased rainfall) (Akresh, Verwimp, and Bundervoet 2011). The pathway through which rainfall affected HAZs was crop failure, with observed gender differences linked to preferential feeding. A similar positive relationship between rainfall and HAZs was found in Kenya, but the degree to which HAZs changed was irrespective of child gender and varied across livelihoods (Grace et al. 2012). The opposite was found in Mexico, where increased rainfall (a positive rainfall shock) in the previous agricultural year was associated with lower HAZs for boys and girls one to four years old, regardless of region and altitude (Skoufias and Vinha 2012). The authors postulated that the pathway from a change in rainfall to a change in HAZ was through a change in communicable disease (Skoufias and Vinha 2012).

A change in rainfall was also shown to impact low birth weight, defined as less than 2,500 grams, in Africa south of the Sahara, where an increase in growing-season rainfall during the three months prior to conception and the first trimester of pregnancy decreased the risk of low birth weight for agriculturalist households and those with other livelihoods, respectively (Grace et al. 2015). This result was irrespective of household wealth, birth season, or country of residence (Grace et al. 2015). A change in rainfall due to climate change could therefore have a positive or negative effect in terms of food production, communicable disease, and child nutrition outcomes. An increase in rainfall could support food production, especially in countries in Africa south of the Sahara where advanced irrigation technologies are uncommon, and result in higher quantities of food available during pregnancy and infancy (Grace et al. 2015). Increased food availability could also influence food prices, which in turn affect the food access of these households. However, the opposite could also be true, with increased rainfall damaging crop output, which in turn could negatively affect child nutritional status through these same pathways (Akresh, Verwimp, and Bundervoet 2011).

Effects of Changes in Temperature on Nutritional Status

Similar to precipitation, changes in temperature have both positive and negative impacts on nutritional status, with regional differences. In Kenya, no relationship was found between an increase in temperature in the previous agricultural year and HAZ (Grace et al. 2012). In Mexico, however, negative temperature shocks had negative impacts on child height in the central and southern parts of the country (Skoufias and Vinha 2012). Although there were no statistically significant impacts from positive temperature shocks on overall HAZ, negative impacts were found in certain subpopulations: boys, children between 12 and 23 months old at the time of measurement, and children of less educated mothers were more vulnerable, possibly due to suboptimal care practices (Skoufias and Vinha 2012). Changes in temperature have also been found to affect birth outcomes. Grace and others (2015) found that an increase in the number of hot days (37.8°C or warmer) at any point during pregnancy led to an increase in the risk of low birth weight; the authors suggested this effect may be related to heat stress instead of a change in food production. A similar relationship with high temperatures was found for preterm birth in California, where an 8.6 percent increase in preterm birth was associated with a 5.6°C increase in weekly average temperature (Basu, Malig, and Ostro 2010). The effect of temperature was found in all mothers, regardless of maternal ethnicity, age, or education, or sex of the infant (Basu, Malig, and Ostro 2010). An increase in the agricultural workload of pregnant women is known to increase the risk of preterm birth, and researchers have suggested that bending and standing exacerbate this risk (Owens et al. 2015). With increasing temperatures and heat stress, it is likely that we will observe a higher prevalence of preterm births in populations in which women participate in agricultural work.

Effects of Extreme Weather Events on Nutritional Status

The IPCC has stated, “malnutrition linked to extreme climatic events may be one of the most important consequences of climate change” (IPCC 2007, 413–414). A growing body of literature quantifies the effects of extreme weather on nutritional status, with evidence suggesting that temporary shocks have permanent effects (Dercon et al. 2013). A study in India looked at the effect of being exposed to any sort of natural disaster and found that such exposure of children younger than five in the past year reduced HAZ and weight-for-age *z*-score by 0.15 and 0.12 units, respectively, and increased the likelihood of stunting and underweight by 3 percent (Datar et al. 2013). Boys were less likely than girls to be stunted and wasted, suggesting preferential feeding in favor of boys (Datar et al. 2013). Moreover, infants seemed to fare better as well, suggesting a protective effect of breastfeeding (97 percent of children under the age of one were breastfed). Climate effects seemed to be as important as socioeconomic indicators for nutrition outcomes, implying the importance of climate change mitigation (Datar et al. 2013).

The different types of extreme weather that result from climate change have varying effects on maternal and child nutritional status. For example, drought has been found to be associated with stunting in Africa south of the Sahara (UNDP 2007). In Niger, children two years old or younger who were born in a drought year were 72 percent more likely to be stunted, compared with those born in a nondrought year (UNDP 2007). In Ethiopia, children five years old or younger were 41 percent more likely to be stunted if they were born during a drought year and affected by it (the report did not mention the pathways of effect) (UNDP 2007). Children in rural Zimbabwe who were between 12 and 24 months old in a drought year experienced slower annual growth rates (1.5 to 2.0 cm less) than children of a similar age in nondrought years (Hoddinott and Kinsey 2001). The authors considered a shortage in food consumption and a loss of income as pathways from drought to slowed growth. This slowdown in growth was not observed in older children (24 to 60 months) (Hoddinott and Kinsey 2001). A similar effect between drought and child height was found in Ethiopia for children 6 to 24 months old (Woldehanna 2010). The effects of drought on underweight are similar to those on height, with children five years old or younger in Kenya and Ethiopia found to be 50 percent and 36 percent, respectively, more likely to be underweight if they were born in a drought year (UNDP 2007).

On the other end of the spectrum of extreme weather, flooding also has short-term and long-term detrimental effects on nutritional status. In Bangladesh, flood-exposed children were smaller than their peers in non-flood-exposed areas and had poor prospects for catch-up growth (del Ninno and Lundberg 2005). In rural eastern India, children living in households that had experienced flooding were more likely to be stunted and underweight than children in households that had no experience with flooding. Children were especially at risk for stunting if they experienced flooding during infancy (Rodriguez-Llanes et al. 2011). The pathways through which flooding may have affected nutritional status were not explicitly discussed in these papers and warrant further research. In Tumbes, Peru, the 1997–1998 El Niño was associated with children’s having a lower mean HAZ if they were born at or shortly after its onset, compared with a scenario in which El Niño did not occur. The most vulnerable children, showing poor prospects of any future improvement in growth, were those living in the households most likely to be flooded due to El Niño (Danysh et al. 2014); the effects of El Niño appeared to be long-term and were found in children three years after the initial flood. The pathway of the negative effects of El Niño on child growth was through flooding, whereby floods could have led to an increase in infectious disease and decreased food availability. Children born at or shortly after the start of El Niño had less lean mass, but not fat mass, than what would be expected if El Niño had not occurred. This pathway from El Niño to poor child growth could potentially be due to decreased availability of calorie- or nutrient-dense foods (Danysh et al. 2014).

Impacts of Seasonality on Nutritional Status

Seasonal variation affects food supply and agricultural income. In some areas, seasonal variation is well established and predictable, and farmers have been able to rely on these variations for planting and harvesting.

Even when these predictions are accurate, climate still drives seasonal patterns of food insecurity, including the availability of micronutrient-rich foods, and patterns of human behavior, to generate a complex series of interacting effects (Devereux et al. 2013). These effects are particularly acute in regions where the rains are highly seasonal and agriculture is rainfed. Seasonal food insecurity can lead to low dietary diversity and a concomitant insufficiency of micronutrients such as dietary iron (Savy et al. 2006). Most of the world’s acute hunger and undernutrition occurs not during conflicts and natural disasters but during these annual “hunger seasons,” the times of year when the previous harvest’s stocks have dwindled, food prices are high, and jobs are scarce. These hunger seasons are most severe when unpredictable rainfall or extreme weather events occur. What happens during seasonal hunger and what happens during famine differ only in severity, but coping sequences are similar (Devereux et al. 2015).

The frequency and the intensity of seasonal hunger is expected to increase with climate change and to be especially severe in Africa south of the Sahara. Climate change disrupts seasonal weather patterns, changing the timing and intensity of precipitation and making weather prediction more difficult. Climate change causes changes in the onset and end of overall seasonal rains as well as the timing of rain within the season, often condensing rains into fewer, more intense storms with longer intervals between them. These changes in seasonal weather cause problems for farmers in planning their planting and harvesting, and can result in crop damage and failure, either from too little water or from direct storm damage (Devereaux et al. 2013). All of these factors are detrimental to food production, negatively affecting food quantity and agricultural income. Many of the poorest rural populations rely on this income to supplement their food intake, and this loss in income means less food intake overall and a decrease in the most nutrient-dense foods, which also happen to be the most expensive. The situation is worst for those with no income diversification who depend solely on agricultural income (GLOPAN 2015).

Summary of Climate Change Impacts on Nutrition

What are some of the key pathways that link climate change to nutrition? The effects of climate change on nutrition vary based on wealth status and livelihood (Grace et al. 2012), but overall, undernutrition is projected to worsen relative to a no-climate-change scenario if no action is taken. In that case, we will see a slowing of current downward trends in underweight and stunting. Wasting will also worsen, in the context of both seasonal changes and humanitarian situations.

Change in rainfall (level, pattern, or variability) results in crop failure, which affects nutritional status (stunting in particular) (Akresh, Verwimp, and Bundervoet 2011; Phalkey et al. 2015), but this effect varies by region (Phalkey et al. 2015). Furthermore, rainfall influences the amount of food available during pregnancy, which influences birth weight (Grace et al. 2015). Increased temperatures increase the risk of heat stress, which could influence birth weight as well (Grace et al. 2015). The combination of increased temperatures, decreased rainfall, and unstable food production will result in increased risk of future low-birth-weight babies in Africa south of the Sahara (Grace et al. 2015). Natural disasters also make an impact. Drought has the potential to lead to a shortage in food consumption as well as loss of income, resulting in slowed growth in children younger than two years (Hoddinott and Kinsey 2001). Flooding has short- and long-term effects on child height through changes in food consumption and infectious disease (Danysh et al. 2014; del Ninno and Lundberg 2005; Rodriguez-Llanes et al. 2011).

5. CLIMATE CHANGE DISRUPTIONS TO THE FOOD SYSTEM, TO FOOD ENVIRONMENTS, AND TO DIETS

Key Points

1. The global food system is one of the primary drivers of climate change, contributing between 19 and 29 percent of worldwide greenhouse gas emissions, but at the same time it is also directly affected by climate change, which will have serious impacts on its ability to produce enough safe and nutritious food.
2. For food production, climate change is expected to cause wet areas and seasons to become wetter and dry areas and seasons to become drier. These effects will cause changes in where food can be produced and increase heat and water stress, pests, and diseases in crops and livestock. All of these factors will result in decreased yields while also decreasing the nutritional value of food through carbon dioxide effects that decrease protein, iron, and zinc, and degraded soil that decreases overall nutritional quality.
3. For food storage, processing, and transportation, climate change is expected to increase foodborne pathogens and mycotoxins, increase cold storage requirements, increase food waste from extreme weather events, and pose new transportation challenges.
4. For food marketing and retail, climate change is expected to cause decreased food availability and increased food prices that will lead to decreased food for those who are already food insecure or at risk of being so.
5. For consumption and utilization, decreased consumption paired with increased nutritional needs and decreased intestinal nutrient absorption due to increased infectious diseases will lead to serious nutritional challenges, relative to no climate change, that will be the most severe in the most vulnerable populations.

Introduction

The food system encompasses everything from food production to food consumption and the many steps in between. Each one of these steps in the value chain has the potential to impact nutrition and can be nutrition sensitized in order to ultimately increase people's consumption of nutritious foods (Fanzo et al. 2017). Food production determines what food is available and what its nutritional quality is. The food environment determines what food people have access to, in terms of both availability and price. Many additional complicated factors, ranging from personal preference to convenience, further influence what foods people choose to buy and ultimately consume. The diversity of what people consume is critical for their nutritional status. Dietary diversity, as measured through the number of food groups consumed and the amount of highly nutritious vegetables, fruits, and animal-source foods consumed, is connected to adequate nutrition, especially micronutrient adequacy (Arimond et al. 2010; Ruel, Alderman, and Maternal and Child Nutrition Study Group 2013). Finally, health status impacts how the nutrition in consumed foods is absorbed and used by the body. Therefore, in order to improve nutrition status, the entire food system must be addressed. It is crucial to act at every step of the value chain, because all the steps are interrelated and act together to impact nutrition.

The world is experiencing climate change and variability that is affecting temperature and precipitation, as well as the frequency and severity of extreme weather events. Increases in temperature, heat waves, and droughts are likely to impact agriculture, with the largest impacts being decreased crop yields and livestock productivity, as well as declines in fisheries and agroforestry in low-resource areas that are already vulnerable to food insecurity (FAO 2016a). These impacts will further decrease access to sufficient nutrient-dense foods and impair nutritional status, as well as result in lower income and lower climate resiliency, in low-income communities (Mason and Shrimpton 2010).

Climate change is already challenging our ability to meet the world's food security and nutrition needs, and will increasingly do so in the future. The countries and communities in the southern tropics that do not have adaptation strategies in place will likely see a reversal of their previous gains in reducing food insecurity and undernutrition.

Food systems, which include all aspects of a functional food supply chain, from agricultural production through processing, distribution, retail, home food preparation, and consumption, contribute 19 to 29 percent of global anthropogenic greenhouse gas emissions (Vermeulen, Campbell, and Ingram 2012). Including indirect emissions associated with land-cover change, agricultural production contributes 80 to 86 percent of total food system emissions, with significant regional variation (Garnett et al. 2013). Modeling indicates that the impact of climate change on food systems will be widespread and variable, both geographically and temporally, because it is influenced by socioeconomic conditions. There is strong evidence that climate change will affect agricultural yields, food quality and safety, and food prices and access, which in turn will have significant implications for human health (Vermeulen, Campbell, and Ingram 2012).

It is also clear that the way in which animal-source foods are produced and consumed has an enormous impact on the environment and climate via water and land demands and direct and indirect greenhouse gas emissions, including the direct intensification of methane production. Ruminants, primarily beef cattle, have a much greater impact than animals such as pigs and chicken that are lower on the food chain. That said, ruminants have the advantage of being able to utilize native grazing lands that do not have alternative uses (Ranganathan et al. 2016). However, not all ruminants are raised on pasture, and those that are raised on concentrated feeds produce less methane than those that only graze (Harper et al. 1999). Therefore, the issue of ruminants' environmental impact is a complex one. Nevertheless, if current dietary trends continue at their present rate, there could be an 80 percent increase in agricultural greenhouse gas emissions by 2050 from food production and the required land clearing (Ranganathan et al. 2016). Moreover, these dietary shifts are greatly increasing the incidence of noncommunicable diseases related to overconsumption and obesity (You and Henneberg 2016; Bouvard et al. 2015).

Current animal-source food production systems and practices create substantial negative impacts on the environment because of emissions of greenhouse gases and other air pollutants, contamination of surface and groundwater, and degradation of ecosystem services (Ranganathan et al. 2016; Gerber et al. 2013). These impacts arise directly from the animals, such as from enteric fermentation and waste, and indirectly from the production of animal feed (Bouwman et al. 2013; Walker et al. 2005). In many agricultural contexts, however, animals are positively valued as investments and sources of fertilizer and energy (Steinfeld, Wassenaar, and Jutzi 2006).

Climate adaptation and climate-smart agriculture engage producer and consumer decision making through the triple-win scenario of improving food productivity and minimizing food loss, reducing greenhouse gas emissions coming from agriculture, and implementing adaptation strategies for the most vulnerable (Lipper et al. 2014). Producers have the ability to produce more nutritious foods while curbing greenhouse gas emissions and reducing food losses. Consumers can make better choices with their diet—consuming foods with lower environmental impacts, buying and eating only what is needed to decrease waste, and supporting local farm systems and producers (Scherr, Shames, and Friedman 2012).

A Nutrition-Sensitive Value Chain Framework

The food value chain provides a useful framework for examining how climate change will impact our food system and evaluating where nutritional outcomes may be at risk. Sites in the chain that are vulnerable to the impacts of climate change can be evaluated and interventions can be designed and "leveraged for change" in order to address food insecurity and malnutrition (Hawkes 2009).

The way food is produced and moves along the value chain can affect nutrition and diets, both positively and negatively, by creating both entry and exit points for nutrition along the chain. Value chains have been highlighted as a potential way to leverage agriculture to improve nutrition, particularly with regard to traditional value chains for micronutrient-rich foods (Ruel, Alderman, and Maternal and Child Nutrition Study Group 2013). However, value chains need to be considered more broadly in terms of the way in which all foods are produced, processed, distributed, and marketed, and how these activities can affect the nutritional quality of the foods that are accessible, affordable, and acceptable within the food environment.

It is also important to understand whether potential entry points are conceived to enhance (or prevent losses in) the nutritional value of foods during processing, or to fortify (or restore the nutrient content of) foods. Entry points to educate and raise awareness among the different actors in the value chain are also important because they can stimulate demand for targeted products. On the other hand, they can lead to an exit of nutrition from the chain when nutrients are removed from a given food as it moves along the value chain. Economic constraints, lack of knowledge and information, and related lack of demand for nutritious foods are critical factors that limit the access of poor populations to such foods. Figure 1.1 depicts the ways in which nutrition can enter and exit the value chain (Fanzo et al. 2017).

Changes in Food Production

Depletion of Natural Resources and Biodiversity in the Overall System

Agricultural production strains the most important natural resources, such as water and land. It uses an overwhelming amount of the freshwater supply, consuming more than 80 percent of the freshwater in the United States and 70 percent in the world (Marlow et al. 2009). Though 90 percent of crops are rainfed, irrigated crops have higher yields; for instance, the 10 percent of crops that are irrigated produce 40 percent of the cereal yield. However, irrigation adds to the large agricultural demand for water (FAO 2011a). Agriculture also uses 38 percent of the land in the world. Livestock is especially land intensive, using 70 percent of this land (UNEP 2010). The large demand for water and land strains natural resources and leads to conflicts. It also makes it impossible to simply scale up current agricultural production in order to meet projected needs.

Livestock provide animal products that are a key component of people’s diets. They provide 13 percent of all calories and 25 percent of all protein (FAO 2016b). In some cases, they are the main supply of protein as well as micronutrients such as calcium, iron, and zinc (Hobbs, Lovegrove, and Givens 2015). However, livestock are intensive in both water and land use. When livestock are fed grains, these must be grown on arable land. Currently 35 percent of the world’s crops are fed to livestock. Livestock also have varying efficiency in turning grain into meat. Beef is the most demanding, requiring up to 30 kilograms of grain to produce 1 kilogram of beef (Foley 2011). Livestock can be raised at pasture, using grass as feed, but currently only 14 percent of livestock are raised in this way, with another 16 percent raised on inedible crop byproducts. These methods are preferable because they do not pit livestock against people in a competition for food (Bajželj et al. 2014). Livestock also contribute to climate change through greenhouse gas emissions such as direct methane emissions.

Soil quality has also been declining due to intensive agriculture that favors monocropping as well as heavy agrochemical use (UNEP 2010). Soil quality is key for the micronutrient content of crops (Parr et al. 1992). Several studies have shown a decrease in micronutrients over the past century. Between 1950 and 1999, there were declines in protein, calcium, phosphorus, iron, riboflavin, and vitamin C in 43 different fruits and vegetables (Davis, Epp, and Riordan 2004). Between 1930 and 1980, there were decreases of 9 percent in calcium, 22 percent in iron, and 14 percent in potassium in 20 different vegetables (Mayer 1997). Declines in micronutrient content are not caused solely by soil quality; changes in cultivated varieties, anomalies in measurement, changes in the food system, and changes in agricultural practices are all possible explanations (Davis, Epp, and Riordan 2004; Mayer 1997). However, there is a clear link between soil quality and micronutrient content that warrants heightened awareness of soil quality.

Fisheries are another important source of protein, omega-3 fatty acids, and micronutrients for many populations. For 3.0 billion people, they provide 20 percent of total protein, and for 1.3 billion people, they provide 15 percent (FAO 2016b). However, overfishing has decimated ocean populations, and fish farms have created pollution and spread disease, all of which threaten this food source (UNEP 2010). The productivity of ocean fisheries peaked in the 1990s, and currently 57 percent of fisheries are used to their fullest potential and 30 percent are overexploited and expected to decline. We now get 50 percent of our fish from aquaculture, but this could be scaled up. In some cases, the inputs for aquaculture are not sustainable. Higher-value and more highly commercialized species, including shrimp and salmon, are carnivorous and require fish meal and fish oil in their diets. Aquaculture uses 63 percent of global fish meal and 81 percent of global fish oil to feed these and other carnivorous species (WRI 2013). Other species, including tilapia, catfish, and carp, are not carnivorous and can be more easily raised on plant-based proteins and oils. Of these, carp have an especially low feed intensity. Aquaculture is increasingly becoming more efficient, and feed efficiencies are improving, but it will be important to focus on these lower-intensity species. Despite the input requirements, aquaculture is important for food and nutrition security now and into the future, and it has the potential to be a sustainable source of animal protein (Msangi and Batka 2015).

Agriculture uses 30 percent of all fossil fuels and produces 20 percent of all greenhouse gas emissions (FAO 2011a). The conversion of energy from fossil fuels to calories requires 0.33 to 0.50 kilocalories of fossil fuels to produce 1.00 kilocalorie of grains or legumes, 1.00 kilocalorie of fossil fuels to produce 0.50 kilocalorie of fruits or vegetables, and 1.00 kilocalorie of fossil fuels to produce 0.01 to 0.05 kilocalorie of animal products. This comparison shows how much less efficient animal products are than grains and legumes. Fossil fuels are used in nitrogen fertilizer, synthetic agrochemicals, and fuel for machinery and transportation (Marlow et al. 2009). Some of the emissions from agriculture are carbon dioxide from fossil fuel use as just described, and others are methane emissions, primarily from cows but also from other ruminants and rice (Sjörs et al. 2016).

Humans are increasingly influencing ecosystems, largely in negative ways, which is causing irreversible changes to natural resources on which we rely for our food security (Whitmee et al. 2014). Forests, grasslands, and wetlands are being purposefully converted to farmland to feed a growing population, along with the animals that we consume (Ranganathan et al. 2016). This conversion is threatening many of the “planetary boundaries” within which our Earth can sustain itself (Rockström et al. 2009). Planetary boundaries are the central concept in an Earth system framework designed to define a “safe operating space for humanity” (Rockström et al. 2009) as a precondition for sustainable development. This framework is based on scientific research indicating that since the Industrial Revolution, human actions have gradually become the main driver of global environmental change (Whitmee et al. 2014). Scientists assert that once human activity has passed certain tipping points, the planetary boundaries, there is a risk of “irreversible and…abrupt environmental change” (Rockström et al.

2009, 472). Nine Earth system processes have boundaries that, to the extent that they are not crossed, mark the safe zone for the planet. However, because of human activities, many of them related to the food system, some of these dangerous boundaries have already been crossed and others are in imminent danger of being crossed. One of the major boundaries already crossed is loss of biodiversity and natural habitats that affect finite water and nutrient flows (Rockström et al. 2009).

Throughout the course of human history, humans have used roughly 7,000 plant species as food sources in addition to a wide array of animal, insect, and other species, including fungi, algae, yeasts, and bacteria (Wilson 1992). A shared axiom of ecosystems, diets, and nutrition is that, within certain ranges, diversity enhances the health and functioning of complex biological systems (DeClerck 2013; Khoury et al. 2014). Species diversity has been shown to stimulate productivity, stability, ecosystem services, and resilience in natural and agricultural ecosystems (Gamfeldt et al. 2013). There are nutrient content differences among varieties and breeds of the same species as well as differences between species (Bennett et al. 2015). Likewise, variation in food species contributing to diets has been associated with nutritional adequacy and food security (Steyn et al. 2006; Moursi et al. 2008; Arimond and Ruel 2004; Kennedy et al. 2007; Graham et al. 2007).

The clearing of forest, grassland, and wetlands results in a loss of both plant and animal species, some of which are key food sources. Their resulting loss decreases dietary diversity for some of the most vulnerable populations, who rely on foraging and hunting for food (UNEP 2010). Extensive use of agrochemicals to control weeds and other pests also causes species loss. Clearing weeds makes crops more productive, but some of these weeds are also edible and could provide a food source that is high in micronutrients. These may also be important food sources for vulnerable populations, such as women (Beuchelt and Badstue 2013). Pesticides also threaten pollinators that are critical for fruit and vegetable yields.

Many varieties of crops have also been lost due to a focus on maximizing productivity. National food supplies are becoming increasingly homogeneous and dependent on a couple of truly “global crops,” including major cereals and oil crops (Khoury et al. 2014), and current agricultural practices are moving further toward intensified monocultures, which increase grain yields in the short term but limit dietary and biological diversity (Graham et al. 2007; Negin et al. 2009; Khoury et al. 2014). Approximately 200 plant species and 5 animal species supply most of the foods consumed at the global level (Groombridge and Jenkins 2002; FAO 2004). Wheat, rice, and maize alone contribute roughly 56 percent of the global dietary energy supply derived from plants (Heywood, Fanzo, and Hunter 2013). In Figure 5.1, "What the Dots Mean" shows that the food supply composition of selected countries (in this figure, Belize, Nepal, Rwanda, Thailand, Kuwait, Niger, the United Arab Emirates, and the United States) is moving toward a more homogeneous state over time from the 1960s to the present day (Khoury et al. 2014). The concentric circles in the figure represent time, and the colored dots indicate food supply composition in relation to time. "Rise and Fall" shows how consumption, as measured in global average calories, for different food crops (wheat, rice, sugar, maize, soybean, cassava, palm oil, coconut, sunflower, sorghum, and millet) has changed during the same time period. In India (not in the figure), the number of varieties of rice that are grown has plummeted from more than 42,000 to just a few hundred (UNEP 2010). This homogenization risks a loss of species that may be key in adapting to climate change and also may have higher nutritional content than species currently being produced. The loss of these species is detrimental to future food production and nutritional quality (UNEP 2010). This homogeneity of the food supply will impact the availability of and people's access to a diverse set of foods that would contribute to dietary diversity and quality.

Figure 5.1 Homogeneity of the world's food supply

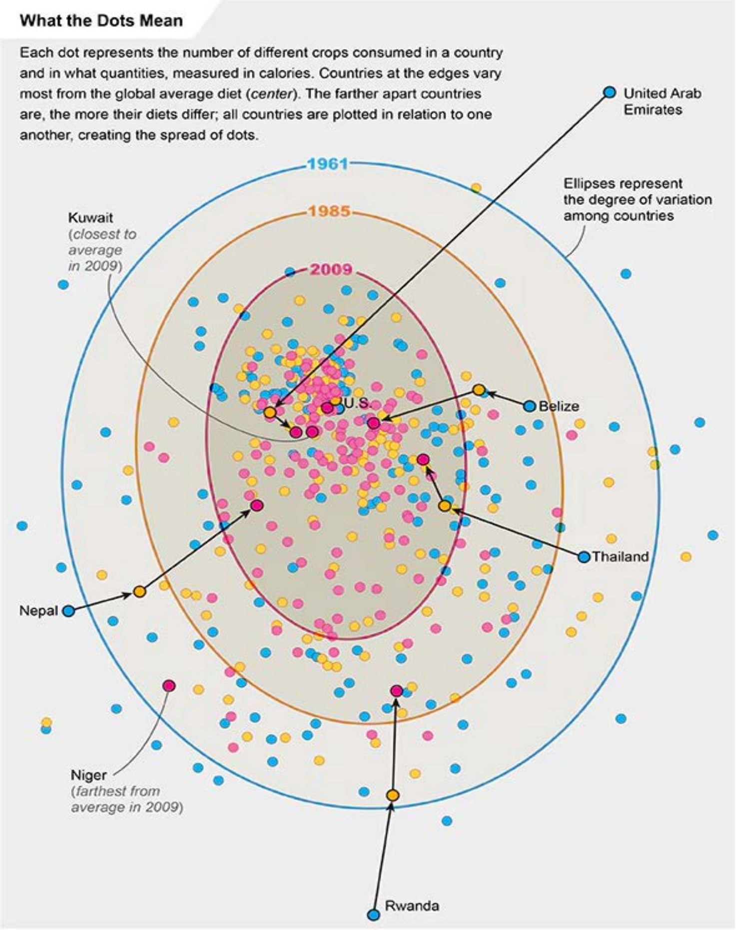
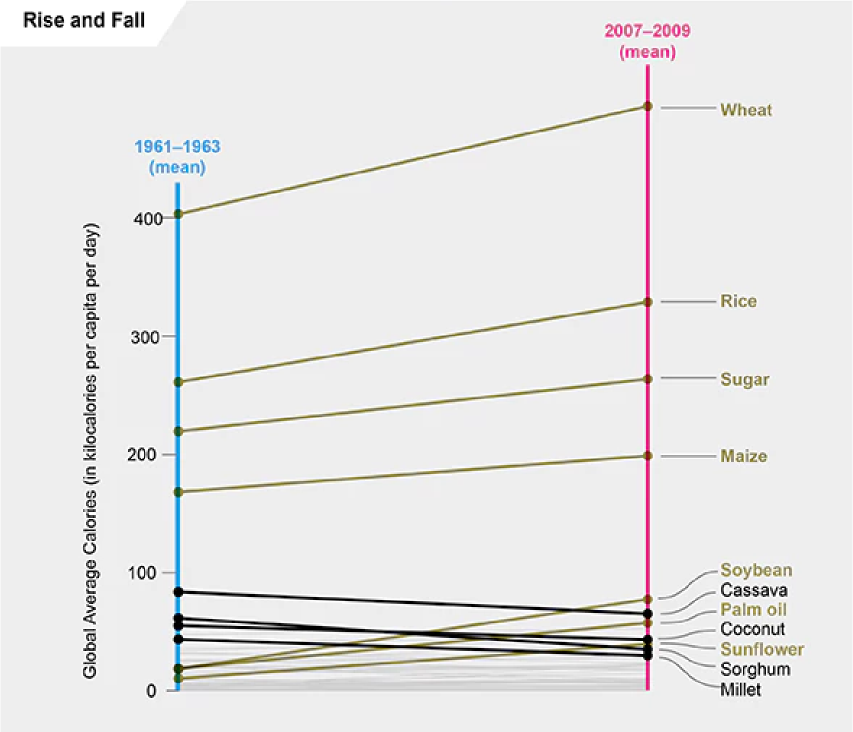


Figure 5.1 Continued



Source: Adapted from Khoury et al. (2014).

Unsustainable management of land, water, and other natural resources can lead to soil erosion, siltation in watersheds, seasonal water scarcities, and waterborne and insect vector–transmitted diseases. These situations, in turn, have negative effects on agricultural yields and incomes as well as on nutrition and health. Studies have shown that environmental degradation is associated with food insecurity, and malnutrition and certain ecosystem types are associated with infant mortality. Drylands, which offer limited ecosystem services, tend to have high rates of infant mortality (MEA 2005). For example, one study in West Africa demonstrated that child mortality is correlated with high soil degradation (Herforth 2010). Industrial agriculture often requires fossil fuel–based inputs such as fertilizers and pesticides. If not managed appropriately, agricultural runoff can contaminate soils, groundwater, and streams with volatile organic compounds. This contamination, in turn, can create dead zones that have impacts on ecosystems, economies, and human health. Pesticides have been shown to affect neurological, respiratory, and reproductive systems, and some have the potential to be carcinogenic (Landrigran and Benbrook 2015; Pimentel 2005).

Impacts on Food Quantity and Quality

According to the 2014 climate change report of the IPCC, climate change will affect food production in several regions of the world, including the size, diversity, and distribution of harvested aquatic species (IPCC 2014a). These effects are expected to have negative impacts on food security and nutrition for especially vulnerable people, particularly in some tropical low- and middle-income countries.

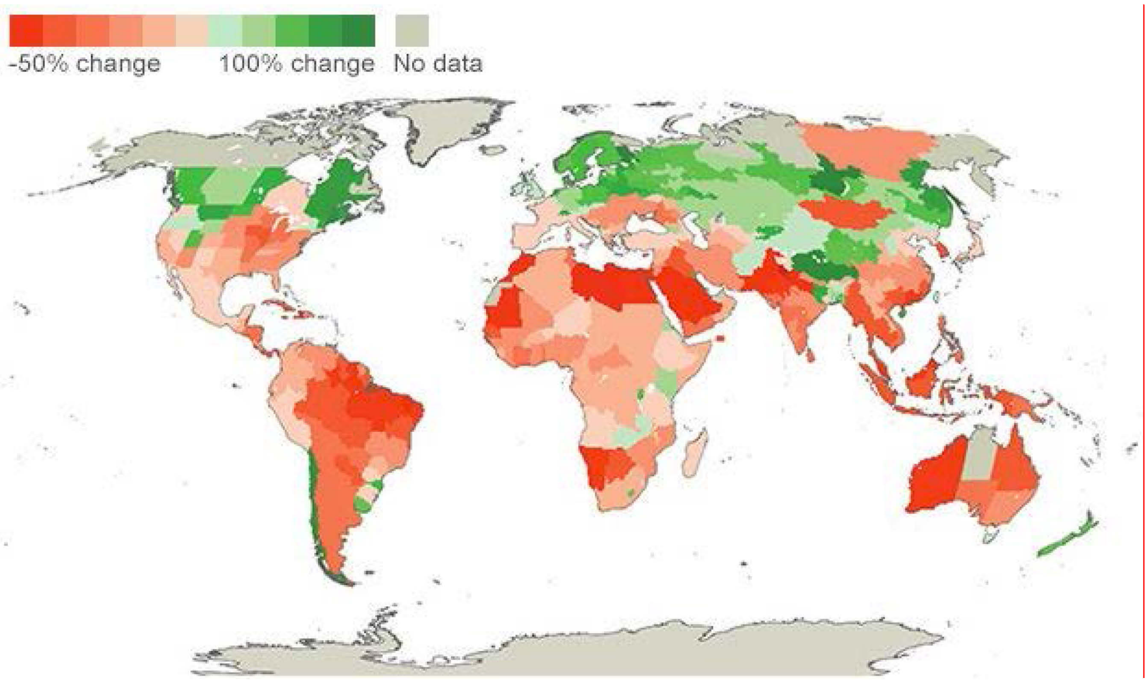
There are, of course, downstream negative impacts on food security, nutrition, and health outcomes from soil and water degradation, loss of biodiversity, and reduction of ecosystems. Temperature and rainfall shifts also have human health impacts due to weather extremes such as heat waves, droughts, and floods. Land degradation, water issues, soil nutrient loss, and the erosion of crop genetic diversity threaten people's present and future livelihoods as well as their nutritional status. Furthermore, climate change modeling shows reductions in global food availability with decreases in consumption of fruits, vegetables, and red meat by 2050. These reductions will potentially contribute to 529,000 deaths globally (Springmann, Mason-D'Croz, Robinson, Garnett, et al. 2016).

Climate change causes changes in atmospheric carbon dioxide, temperature, and precipitation. All of these affect crop and livestock productivity. Temperature increases past a suitable threshold stress plants and livestock directly and also cause many other indirect negative effects. Increasing temperatures cause increased water demands. They also increase diseases and pests, making them able to survive in new locations as well as earlier and later in the season. Heat-stressed plants are also more susceptible to pests and disease, decreasing yields and possibly also leading to increased use of agrochemicals for pest control.

Yields in maize and wheat have already decreased, as has quality in rice. In 2000, global estimates of yield losses due to increased ozone ranged from 2.2 to 5.5 percent for maize, from 4.0 to 15.0 percent for wheat, and from 8.5 to 14.0 percent for soy (Porter et al. 2014). By 2100, these decreases are expected to rise to 20 to 45 percent for maize, 5 to 50 percent for wheat, and 30 to 60 percent for soy, as well as 20 to 30 percent for rice (FAO 2016b). The wide ranges in these predictions come from the complicated interactions of known variables as well as the existence of many unknown variables. Even less is known about the yield changes in fruits and vegetables that are key sources of micronutrients. Decreases in winter chill may have detrimental effects on fruit and nut trees (FAO 2016b). Livestock are also susceptible to increased temperature stress, resulting in decreased milk production (IPCC 2014a). They are also susceptible to increased pests and disease.

Climate change exacerbates the problem of water availability and is expected to cause wet areas and seasons to become wetter while dry areas and seasons become drier (IPCC 2014a). Climate change is already causing changes in precipitation, such as increased variability in rain. This is a large problem in areas where agriculture depends on rainwater and planting schedules are based on rain predictions. In Ethiopia, changes in rainfall have already caused food shortages, undernutrition, and child stunting and wasting (Hagos et al. 2014). Another effect of climate change is that it changes the amount and timing of snow melts. As glaciers recede, there is less available water, and as temperatures rise, the snow melts earlier (FAO 2016a). Climate change also causes salinization of aquifers due to sea level rise. All of these factors cause large changes in water availability and will potentially increase irrigation needs (IPCC 2014a; FAO 2016a). Decreased water availability causes decreased crop yields as well as livestock dehydration and death. Drought periods, which will increase in frequency in some areas in connection with climate variability and change, lead farmers to use arsenic-rich groundwater to irrigate crops; while the data are still inconclusive, there are indications that arsenic concentrations are increasing in soils because of this irrigation and that there may be a risk of arsenic's affecting crop production (Tirado et al. 2010). Though climate change primarily decreases yields, it also shifts where crops can be grown as well as making some areas more productive. However, as temperatures continue to increase beyond the +3°C level, yields are predicted to decrease in the majority of areas where crops are grown, particularly the global South (Vermeulen, Campbell, and Ingram 2012; Ranganathan et al. 2016) (Figure 5.2).

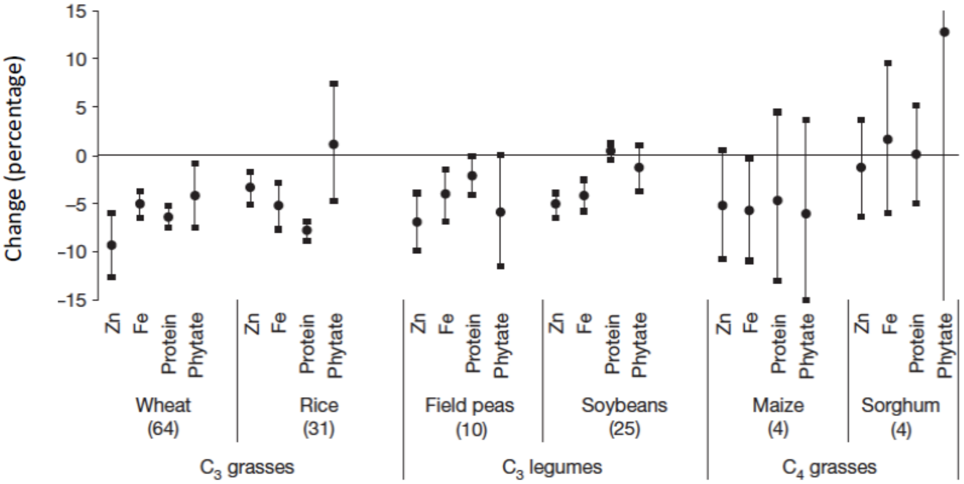
Figure 5.2 Estimated impact of +3°C change on crop yields by 2050



Source: Ranganathan (2016).

Climate change also affects the nutritional quality of crops. Atmospheric carbon dioxide directly affects plants, causing increased photosynthesis rates and increased growth. Some have argued that these effects will offset the yield-decreasing effects of climate change (Müller, Elliott, and Levermann 2014). The nutritional content of some foods may increase due to carbon dioxide fertilization effects, but that of others will decline (Smith and Haddad 2015). Increased carbon dioxide has been shown to decrease nutritional content, mainly in C_3 grains and legumes, including wheat, barley, rice, soy, and peas. Myers and colleagues (2014) showed that increased carbon dioxide (in the range of 546-586 ppm) results in decreased protein, iron, zinc, and other micronutrients in these crops (Figure 5.3). Wheat, for instance, had 6.3 percent less protein, 5.1 percent less iron, and 9.3 percent less zinc. Rice had 7.8 percent less protein but was otherwise unaffected. However, there were large variations across different varieties of rice. This latter finding is critical because these cereal crops are the main source of protein and micronutrients in many low-income countries. There are 1.9 billion people who get 70 percent of their iron and zinc from these crops and 2.3 billion who get 60 percent. Decreased protein content leads to increased carbohydrates, which may increase the risk of cardiovascular disease and diabetes (Myers et al. 2014). Different crops may be grown to adapt to climate change, and these may also have different nutritional content. Wheat bred for productivity, for example, has been found to have lower zinc, iron, copper, and magnesium than other wheat (Lake et al. 2012).

Figure 5.3 Carbon dioxide fertilization effects on crop nutrients



Source: Adapted with permission from Myers et al. (2014).
Note: Fe = iron; Zn = zinc. Elevated carbon dioxide levels ranged from 546 to 586 ppm.

Climate change causes increased stress on livestock in many ways. Increasing temperatures cause direct stress, and changes in precipitation make finding water difficult, which leads to animal dehydration. There may also be increased contamination in feed, such as with mycotoxins. Minor stresses can cause animals to produce less milk or to grow more slowly, producing less meat; these outcomes decrease the calories and nutrition available for human consumption. It is possible that climate change could cause a 10 to 25 percent decrease in the production of milk (IPCC 2014a), which also serves as an important nutrient source for children (Marquis et al. 1997). Large stresses can lead to animal loss that can be detrimental to farmers. Over the past two decades, cattle losses have been as high as 20 to 60 percent of the total cattle population during periods of severe drought in Africa south of the Sahara (FAO 2016b).

Changes in temperature and water also lead to new diseases and pests that can cause large economic losses and price increases, as well as food shortages (Tirado et al. 2010).

Climate change also impacts fisheries through changes in ocean temperatures, salinity, oxygen, and acidification, as well as freshwater temperatures and water levels. The warming of the ocean makes a large impact on where different species can survive. Many species are moving away from the tropics and toward the poles, leading to a 40 percent decrease in fish in the tropics and a 30 to 70 percent increase at the poles (Cheung et al. 2010). Ocean warming, as well as pollution from agricultural runoff, also favors dinoflagellate populations that cause algae blooms. The blooms, in turn, use up a lot of oxygen and cause dead zones that decimate fish populations. Decreased oxygen content also decreases fish growth and limits fish size (FAO 2016b). Every 1°C increase in temperature also causes a 3 to 5 percent increase in methylation of mercury (Tirado et al. 2010). Ocean absorption of carbon dioxide results in acidification that causes stress to fish and other impacts including shellfish degradation and coral reef bleaching.

Many people's diets depend on fisheries, especially for key nutrients. Globally, fish provide 17 percent of animal protein; however, this proportion is even greater in some countries. In Africa, fish provide 63 percent of the animal protein in Sierra Leone, 63 percent in Ghana, and 62 percent in Gambia. In Asia, fish provide 71 percent of the animal protein in Maldives, 59 percent in Cambodia, 57 percent in Bangladesh, 54 percent in Indonesia, and 53 percent in Sri Lanka (David 2013). Fish harvests have increased overall due to increases in aquaculture, although ocean populations have decreased, especially around Asia and Africa (Cheung et al. 2010). Although people can also get protein from other animal-source foods and from plant-based sources, the former are often prohibitively expensive and the latter are often not as high in quality. For the poor, fish provide the best source of high-quality protein. Fish also provide omega-3 fatty acids in the form of bioavailable docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), as opposed to plant-based sources that have alpha-linolenic acid, which must be converted to DHA and EPA. These omega-3 fatty acids are especially important for maternal and child nutrition due to the role of DHA in child development. Fish also provides micronutrients, including calcium, iron, zinc, iodine, and vitamins A and D. The loss of ocean habitat negatively impacts fisheries, decreasing the availability of this nutritious food source (David 2013). Thus, continued increases in aquaculture will be required to meet nutritional needs.

Impacts on Food Safety

Climate change has a large impact on food safety. Changes in temperature affect which foodborne pathogens can survive, proliferate, and be transmitted, as well as how susceptible plants and livestock are to these pathogens. For every 1°C increase in temperature, salmonella was found to increase by 5 to 10 percent (Tirado et al. 2010). Changes in ocean temperature and acidity affect vibrio species that can cause food poisoning in seafood as well as algae blooms. Algae blooms can produce toxins that can contaminate the food supply with diseases such as diarrheic shellfish poisoning, ciguatera fish poisoning, and several others caused by dinoflagellates that thrive in warmer water (Tirado et al. 2010). More vigilance, including the creation and enforcement of regulations for seafood producers, are needed to ensure that producers halt harvesting during these blooms to prevent contamination of the food chain. Because informal and illegal producers pose the greatest risk, enforcement is key.

Increasing temperature also affects fungi that produce mycotoxins and can contaminate the food supply. At higher temperatures and with increasing carbon dioxide, plants have higher nitrogen content in their leaves that makes them more susceptible to fungal infection. Also, increased damage from pests can cause openings for fungal infections. At high doses, mycotoxins can cause acute symptoms in humans, but more commonly people are exposed at chronic low levels, where they are carcinogenic, immunosuppressive, neurotoxic, or otherwise harmful. One of the most important mycotoxins is an aflatoxin that is produced by *Aspergillus* and can contaminate maize, groundnuts, figs, dates, and cottonseed. In Iran, aflatoxin has increased with increased temperature (Tirado et al. 2010). Aflatoxin is a potent carcinogen and is linked with liver cancer, especially in areas where it occurs alongside high rates of viral hepatitis (Khlangwiset, Shephard, and Wu 2011).

Increased pests also lead to increased use of agrochemicals, causing increased exposure to workers and consumers. Changes in precipitation, including large storms and flooding, can also result in contamination of food in the field with sewage or agricultural and industrial waste. Soil can also be contaminated with polychlorinated biphenyls (PCBs) and dioxins during flooding (Tirado et al. 2010).

Extreme Weather Events and Production

Climate change is expected to cause more extreme weather events, including heat waves, droughts, and storms producing heavy rain and wind. These events cause crop and livestock damage and loss, and take a large toll on food security. Storms and flooding can damage fields and destroy crops. After Hurricane Matthew in Haiti, almost 100 percent of the crops had been destroyed and more than 50 percent of the livestock had been killed in the areas that were hardest hit (WFP 2016).

In Africa south of the Sahara, both droughts and floods lead to crop loss and acute food shortages, thus increasing hunger and undernutrition. Wang, Kanji, and Bandyopadhyay (2009) found that extreme weather events caused wasting in children younger than three years, but this was a combined effect of decreased food intake and increased incidence of diarrheal disease. Extreme weather events primarily cause wasting, which is a short-term measurement of undernutrition. However, they also have long-term impacts on child growth (Wang, Kanji, and Bandyopadhyay 2009). Del Ninno and Lundberg (2005) found that children in Bangladesh exposed to floods were half a standard deviation shorter than children who were not, which is 5.0 centimeters for three-year-olds. These children had not made up this growth 15 months later (del Ninno and Lundberg 2005). Hoddinott and Kinsey (2001) found that children in Zimbabwe who were between one and two years old during a drought lost between 1.5 and 2.0 centimeters of growth per year and had not made up this growth four years later.

The largest food crises requiring food aid in Africa south of the Sahara have been either partly or completely due to extreme weather events, most commonly drought. Crop losses also lead to loss of income, exacerbating poverty. Despite being caused by an acute event, these effects are long lasting and recovery can take years. The effects can also reverberate throughout society, and what started with crop losses can ultimately result in migration, violent conflict, and political instability (Haile 2005).

Changes in Food Transportation, Processing, and Storage

Contributions to Climate Change from Food Transportation, Processing, and Storage

Though studies of the relationship between the food system, climate change, and nutrition often focus solely on food production, climate change and the food system are closely related at every step of the value chain. The transportation, processing, and storage of food contribute to climate change, and in turn, climate change will have serious implications on the functioning of these intermediate value chain steps.

Transportation, processing, and storage require energy in the form of fossil fuels and contribute to greenhouse gas emissions. The food system is a complicated global network, and food may be transported long distances from where it is produced to where it is ultimately consumed. Pirog and colleagues (2001) found that food grown in the United States traveled an average of 2,000 miles. More than 15 percent of all food is transported internationally (Brown et al. 2015). This mobility is advantageous in that it allows food to be moved from areas of surplus to areas of shortage, helping to decrease food insecurity and food price volatility. In addition, there is a high demand for foods that either cannot be produced locally or would require large amounts of resources, such as growing produce in the off-season in heated greenhouses with large water requirements. In these cases, it is more sustainable to produce food in other areas and transport it to where the demand is (Wakeland, Cholette, and Venkat 2012).

These advantages come at a cost and require transportation infrastructure. Food can be transported via water, rail, road, or air. All of these modes require fossil fuels that contribute to greenhouse gas emissions, with air transportation having the most significant emissions and rail having the least. Estimates vary, with Heller and Keoleian (2000) estimating that transportation accounts for 25 percent of all the food-related energy demand in the United States, and Weber and Matthews (2008) putting this estimate at 11 percent. Greenhouse gas emissions associated with food transportation are much lower in low-income countries because food travels fewer miles, precluding the advantages discussed above and resulting in increased food scarcity and food waste. This is often due to poor transportation infrastructure. Rail transportation infrastructure is especially weak in Africa due to its origins as a means for colonial extraction as well as its current inability to compete with roads (Foster and

Briceño-Garmendia 2010). Increasing urbanization in low-income countries is also causing an increase in food miles because food must be brought into cities. This necessity, combined with poor infrastructure, results in increased energy use and greenhouse gas emissions (Jones 1991).

Food is processed in order to make it more stable, safe, and in some cases, nutritious. There are many different methods for processing, but each requires inputs, from water to energy, and produces greenhouse gases. Cookers, boilers, and furnaces emit carbon dioxide, and wastewater emits methane and nitrous oxide. The most intensive processing is wet milling of maize, but processing sugar and oils also requires large amounts of energy. Packaging requires energy for the production of packaging materials and for the packaging process itself, but this is a very minimal contribution compared with the rest of processing (Vermeulen, Campbell, and Ingram 2012).

Foods are stored at several points along the value chain, both before and after processing. Different foods have different storage requirements necessary to maintain food safety and quality. Cold storage for food is one of the largest energy requirements in the value chain, and the greenhouse gas emissions from cold storage can be substantial. Vermeulen, Campbell, and Ingram (2012) found that cold storage accounts for 15 percent of all energy use and 1 percent of all greenhouse gas emissions globally. Carlsson-Kanyama (1998) found that for some foods, cold storage was the largest source of emissions. As an example, for carrots, cold storage makes up 60 percent of greenhouse gas emissions. Cold storage also requires refrigerants that are damaging to the ozone layer (Carlsson-Kanyama 1998). In some cases, food may be produced and then stored for long periods of time in order to have it available during the off-season. When this practice requires cold storage, it is more energy intensive than it would be to transport the food long distances (WRI 2013).

Impacts of Climate Change on Transportation Infrastructure

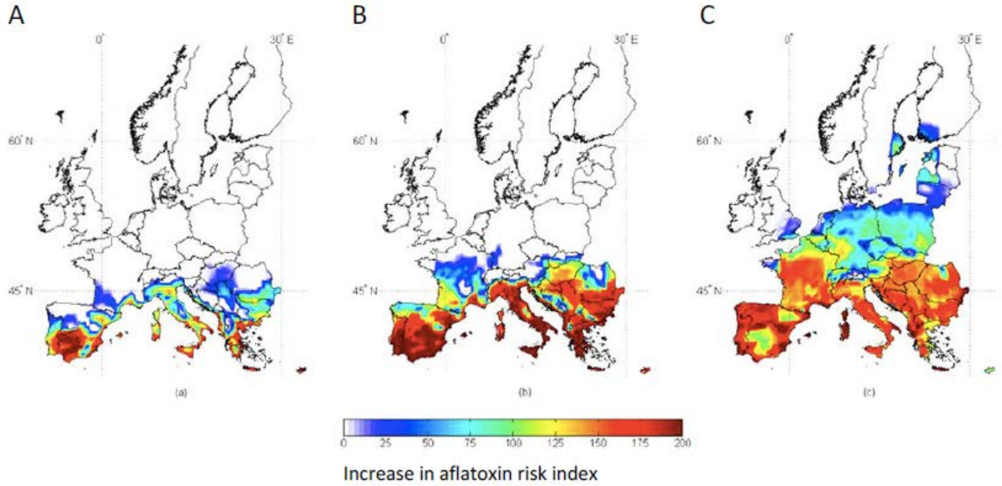
Transportation, storage, and processing contribute to climate change, and they are also impacted by it. Disruptions in these steps of the value chain can lead to increased food waste, thereby decreasing food availability and increasing prices. Transportation is directly affected by weather. Changes in temperature and precipitation, as well as extreme weather events, threaten the transportation infrastructure. Increases in temperature may make some rail lines and roads that traverse ice or permafrost unusable. However, they also may also open up new shipping routes or new areas that trains and trucks can access. Sea level rise, as well as changing water levels in rivers and lakes due to changes in precipitation, may make other rail lines and roads unusable. These are all relatively slow changes. However, extreme weather events can cause acute disturbances such as delaying transportation until weather conditions stabilize. Extreme weather events can also permanently damage transportation infrastructure, leading to longer delays and increased costs for repair. In Mozambique, for example, regular floods and storm surges are already damaging infrastructure such as roads and bridges, and high temperatures are increasing wear to road surfaces. Models show all of these challenges increasing in the face of climate change at a great economic cost (Arndt et al. 2011). Such effects of extreme weather particularly impact the transportation of food because it is time sensitive and delays can cause spoilage and increase waste. As temperatures and precipitation change, some geographic areas will become less productive while others will become more so, forcing crop production to move and transportation systems to adapt in order to move food from new production locations to areas where it is needed (Brown et al. 2015).

Emerging Food Storage Challenges

Storage is also impacted by climate change, particularly among crops with improper or subpar postharvest storage facilities, which are very common among subsistence farmers. As the temperature increases, food quality and safety are affected. Foodborne pathogens are better able to survive and proliferate, and in some cases are also more virulent, potentially leading to increased spoilage and food waste. Storage temperature is directly related to storage life: every 2°C to 3°C increase in temperature, up to 10°C, is associated with a decrease in storage life of 50 percent (Vermeulen, Campbell, and Ingram 2012). This problem is greatest in the most nutrient-dense foods, such as animal-source foods, vegetables, and fruits. As temperatures increase, cold storage will be increasingly necessary and may need to be scaled up in some countries and developed in other countries that do not already have that capacity. For example, in India, the need for cold storage for potatoes will increase as temperatures increase, in turn requiring increased energy use as well as new infrastructure and the costs associated with both of these. Increasing temperatures may also stress the electrical grid, especially in areas where it is already overwhelmed, potentially leading to rolling brownouts, blackouts, and losses of power that can cause food waste (Vermeulen, Campbell, and Ingram 2012).

One of the most concerning challenges to food safety at the storage stage is aflatoxins. Climate change is expected to cause increased fungal growth at the production stage, as discussed earlier. However, increased temperatures and carbon dioxide also cause changes in gene expression that lead *Aspergillus* to produce 15 to 80 times more aflatoxins (Medina, Rodriguez, and Magan 2014). In major crops such as maize and wheat, models show that with increased temperatures, aflatoxin contamination increases. Figure 5.4 shows three different climate scenarios in Europe—the present day, + 2°C, and + 5°C—and the increased contamination of aflatoxin B_1 in maize with these increasing temperatures.

Figure 5.4 Increased aflatoxin B_1 in maize with climate change in Europe



Source: Adapted with permission from Battilani et al. (2016).
Note: Panel A represents the present day, Panel B a temperature increase of 2°C, and Panel C a temperature increase of 5°C.

The combination of increased *Aspergillus* growth in the field and increased aflatoxin production in storage could significantly increase the mycotoxin burden in the diet. Aflatoxins are known to cause liver cancer and have also been associated with childhood growth impairment. Aflatoxin exposure has been show to occur in utero, through breastfeeding, and in early feeding, especially in areas where maize and groundnuts are staple foods. In low-income countries where stunting is highest, up to 100 percent of children had detectable serum aflatoxin-albumin adducts or urine aflatoxin (Khlangwiset, Shephard, and Wu 2011). Several studies have shown an association between aflatoxins and both wasting and stunting. One of these studies also showed a dose-response relationship for both (Khlangwiset, Shephard, and Wu 2011).

Extreme weather events also impact storage by causing power losses that disrupt the cold chain and lead to spoilage, or even by directly destroying stored food (Vermeulen, Campbell, and Ingram 2012). These effects have been seen in hurricanes both in high-income countries such as the United States during Hurricane Katrina and in low-income countries such as Haiti during the more recent Hurricane Matthew. Other extreme weather events, such as floods, can cause similar damage. Bangladesh has suffered several severe floods that have damaged crops in the field and in storage. A flood there in 1974 damaged 0.6 million tons of food. This level of destruction leads to food scarcity that directly affects people in the area and can also lead to increases in food prices that affect people around the world (Douglas 2009).

Food Processing Energy Requirements

Processing is also affected by climate change. The types of processing that are needed may change with increased temperature and increased foodborne pathogen risks. As temperatures increase, more food may need postproduction cooling that will require infrastructure and energy (Brown et al. 2015). Different crops also need different processing. For example, cassava, due to its resistance to both temperature and drought, may become a more important crop in the face of climate change. However, cassava must be processed correctly because of high levels of cyanide in some varieties. If it becomes more widely grown, people who are unaware of the processing requirements may consume it, resulting in increased cyanide toxicity and cases of konzo. Those affected by konzo have permanent weakness and spasticity that primarily affects the legs and varies in severity but can affect mobility. There are already increased cases of konzo during times of drought and food scarcity, and these may increase further (Thompson, Berrang-Ford, and Ford 2010).

Biofortification

Although incorrect processing has the potential to cause illness and debilitating disease, proper processing has the potential to improve nutrition. Biofortification of staple crops or fortification of milled grains done at the processing stage can add nutrients that are lacking or have been lost in crops. As discussed earlier, increased carbon dioxide levels impact the nutrient content of crops, with many grains and legumes losing protein, iron, and zinc. If these and other nutrient changes are known, they can be addressed during processing (Lake et al. 2012).

Changes in Food Retail and Marketing

Contributions to Climate Change by Retail and Marketing

How food is sold and marketed affects climate change. Some food retailers, especially large hypermarkets and superstores, use large amounts of energy. Most of this energy is used for electricity, primarily to maintain cold storage but also for lighting, climate control, and food preparation. This energy use requires fossil fuels and emits greenhouse gases. Retail also has indirect greenhouse gas emissions from plastic shopping bags, packaging, and food waste. However, these contributions are small compared with those of cold storage (Tassou, Hadawey, and Marriott 2011). Marketing affects which foods consumers purchase, and these purchases feedback to production, which has a large impact on resource use and greenhouse gas emissions, as will be discussed later.

Impacts of Climate Change on Retail

Climate change also affects retail and marketing. Many different food retailers, ranging from small food stands to large hypermarkets, all operate in parallel. Those serving the most vulnerable populations are also at the highest risk from climate change. The smaller stands often rely on food that is produced locally and serve people in the area. As food production patterns change due to changes in temperature and precipitation, the food available at these stands may change as well. These stands also have little to no permanent infrastructure, including access to water or cold storage. As temperatures increase and water is more limited, this lack of access may create problems for food quality and safety, including more food spoilage and waste (Vermeulen, Campbell, and Ingram 2012). As food availability decreases, people are forced to sell food that otherwise would not be fit for consumption, such as food contaminated with aflatoxins that would otherwise be disposed of, increasing people's exposure to mycotoxins (Tirado et al. 2010). Changes in temperature and precipitation, and extreme weather events, may also limit access to retailers, especially for the most vulnerable populations, those living where poor roads and access to transportation already limit access.

Increasing Consumer Interest in Food Systems

Marketing is already being influenced by climate change. As consumers become more aware of climate change, they are looking for information about how their food is produced and what its impact on the environment is. Agribusinesses and retailers are stepping up to meet these demands with a variety of labels that address everything from deforestation to food miles to greenhouse gas emissions. However, there is a large discrepancy in the quality and use of these labels, as well as questions about how much impact they have on consumer behavior. Regardless of these shortcomings, they are representative of a shift in marketing to focus on the impact of food products on the environment and on climate change.

Government and public health organizations have also been active in connecting diet and climate change. In the United States, the Dietary Guidelines Advisory Committee included sustainability and decreased meat consumption in its 2015 guidelines (cited in de Boer, de Witt, and Aiking 2016). Brazil considered sustainability even earlier, in its 2014 guidelines, which focused on nonprocessed or minimally processed plant-based foods. The result of a three-year process that included the Ministry of Health, other health institutions, civil scientists, the public, and many others, these holistic guidelines considered the many aspects of diet, from nutrition to culture to sustainability. For sustainability, the guidelines aimed to protect air, water, and soil quality; preserve biodiversity; and decrease resource use and greenhouse gas emissions (Monteiro et al. 2015).

Public campaigns have also been using sustainability to influence consumer behavior. Meatless Mondays started in the United States but have become a worldwide initiative used in 44 countries including Honduras, Peru, Bolivia, Chile, and Togo. Many of these countries were inspired by Brazil, where Segunda Sem Carne, which began in 2009, is very popular and is promoted by local celebrities who wear campaign T-shirts and publicize it on social media. Twice a month, São Paulo offers 1 million vegetarian meals to its residents as another promotion of the campaign (Morris, Kirwan, and Lally 2014; The Monday Campaigns 2017).

There is also a large food movement with a focus on local, organic, and sustainable foods. Along with public health campaigns focused on the food system, climate change, and nutrition, there has also been a dramatic increase in articles and books in the mass media that address these relationships. Awareness of the food movement in the consumer consciousness affects how agribusinesses produce and then market their products and how consumers make their purchasing decisions.

Changes in Food Consumption and Utilization

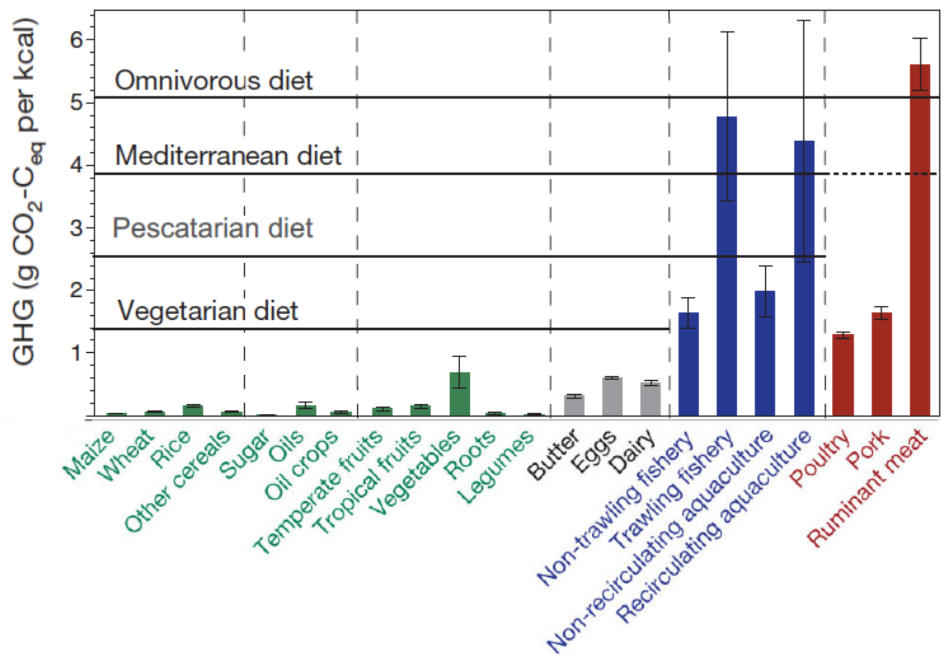
Contributions to Climate Change by Animal-Source Foods

Consumer demand for certain types of food drives supply from agricultural production to the remainder of the value chain, which can have various impacts on climate change triggers. In a large-scale dietary transition that is happening globally, as populations urbanize and incomes increase, there is a higher demand for animal-source foods. If left unchecked, meat consumption is expected to increase by 82 percent by 2050 (WRI 2013). Animal-source foods are healthful and provide protein as well as micronutrients such as iron, zinc, and vitamin B_{12} in meat, and calcium and B_{12} in dairy (Dewey and Adu-Afarwuah 2008; Black et al. 2013). Deficiencies in these nutrients lead to anemia, immunodeficiency, rickets, neuromuscular deficits, impaired cognitive performance, morbidity, and mortality. Livestock are also a key source of income. It is important to keep livestock and animal-source foods in the food system for these reasons, but currently consumption is inequitable, with some populations eating large amounts of meat and others eating little to none. In the United States the average meat consumption is three times the global average, and in many European countries it is twice the global average (de Boer, de Witt, and Aiking 2016). Overconsumption of meat high in saturated fats contributes to increased risk of obesity and noncommunicable diseases (You and Henneberg 2016; Bouvard et al. 2015). Although many countries are shifting from plant-based diets to more animal-source foods, access to these foods by the poorest remains limited (Keats and Wiggins 2014; Zeisel and Da Costa 2009), and it is equally important for those eating more than is nutritionally necessary to decrease their consumption (WRI 2013).

Many studies have investigated how different foods and different diets affect the environment and climate change. Diets high in animal-source foods are generally more resource intensive than other diets with regard to water, land, and greenhouse gas emissions (Ranganathan et al. 2016; Tilman and Clark 2014). Several studies have shown that decreasing consumption of beef and other ruminant meat makes the largest impact on climate change. The impact is significant when such meat is replaced with pork or chicken, but it is even greater when it is replaced with plant-based foods. Figure 5.5 shows the greenhouse gas emissions per kilocalorie for 22 different foods that make up four different diet types.

Marlow and colleagues (2009) compared multiple diets in California and found that a nonvegetarian diet used 2.5 times more energy, 2.9 times more water, 13 times more fertilizer, and 1.4 times more pesticides than a vegetarian diet. Most of these impacts were from beef production. The study also compared changes in diet with other lifestyle changes. For example, a vegetarian diet decreased individual water use by 54 percent, compared with 35 percent for using water-efficient household fixtures and fixing household water leaks (Marlow et al. 2009). Sjörs and others (2016) found that meat and dairy had the highest environmental impact among food groups. They also compared different types of meat and found that although a kilogram of beef produced 48 kilograms of carbon dioxide equivalents, a kilogram of chicken produced only 4 kilograms of these emissions. Hobbs, Lovegrove, and Givens (2015) considered the high environmental impact of animal-source foods in relation to their nutritional benefits. Dairy is a key source of protein, calcium, phosphorus, iodine, and B_{12}. The study found that a plant-based diet with similar levels of these nutrients would also include higher levels of fat, a higher cost of food, and more greenhouse gas emissions (Hobbs, Lovegrove, and Givens 2015).

Figure 5.5 Greenhouse gas emissions of different diet types



Source: Adapted with permission from Tilman and Clark (2014).
Note: GHG = greenhouse gases.

Dietary Contributions to Climate Change

Other studies have looked at the role of diet in climate change outside of just meat consumption. Hallström, Carlsson-Kanyama, and Börjesson (2015), for example, conducted a review of 14 studies that covered 49 diets in order to compare greenhouse gas emissions and land use. They found that diet changes in high-income countries had the potential to decrease diet-related emissions by 50 percent. A vegan diet decreased emissions by 25 to 55 percent, a vegetarian diet by 20 to 35 percent, and a diet that replaced beef with pork or chicken by 25 to 35 percent. A vegan diet also decreased land use by 50 to 60 percent and a vegetarian diet by 30 to 50 percent. The largest determinant of land use is beef and other ruminant meat. Replacing 75 percent of beef with pork or chicken would reduce land use by 40 percent—a proportionally larger impact than eliminating all meat, because replacing 50 percent of pork or chicken with plant-based food decreased land use by only 5 percent. Healthy diets that include all types of meat had inconsistent results depending on how "healthy" was defined. These diets decreased dietary emissions by up to 35 percent and land use by 15 to 50 percent. However, five of these diets had emissions decreases that were less than 10 percent.

Tom, Fischbeck, and Hendrickson (2015) evaluated three different dietary changes—decreasing calories; shifting to the diet recommended by the US Department of Agriculture (USDA), which recommends including the consumption of vegetables, fruits, and dairy, and limiting sugars and fats; and doing both—for their water and land use and their greenhouse gas emissions. Decreasing calories decreased dietary emissions by only 9 percent. Shifting to the USDA-recommended diet increased emissions by 11 percent and increased water use by 16 percent. Shifting to the USDA diet and also decreasing calories still increased emissions and water use but less so, by 6 and 10 percent, respectively. The authors compared these results with data from Germany, where sustainability is a larger factor in dietary guidelines, and found that shifting to the German government's recommended diet would decrease emissions by 15 percent and water use by 7 percent. These results differ slightly from those of previous studies in that Tom, Fischbeck, and Hendrickson (2015) accounted for food waste. Overall, the results show that decreasing overconsumption is critical, as is incorporating sustainability into food recommendations.

Motivations behind Consumer Choices

Although food availability is a key determinant of dietary choice, consumer behavior is motivated by much more complicated factors, such as personal preference, cost, and convenience. Climate change is expected to increase food prices. For many people, especially those living in poverty, this will impact what foods they purchase. The most nutritious foods are animal-source foods, vegetables, and fruits, but unfortunately, these are also the most expensive foods. When food prices increase, many people buy fewer of these foods and more ultra-processed foods and fast foods, which are cheaper and more immune to price increases but also high in fat, sugar, and salt (Lake et al. 2012; Lock et al. 2009; Vermeulen, Campbell, and Ingram 2012). Lock and colleagues (2009) found that during food price increases, fast food companies saw increased profits. These changes in diet composition directly impact nutrition.

Increased prices that make food unaffordable for the poor can lead to decreased overall food consumption and undernutrition, but at the same time can also cause an increase in consumption of ultra-processed and fast foods. These foods are key contributing factors to overweight, obesity, and resulting noncommunicable diseases. Both decreased overall food consumption and a shift from nutritious foods to ultra-processed and fast foods decrease diet quality and can cause micronutrient deficiencies. For those who depend on agricultural incomes, including most of the rural poor, these changes in food consumption are exacerbated by decreased agricultural income due to climate change (Lake et al. 2012; Vermeulen, Campbell, and Ingram 2012).

In 2016, de Boer, de Witt, and Aiking looked at the impact of education on dietary choice. If consumers think climate change is important and is driven by humans, they are more likely to think interventions are effective and therefore more willing to make changes. The study looked at consumer willingness to change to a diet with less meat, a diet with more local food, and a diet with more organic food. These diets have different efficacy in addressing climate change. Decreasing meat, the authors found, may decrease dietary greenhouse gas emissions by up to 35 percent, but eating locally produced foods would decrease emissions by only 5 percent and shifting to organic foods would have no change. Despite this large difference, only 6 percent of Americans thought eating less meat was the most effective intervention, highlighting a key area for education (De Boer, de Witt, and Aiking 2016). If people are willing to make changes, it is important for them to be making the most effective ones.

Diet and Human Health

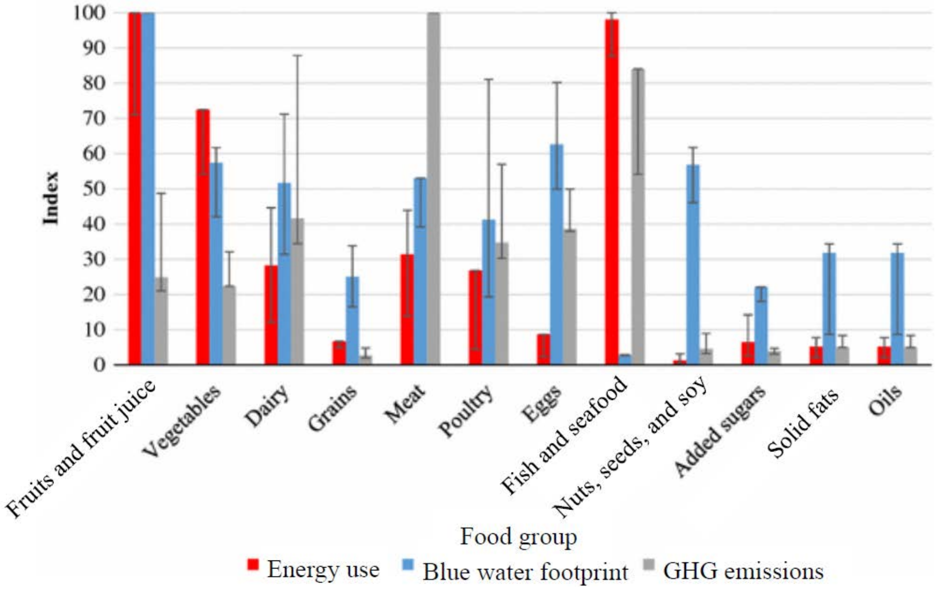
Just as diet affects the environment and climate change, it also has a large effect on human health. Payne, Scarborough, and Cobiac (2016) reviewed more than 100 different diets from 16 studies. Although the results were mixed, diets that were more environmentally sustainable often had worse health outcomes. Still, diets with decreased animal-source foods had lower greenhouse gas emissions and some health benefits, including decreased saturated fat and salt. However, most of these diets had increased sugar as well as lower levels of micronutrients, including iron, zinc, calcium, and B_{12}. Rates of cardiovascular disease were higher for diets with lower greenhouse gas emissions, but cancer and overall mortality were inconsistent. Another systematic review (Aleksandrowicz et al. 2016) found that for diets in which there was a decrease in the consumption of animal-source foods, there were similar reductions in environmental footprints including greenhouse gas emissions, water use, and land use. These shifts to more sustainable, plant-based patterns also demonstrated modest benefits in all-cause mortality risk.

Springmann, Godfray, and colleagues (2016) looked at diets with no meat, decreased meat, and decreased beef. Projecting out to 2050, the authors found these diets to be associated with decreased greenhouse gas emissions of 29 to 70 percent and decreased overall mortality of 6 to 10 percent. The decrease in mortality came from decreases in coronary heart disease, stroke, diabetes, and cancer.

Trade-offs between Climate Change Mitigation and Human Health

These studies show the potentially conflicting interests of environmental and human health. Some foods that have high caloric value for their emissions, such as sugar and oils, are detrimental to human health by being direct causes of diabetes and cardiovascular disease. Vegetables and fruits do not provide many calories and have higher emissions but provide key micronutrients that are critical for health and associated with lower levels of all noncommunicable diseases. Compared with other food groups, fruits require the greatest amount of energy per kilocalorie as well as the largest amount of water use. Vegetables are third in energy use and third in water use by calorie content. These ratios are so high because fruits and vegetables are both low-calorie foods. Animal-source foods are the most environmentally damaging, requiring disproportionate amounts of water and land and producing most of the greenhouse gas emissions (Figure 5.6). Although they are high in saturated fat, they are also an important source of protein and micronutrients (Tom, Fischbeck, and Hendrickson 2015). Downs and Fanzo (2015) examined a cardioprotective diet and found that although vegetables, fruits, and whole grains had lower carbon and water footprints, nuts and olive oil had much higher water footprints and fish had a high overall ecological footprint. These trade-offs are complicated but must be evaluated together in making dietary recommendations.

Figure 5.6 Energy, water, and greenhouse gas emissions for different food groups per kilocalorie



Source: Adapted with permission from Tom, Fischbeck, and Hendrickson (2015).
Note: GHG = greenhouse gases.

The balancing of environmental and human health concerns is further complicated by the nutrition transitions that are occurring with increased urbanization and income, as discussed earlier. When people eat more meat, there are negative environmental and health impacts, but when people eat more processed foods that are high in sugars and oils, there are decreased greenhouse gas emissions but even greater negative health impacts. Public health campaigns against sugars and oils are critical for human health but present an example of the competition between the health of the environment and human health. Shifting diets away from these foods and toward more healthful foods often increases greenhouse gas emissions. Several studies have shown that shifting to recommended diets increases greenhouse gas emissions, as discussed earlier.

Food Waste

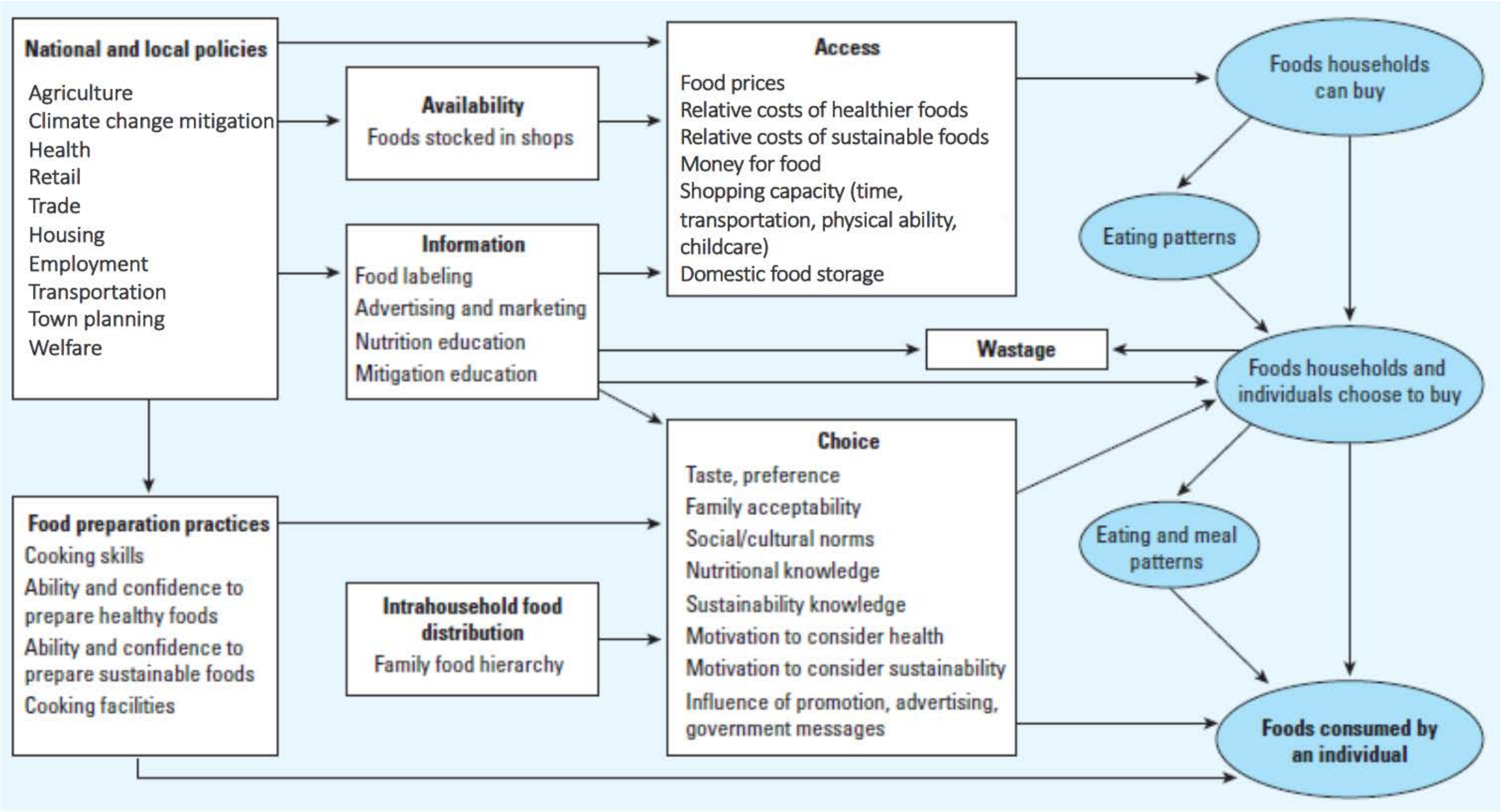
Globally, food is wasted at the rate of 25 percent by calories and more than 30 percent by weight. Though 65 percent of the loss is in harvesting, processing, and storage in low- and middle-income countries, in high-income countries more than half of it is consumer waste. This waste contributes directly to greenhouse gas emissions through methane released from landfills and indirectly by requiring that more food be produced (WRI 2013). Eliminating these losses would decrease emissions by 28 percent (Heller and Keoleian 2014).

Impacts of Climate Change on Food Access

Climate change will also affect consumption, primarily through food access. There may be disruptions in food production and retail, as discussed earlier. Despite recent global decreases in food prices, climate change is expected to increase prices as well as price volatility due to decreased production and increased loss. Climate change will also affect incomes and thus purchasing power, especially for people whose main source of income is agriculture, as is the case for the rural poor. When prices increase and incomes fall, people tend to buy fewer animal-source foods, vegetables, and fruits, and more ultra-processed foods. This shift contributes to overweight, obesity, and noncommunicable diseases, as discussed earlier (Lake et al. 2012; Vermeulen, Campbell, and Ingram 2012). For those who are already food insecure and undernourished, such a dietary shift can exacerbate or cause undernutrition. Food price increases have been linked to micronutrient deficiencies, especially vitamin A and zinc, and to childhood wasting and stunting (Christian 2010).

Changes in crop varieties produced also affect consumption. Changing temperatures and precipitation affect which crops can be grown, as discussed earlier. Even though changing crop varieties may be unavoidable for producers, consumers may not want to eat the new varieties. In India, for example, varieties of rice better suited to climate change are not those that people prefer to eat (UNEP 2010). In Guatemala, there is a similar story with maize. It is problematic to assume that vulnerable populations will eat anything that is available. People have their own agency and make decisions about what to eat based on not only availability and cost but also personal and cultural preferences (Figure 5.7).

Figure 5.7 Framework for consumer food choices



Source: Adapted with permission from Lake et al. (2012).

Impacts of Climate Change on Nutrient Utilization

Climate change will also affect utilization, or how the body is able to absorb and use the nutrients that are consumed. Increasing temperature increases infectious diseases, especially diarrheal diseases. In Peru, a study found that every 1°C increase in ambient temperature was correlated with an 8 percent increase in diarrheal disease (Checkley et al. 2000). Another study in Bangladesh found temperature to be correlated with cholera cases (Tirado et al. 2010). Increases in temperature also affect parasites, such as trematodes, that currently infect more than 40 million people and are expected to increase their range of distribution, potentially affecting many more people (Tirado et al. 2010). People who are affected will be less able to absorb calories and nutrition from the food they are eating. In addition to the acute problems caused by diarrhea, climate change may bring about chronic issues of low-lying long-term disease, especially due to the increased parasite burden. Thus, even if people are eating enough calories and nutrients, they may not be absorbing them and may still be suffering from malnutrition (Brown et al. 2015).

6. MITIGATION AND ADAPTATION STRATEGIES

Key Points

1. Mitigation is action to decrease the impacts of climate change, and adaptation is action to cope with these impacts. The latter is most needed in the global South, such as in Africa south of the Sahara and Southeast Asia, where the effects of climate change will be the greatest but the resources to adapt are the most limited.
2. Without action, climate change is expected to cause a 2 percent decrease in food production every decade until 2050 and much more drastic decreases after that, at a time when increasing population, rising incomes, and urbanization are putting more pressure than ever on an already stressed food system.
3. A climate-smart, nutrition-sensitive food value chain can be used to develop mitigation and adaptation interventions that focus on increasing nutrition while also decreasing greenhouse gas emissions and increasing overall resilience.
4. Food chain interventions include increasing irrigation to provide more reliable water for crops; improving soil quality; increasing the diversity of crop varieties and livestock breeds to increase resilience to heat, drought, pests, and disease while also increasing dietary diversity; developing new varieties and breeds that are adapted to the changing climate; increasing sustainable livestock and aquaculture; drying food before storage to decrease aflatoxin content; drying food to increase nutrition and stability and decrease the need for cold storage; fortifying food to add missing nutrients and make food more nutritious; creating networks for small rural farms; improving energy and transportation infrastructure for small rural food retailers; and promoting sustainability in country dietary recommendations and public health campaigns.
5. Broader interventions include improved social protective services, poverty reduction, women’s empowerment, and rural development.

Introduction

Climate change is already having a large impact on the food system, including the quantity and quality of food available. In order to maintain and improve food and nutrition security, addressing climate change must be a top priority. Mitigation and adaptation should occur simultaneously in order to maximize synergies and minimize trade-offs where possible—we should not wait for one or the other (Vermeulen, Campbell, and Ingram 2012).

In order to delve into both mitigation and adaptation strategies, it is important to define both:

- **Mitigation**, as defined by the IPCC, is "an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases" (cited in IPCC 2007, 750). Mitigation is action taken to decrease the impacts of climate change. It primarily relies on decreasing greenhouse gas emissions and increasing carbon sinks to decrease the amount of greenhouse gas in the atmosphere and limit the increase in temperature, with an overall goal of keeping this increase less than 2°C.
- **Adaptation**, as defined by the IPCC, is an "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (cited in IPCC 2007, 750). Adaptation is action taken to cope with the impacts of climate change. We are already seeing these impacts, and they will get worse even with effective mitigation. Therefore, it is essential to take action to minimize or, when possible, utilize these effects to limit negative effects.

Global action is a necessity, but high-income countries should make more significant efforts toward mitigation because they bear responsibility for most greenhouse gas emissions historically and still produce a large proportion. Unfortunately, the rural and urban poor are the most vulnerable to the negative effects of climate change, especially those in Africa south of the Sahara and South Asia (IPCC 2014a). They are already the most susceptible to shocks, including changes in food availability and prices, and loss of income. They also are the least able to adapt because they do not have the necessary resources. Thus, adaptation needs will be greatest in these areas. Mitigation and adaptation efforts are already being made through climate-smart agriculture policies and programs that focus on the three pillars of sustainably: increasing agricultural productivity, increasing resilience, and decreasing greenhouse gas emissions.

Women play an especially significant role in mitigating and adapting to the effects of climate change on nutrition. A report from the Food and Agriculture Organization of the United Nations (FAO) found that women account for 60 to 90 percent of food production globally, with women in developing countries constituting approximately 43 percent of the agricultural labor force (FAO 2011b). In spite of their active presence, women face extensive disadvantages compared with men: access to information may be limited, as is access to agricultural and other productive inputs. Additionally, far fewer women than men hold ownership of livestock and land, and those who do have smaller plots than their male counterparts. The FAO estimates that productivity gains of 2.5 to 4.0 percent and a 12 to 17 percent decline in undernourishment could be achieved by addressing the gender gap in agriculture (FAO 2011b). It is possible that these gains would be even greater if the effects of climate change were also considered (HLPE 2012).

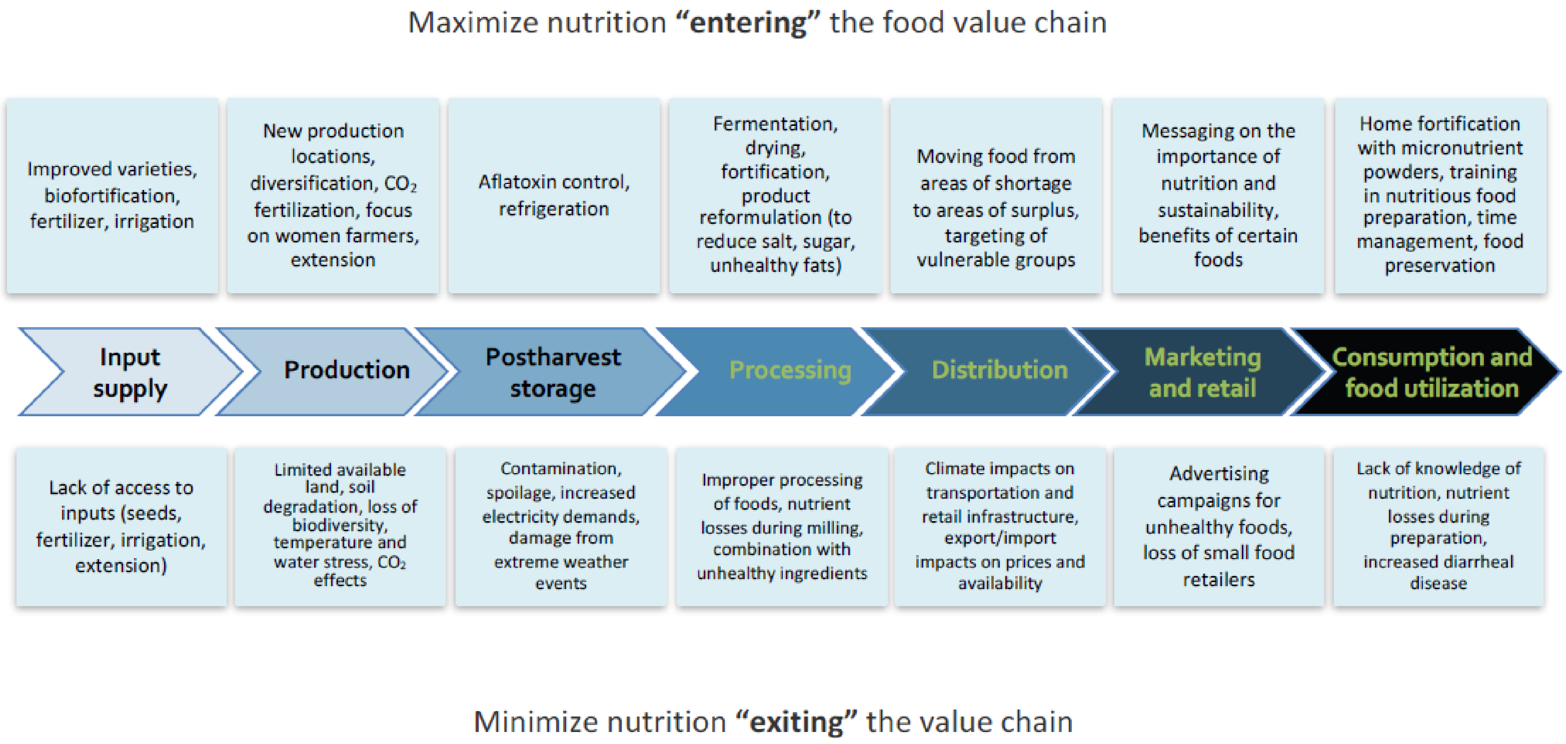
A Climate-Smart, Nutrition-Sensitive Food Value Chain Framework

The food value chain encompasses every step involved in ultimately determining what foods people eat and how they are able to use the nutrition from these foods. The chain starts with agricultural inputs, including seeds, fertilizer, and irrigation, and then moves through food production, storage, processing, distribution, marketing and retail, the transportation needed for all of these steps, and personal consumption and utilization, as discussed earlier.

Climate change will affect each of these steps, primarily in negative ways but in some cases in beneficial ways that can be exploited. Climate change will negatively affect water availability, cause changes in where food can be produced due to changes in temperature and precipitation, decrease crop and livestock productivity due to heat and water stress, increase the presence of foodborne pathogens and mycotoxins in both production and storage, increase food waste from these same changes as well as from extreme weather events, pose new transportation challenges, decrease food availability, and increase food prices, as well as other negative effects. On the positive side, carbon dioxide fertilization may make some crops more productive but potentially with less nutritional value. Increased temperatures may also temporarily make some areas more productive. All of these changes will be discussed in more detail below.

Each of these steps in the food value chain also affects nutrition and provides an opportunity to improve the nutritional quality of the food people eat (Fanzo et al. 2017). Each step also provides an opportunity to adapt to the effects of climate change on the food system (Figure 6.1). Irrigation can provide water when precipitation patterns change but has other trade-offs, discussed later. Farmers can plant different crops and crop varieties that have higher nutritional value and are better suited to higher temperatures and less precipitation. More variety itself also increases dietary diversity and provides climate change resilience. New production locations can be exploited to increase yields and offset losses in other locations. Food storage can be upgraded in ways such as proper drying of cereals to decrease aflatoxin contamination or increasing cold storage for animal-source foods, vegetables, and fruits to keep foods safe and maintain their nutrition. Food processing can be harnessed to increase the stability of nutritious foods, and nutrition can be added to less nutritious foods through fortification. Food retail, especially in low-income countries, can be strengthened to increase resilience to climate change and increase food availability to the most vulnerable consumers. All of these steps and others will be discussed in more detail below.

Figure 6.1 A climate-smart and nutrition-sensitive food value chain

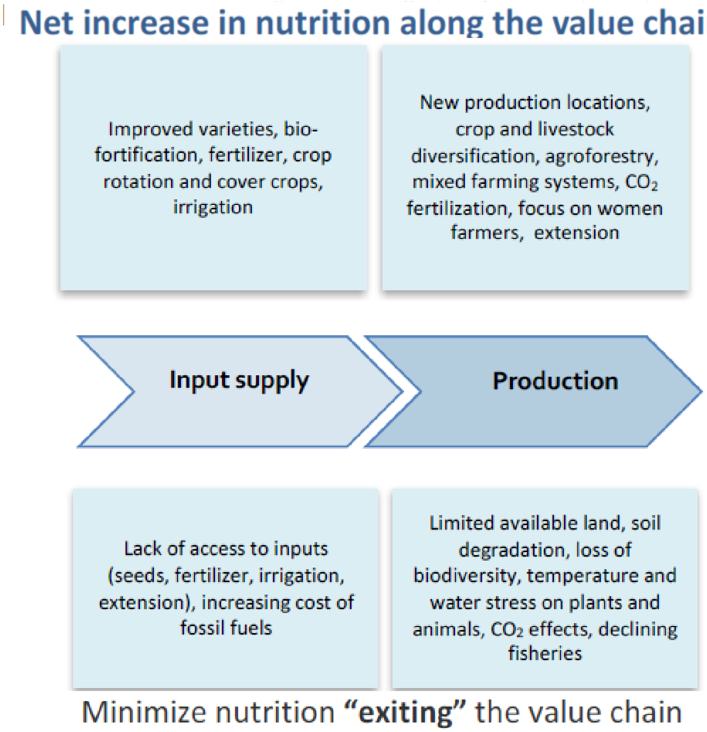


Source: Authors.

Mitigation, Adaptation, and Trade-offs in Food Production

The nutrition impacts of climate change on food production are highlighted in Figure 6.2.

Figure 6.2 Climate change and nutrition entry and exit points in food production



Source: Adapted with permission from Fanzo et al. (2017).

Discussions of the impacts of climate change on the food system have tended to focus on food production, as discussed earlier. Production has also been the focus of adaptation and mitigation strategies. Though there are other key areas of the value chain, which will be discussed later, food production is critical to ensuring there is enough nutritious food available to feed everyone. Without adaptation, climate change is expected to cause a 2 percent decrease in global agricultural production per decade until 2050 (GLOPAN 2015). Climate change will especially impinge on the diets of poor populations in Africa south of the Sahara and South Asia (GLOPAN 2015). Challinor and others (2014) examined several scenarios for changes in yields, finding a wide range, but concluded that rice, maize, and wheat yields would all decline at a temperature increase of 2°C. Adaptation strategies can slow or even avert reductions in agricultural yields, with Challinor and others (2014) showing simulated yields rising by as much as 7 to 15 percent for wheat and rice. However, simply scaling up production is environmentally costly and limited by resource availability. This is why climate-smart agriculture, which also aims to decrease greenhouse gas emissions, is critical. Though it is important to use climate-smart agriculture to increase food production, it is also crucial to consider how its use will affect nutrition.

Estimates of the financial burden of adaptation vary. The International Food Policy Research Institute estimated that it will cost between US$7.1 billion and US$7.3 billion per year until 2050 to provide the necessary research, technology, and infrastructure to maintain productivity. Of this cost, 40 percent is for Africa south of the Sahara, with the majority for rural road development (Nelson et al. 2009). The UN Framework Convention on Climate Change estimated that it will cost between US$11.3 billion and US$12.6 billion per year until 2030 (cited in Parry et al. 2009). Wheeler and Tiffin (2009) looked at the latter as well as other estimates and concluded that although reasonable, they were most likely underestimates.

The inputs of food production are the earliest point of the value chain, and interventions at this stage are key. The seeds, livestock breeds, soil, fertilizer, pesticides, and water that make up this stage are the basis for food quantity and quality.

Crop and Livestock Diversity

Seeds and livestock breeds can be diversified to increase the range of crops grown and livestock raised. Diversity itself is protective for heat and water stress and even more so for pests and disease. Different plants and animals can survive in different ranges of environmental conditions and have different susceptibilities to pests and disease. If one variety is damaged or killed, others may survive to maintain the food supply and farmer incomes. Companion planting, or planting different crops next to each other to take advantage of natural interactions, is another pest management strategy. Some plants naturally repel pests and can protect other species around them. Monocultures are extremely sensitive to large losses from heat, drought, pests, and disease that can be devastating in food and income losses (FAO 2016a).

Research continually supports the importance of dietary diversity for nutritional status. As discussed earlier, eating a larger number of food groups provides key micronutrients that are lacking in staple crops. Although growing more diverse crops is the first step in achieving dietary diversity, it is not sufficient because these more expensive foods may be sold instead of consumed. Therefore, support through education as well as social protection systems is critical, as discussed later (FAO 2016a).

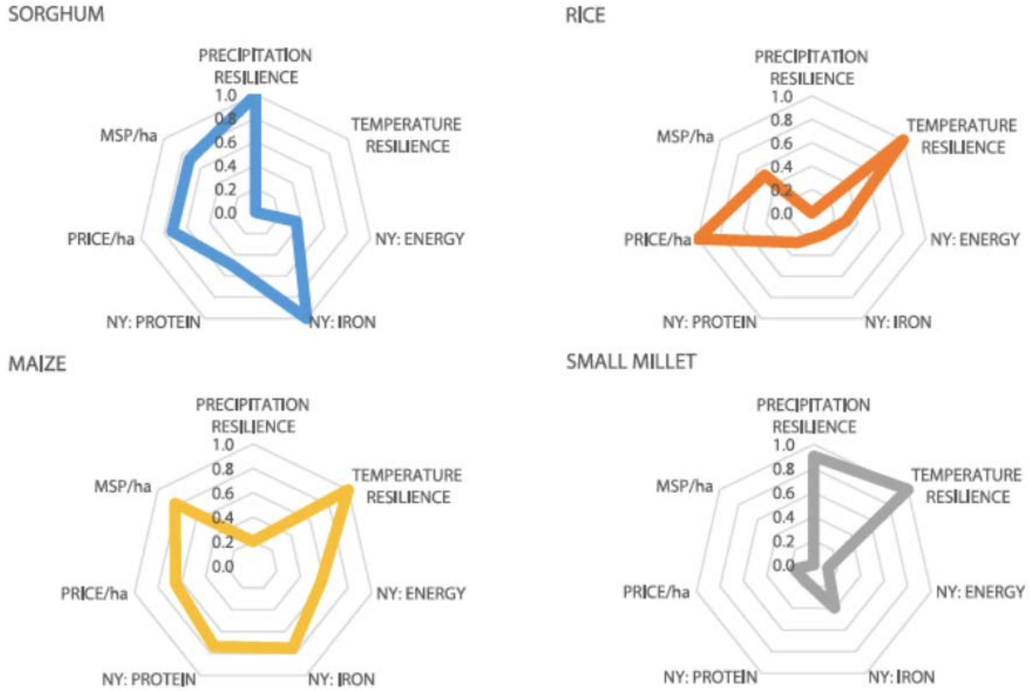
Biodiversity in the form of wild plants and agroforestry is also a key strategy. Wild plants can add micronutrients to diets and increase farmer incomes. They also provide food security when crops fail (Swiderska et al. 2011). Agroforestry utilizes trees and shrubs to decrease soil erosion, improve soil quality, and protect crops by stabilizing microclimates through providing shade and protection from wind. All of these benefits improve productivity and food availability (FAO 2007). Trees also shed their foliage, providing nutrients for the soil. In Africa, acacia trees have been planted in crop fields to improve soil and replace fertilizer (World Agroforestry Centre 2009). After planting acacia trees, one Malawi farmer reported that yields increased from 10 to 25 bags of maize, and in Zambia, maize yields tripled when acacia trees were planted (World Bank 2013).

Crop diversity can be achieved simply by taking advantage of the many varieties that already exist, especially through international cooperation such as the International Treaty on Plant Genetic Resources for Food and Agriculture (FAO 2016a). Farmers can select new crop varieties and livestock breeds that are more resistant to higher temperatures and decreased water as well as pests and disease. Although resistance to these environmental factors receives wide attention, it is also critical to consider productivity and nutrition (Pitesky et al. 2014). Producing food with more micronutrients will improve nutrition and counteract food shortages as well as the carbon dioxide effects that decrease protein, iron, and zinc, as discussed earlier. Research can be provided to low- and middle-income countries through CGIAR and national agriculture research institutes (FAO 2016a).

Increasing crop diversity has proven to be effective at increasing yields in the face of climate change. Swiderska and colleagues (2011) looked at the use of traditional crop varieties by indigenous farmers in Bolivia, China, and Kenya. These farmers are often already growing crops on marginalized land, so the traditional varieties they use are well adapted to harsher growing conditions and fare well with heat and droughts. In all three cases, increased diversity in these varieties resulted in increased yields and higher incomes. One of the study areas in China found increased diversity resulting in 30 percent higher incomes over 10 years. In Bolivia, increased diversity also resulted in better pest control, even with less pesticide use.

Although a lot of diversity has already been lost, it is critical to maintain what still exists through local conservation as well as seed production and sharing via seed fairs and seed banks. Women must be involved because, due to the outmigration of men to cities, they are most commonly the ones who have knowledge of traditional varieties and practices (Swiderska et al. 2011). By comparing the effects of rice blast on diverse rice fields versus monoculture fields, Zhu and others (2000) found that increased crop diversity increased yields through greater resistance to disease. The diverse fields had 89 percent greater yields and 94 percent fewer effects of blast. Moreover, the diverse fields had great enough inherent resistance that fungicide was no longer needed. Figure 6.3 shows the different resiliency characteristics of sorghum, rice, maize, and small millet in India, including precipitation and temperature resilience, price, and nutrition. Understanding characteristics of crops during specific seasons can be important for resiliency, depending on the desired outcome (DeFries et al. 2016). Thus, increasing crop diversity increases yields by protecting against heat and drought stress, pests, and disease, and it also boosts dietary diversity, thereby increasing both food quantity and food quality.

Figure 6.3 Resiliency trade-offs of Indian monsoon crops



Source: Adapted with permission from DeFries et al. (2016).
Note: Minimum Support Price = (MSP); Nutritional Yield = (NY).

Importance of Soil Quality

Soil quality is key for crop productivity and nutrition as well as for carbon sequestration. Improved soil quality improves yields and nutritional content. Soil provides organic carbon and plant-usable nitrogen that are both key for plant growth. Soil quality can be improved through manuring, especially green manuring, and spreading crop residues or synthetic fertilizer; however, it is important to ensure that fertilizer is being used effectively. The production of nitrogen fertilizer is a major source of greenhouse gas emissions and therefore should be reduced when possible. Overuse of fertilizer also contributes to runoff that pollutes waterways. In some areas, such as East Asia, where increases in fertilizer do not increase yields, fertilizer use could be decreased. However, in Africa south of the Sahara, fertilizer is underutilized and should be increased. Fertilizer is a trade-off, whereby increasing food yields requires more energy and greenhouse gas emissions. Farmers can help minimize the negative consequences of fertilizer production by using the right amount of fertilizer in the right place and at the right time. Spot fertilizer applications confer the most benefit and the greatest increases in food quantity while minimizing negative effects. In addition, nitrous oxide emissions can be decreased by adding nitrification inhibitors to fertilizer or adding lime or other bases to the soil to increase its pH. (FAO 2016a).

Soil quality can also be improved through the use of nitrogen-fixing cover crops and crop rotation. No-till farming or other methods that limit soil disturbance are also beneficial. However, using cover crops and crop rotation requires arable land to be inactive for a period of time. These methods increase yield and nutrition, and are especially effective when rainfall variability increases, but the trade-off of letting land lie fallow may still hinder farmer adoption (FAO 2016a).

Improving soil quality can also be a means of climate change mitigation, because soil is one of the largest sources of carbon sequestration, after only the oceans. Vermeulen, Campbell, and Ingram (2012) estimated that soil carbon sequestration is the most important method of mitigation. Improving soil provides an important way to sequester more carbon, and small changes can have a large impact. Lal (2010) found that degraded soil, especially in Africa south of the Sahara, could be improved to dramatically increase carbon sequestration as well as crop production. The soil carbon sequestration rate increases for a few years before peaking but then falls off (Sommer and Bossio 2014). After 30 years, the rate is about half of the initial rate and after 60 years, the rate falls to close to zero (Sommer and Bossio 2014). Therefore, improving soil quality not only increases yields and nutritional quality but also acts to increase carbon sequestration, taking advantage of a synergy between adaptation and mitigation (FAO 2016a).

Water Use

Climate change has a drastic impact on both the timing and the quantity of water available, as discussed earlier. This impact has the largest effect on the most nutritious foods, including animal-source foods, vegetables, and fruits, and on smallholder farmers, who may not have access to irrigation. Droughts threaten crops and livestock, as do large rainfalls from extreme weather events. More than 70 percent of the world’s freshwater supply is currently used for agriculture, and 40 percent of agricultural production comes from irrigated land. Irrigation will become increasingly necessary, yet the freshwater supply for irrigation is finite and increasingly vulnerable. Many of the world's major rivers and groundwater aquifers are already overexploited (HLPE 2012). Better use of agricultural water will not only address these threats but can even have multiple nutritional benefits (Domenech 2015).

Water use can be improved through changes in water management and irrigation, and such improvement is critical in Latin America, Africa south of the Sahara, and South Asia. In rainfed systems, water management can be improved through rainwater management and soil moisture management. Irrigation can dramatically increase production and is a key adaptation strategy. Depending on the type of irrigation system used, however, it can also increase water and energy use and greenhouse gas emissions, so it presents a trade-off with climate change mitigation. The negative effects can be minimized by increasing efficiency through improved education and technology, such as solar-powered irrigation pumps, if made available to the most vulnerable farmers. Farmers can be educated about the best uses of irrigation—which crops to use it for and when. Canals can be lined to prevent loss, and wastewater can be reused. Drip irrigation applies water directly to the plants and thus also decreases water loss; however, it may also use more energy, so it represents another trade-off.

Water management information and technology can be shared through water user associations. In Huai Hai Plain in China, the World Bank ran a program to manage water through promoting crops that needed less water, improving infrastructure to reduce water losses, and increasing the use of drip irrigation. It also formed 1,000 water user associations to train farmers, as well as 220 farmer associations to evaluate how well things were working and experiment with new technologies and practices. These programs impacted 1.3 million farmers (FAO 2016a).

Integrated Land-Use Policies

Integrated land-use policies are an innovative adaptation approach to improving soil and water quality while simultaneously protecting agricultural lands. These policies take a more holistic landscape approach through a range of active and passive methods. As an example, civil engineering units could protect croplands from extreme weather events by constructing levees or coastal defenses in areas close to sea level. Other approaches involve capturing precipitation from extreme weather events, planting moisture-tolerant trees along riverbanks to provide flood control, and paying communities for ecosystem services. Although some of these measures have been implemented, as in the United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation (known as UN-REDD), this landscape approach requires far more political will and financial support than it currently has (HLPE 2012).

Weather Prediction Technology

It is critical to improve our ability to provide information about current temperature and precipitation conditions as well as to predict future conditions, and to make this information widely available, especially to the most vulnerable smallholder rural farmers and pastoralists. These measures are especially important given the increasing availability of mobile phones and related technology around the world (HLPE 2012). Modeling and geographic information systems (GIS) can be used to predict weather and soil conditions (Pitesky et al. 2014). This information, where available, can be used to modify planting, harvest, and irrigation schedules. It is important to understand how changes in weather uniquely affect different countries or regions. For example, in Uganda and Zambia, changes in rainfall have little to no impact on yields, whereas in Malawi and Niger, yields are significantly affected by rainfall. In eastern and southern Africa, farmers who were provided with weather information avoided crop losses worth up to 25 percent of their incomes (FAO 2016a). Furthermore, it is necessary to consider how information needs vary according to gender. In Senegal, for example, men prefer predictions of rainfall onset because they have priority access to animals for field preparation. Lacking the ability to act on rainfall onset information, women need forecasts on rainfall cessation and dry periods. In addition to imposing different agricultural responsibilities, social norms also predicate how women can access information (HLPE 2012). Better early warning systems for extreme weather events are also needed, as well as practices to save crops and stored food (Pitesky et al. 2014).

Predictions are currently being used to modify farming practices and increase yields. In Bangladesh, Thomas and colleagues (2016) used crop models to shift the planting schedule to improve yields. Changing planting by two to three months increased yields for irrigated winter rice. However, this shift affected the planting seasons for other crops, making the practice complicated. In Kenya, similar weather and crop models are being evaluated to make recommendations about where crops should be planted. Some areas are expected to become more productive and others less productive. These predictions can be used to prepare for those shifts (Thomas et al. 2016).

Alternative Wetting and Drying of Rice

Rice paddies are continuously flooded in some areas to increase yields, but such flooding is a large source of methane emissions. Linquist and others (2015) found that drying the fields for a few weeks can decrease methane emissions by 45 to 90 percent, with the added benefits of reducing water use by between 18 and 63 percent as well as decreasing arsenic in rice by up to 64 percent. However, this practice increased weeds, leading to yield decreases of between 1 and 13 percent. Adjusting the timing, drying the fields earlier, and then reflooding them allowed yields to be maintained while still decreasing methane emissions by 45 percent and water use by 18 percent—but arsenic concentrations were the same or even higher.

Sustainable Increases in Animal-Source Food Production

Animal-source foods are nutritionally critical, especially for those most vulnerable to malnutrition. They provide protein and micronutrients such as iron, zinc, calcium, and B vitamins that are often lacking in other dietary sources. In low- and middle-income countries, animal-source foods are an important source of these micronutrients and should be increased in order to address malnutrition. Livestock can also survive environmental conditions that may kill crops, increasing food and nutrition security as well as income stability for vulnerable farmers. These benefits are especially important in areas of Africa where current crop production will be threatened by climate change. Changes in the breeds and types of livestock that are kept may also be necessary. The Fulbe people in Nigeria changed from Bunaji cattle to

Sokoto Gudali cattle due to changes in pastureland. The new breed is able to eat a more diverse diet and therefore less dependent on grass. The Samburu people in northern Kenya started keeping camels in addition to their traditional cattle when cattle productivity decreased (Jones and Thornton 2009).

Livestock require large amounts of resources and directly emit methane, which creates a trade-off to consider. There are relatively sustainable ways to raise livestock (as seen with pastoralists), but these methods also have trade-offs. Raising livestock on pasture that can be used to grow grasses but not crops decreases the land, water, and energy required to produce animal feed, but it produces more methane. Pasture in arid areas also has lower-quality feed, leading to decreased livestock productivity and decreased feed conversion efficiency. Raising livestock on feed decreases methane emissions. Feed can be formulated to maximize these decreases as well as to increase productivity and feed conversion efficiency. However, raising livestock on feed requires food to be used for animals instead of people, and growing feed is resource intensive (Herrero et al. 2010). Half of the energy used in livestock production is in feed production. Also, when production occurs through concentrated animal feeding operations, it produces large amounts of air and water pollution (Garnett 2009).

Cattle can be raised with increased efficiency to decrease their environmental impact. More efficient breeds have better feed conversion efficiency. In the United Kingdom, farmers used more efficient cattle to decrease the number of animals but maintain production, which decreased methane emissions by 28 percent between 1990 and 1999 (FAO 2016a). In Uganda, Rwanda, and Kenya, the East Africa Dairy Development program modified feed to increase milk supply and improve milk quality. The program also helped farmers reach more markets through dairy farmer business associations (GLOPAN 2015).

If current best practices were used for all livestock production, there would be a dramatic decrease in livestock greenhouse gas emissions—between 18 and 30 percent, according to Gerber and colleagues (2013), or between 14 and 41 percent, by the estimates of Mottet and others (2017). Other livestock, such as pigs and chickens, have higher feed conversion efficiencies and do not produce methane, making them potentially better sources of nutrition.

Farmed fish have even higher feed conversion efficiencies and are also a key source of nutrition, including protein, omega-3 fatty acids, and micronutrients. Declining ocean fisheries, as well as temperature-mediated changes in fish location away from the tropics and toward the poles, threaten capture fishing as a food source. Aquaculture presently provides a large source of fish and may be scaled up. It is currently focused in Asia, where two-thirds of global aquaculture production is located. Aquaculture is also susceptible to climate change via increasing disease outbreaks. Although it is more protected from changing environmental conditions than capture fisheries because some of its inputs can be controlled, a higher level of control increases the energy requirements, presenting another trade-off between nutrition-sensitive adaptation and climate change mitigation. In addition, fish farms may displace natural coastal habitats such as mangroves, which are an important source of carbon sequestration.

Trinh, Tran, and Cao (2016) reported on aquaculture using tilapia, shrimp, mud crabs, and seaweed in Thanh Hoa Province in Viet Nam. These integrated systems provided increased diversity and increased yields. The tilapia fed on waste, improving water quality for the shrimp and crabs. Similar systems in Ecuador increased shrimp production by 13 to 17 percent and shrimp size by 18 percent compared with single-species systems. In addition, integrated systems increased incomes by 14 to 43 percent compared with single-species systems. They also decreased the need for industrial feed, reducing the greenhouse gas emissions as well as system costs. The program also specifically worked with women in order to increase their role in decision making.

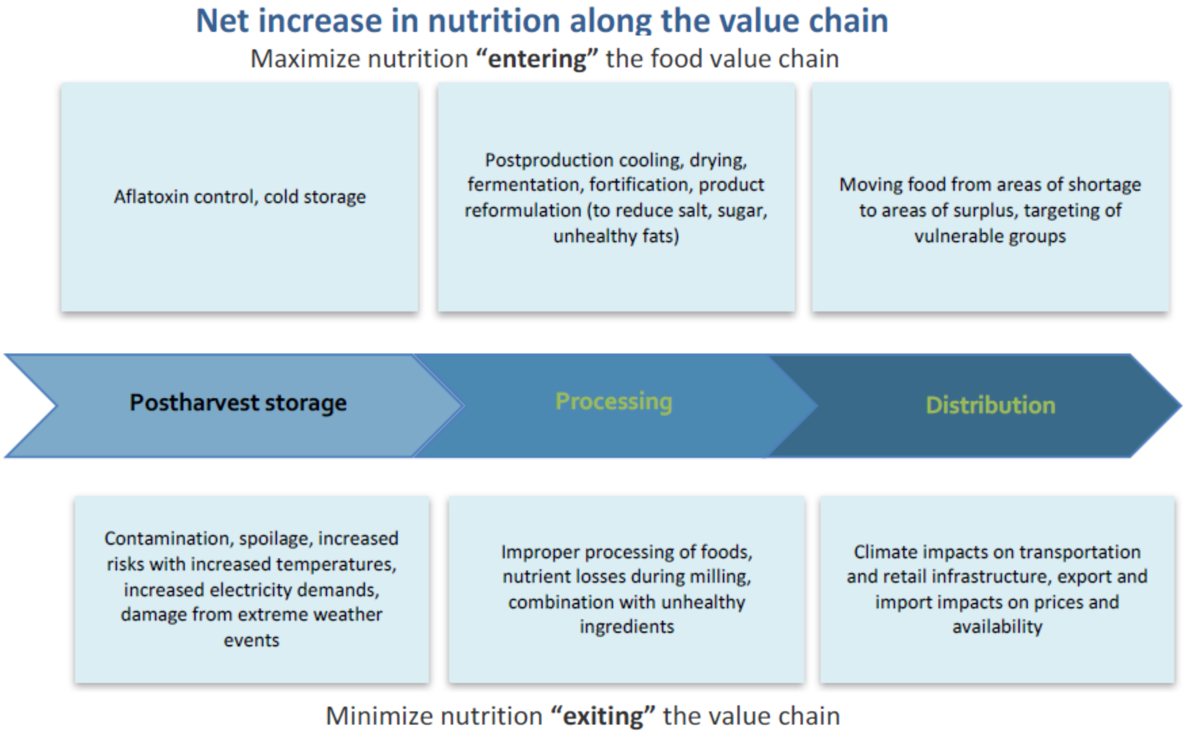
Mixed Systems

Mixed crop and livestock systems can increase both the amount and the nutritional quality of the food produced. As discussed earlier, animal-source foods are a valuable nutrition source. Raising livestock can be environmentally taxing, but livestock can also be raised in more sustainable ways or in ways that harness their benefits to make a better overall system. Livestock waste can be used as fertilizer to improve soil quality and crop yields. Mixed systems also provide additional income that is more stable than income from crops or livestock alone, and they offer resilience to crop losses (Herrero et al. 2010). For example, pigeon peas, a nutritionally valuable legume, can be integrated into crop plans. Pigeon peas also fix nitrogen, improving the soil quality. The pods can be fed to livestock, and the leaves and livestock waste can be used as fertilizer (FAO 2016a). Fish can also be raised in flooded rice paddies to provide similar benefits of an additional source of nutrition and income. They also offer the added benefit of mosquito control, thus decreasing mosquito-borne disease (Fernando 1993).

Mitigation, Adaptation, and Trade-offs in Food Transportation, Processing, and Storage

The impacts of climate change on nutrition in food transportation, processing, and storage are highlighted in Figure 6.4.

Figure 6.4 Climate change and nutrition entry and exit points in food transportation, processing, and storage



Source: Adapted with permission from Fanzo et al. (2017).

Transportation Infrastructure

Pitesky and colleagues (2014) argued that transportation and storage of food are the most critical points for adaptation, especially in the short term. Although estimates vary, global food production may not be challenged until 2050. Although global production may stay the same, there will be changes in when and where food is produced. By 2050, we may be growing wheat in Alaska instead of Kansas. These changes will be exacerbated by continued trends of urban migration, which will make it critical to be able to move and store food so that it is available when and where it is needed (Pitesky et al. 2014). New transportation infrastructure will need to be built to move food from where it can be produced to where it is needed. Changes in landscapes as well as extreme weather events also threaten current transportation infrastructure, as discussed earlier. New infrastructure will need to be built and damage repaired quickly to maintain food supplies and decrease food waste (Brown et al. 2015).

Food Processing for Safety and Nutrition

With increasing temperatures, many foodborne pathogens will be able to survive in new locations and in new seasons, and they may be present in food at higher levels, as discussed earlier. Food may need to be processed at higher temperatures in order to maintain its safety (Tirado et al. 2010).

The way that food is processed can either add or remove nutrients. Processing also affects food stability and consumption. Food can be fortified at the processing stage to increase nutrients in staple crops and to replace nutrients that are lost due to carbon dioxide effects. Food processing can also increase the stability and thus the availability of the most nutritious foods. Animal-source foods, vegetables, and fruits are the most important foods from a nutritional standpoint, but they are also the most perishable. In their unprocessed state, they require immediate use of cold storage that is often unavailable and in any case is energy intensive. Processing can increase stability and even improve nutrition (GLOPAN 2015). For example, drying and salting meat and fish makes them last longer and preserves their essential nutrients. This type of preservation can be done on a large scale or even by consumers at home. One concern is the amount of salt, but it is possible to minimize salt or even dry meat without any salt (FAO 2016a). Dairy can be processed as milk, cheese, and yogurt. Berlin, Sonesson, and Tillman (2008) compared these three to see whether there were any key differences. They found that processing into yogurt and cheese decreased waste due to longer shelf lives and also increased incomes due to higher prices. Dairy can be cultured into products such as kefir or yogurt. Cultured dairy is more stable and also provides the additional nutritional benefit of containing probiotics. Although drying of fruits and vegetables removes some water-soluble nutrients, such as vitamin C and B vitamins, it increases the food's stability and preserves many other nutrients. All of these methods decrease the need for cold storage and make nutritious foods more stable and thus available to consumers. Smallholder farmers, fishers, and pastoralists can use these methods to increase the marketable amount of their output and thus their incomes, and consumers can use them at home to improve their own nutrition (FAO 2016a).

Cold Storage

Cold storage is the most energy-intensive step in the value chain besides production. However, it is also necessary to maintain the freshness and safety of the most nutritious foods, including animal-source foods, vegetables, and fruits. The cold chain is lacking or incomplete in many low- and middle-income countries and therefore should be increased and strengthened in order to increase nutrition security. When not necessary, cold storage should be minimized or eliminated. For example, processing that makes cold storage unnecessary, such as drying, should be increased. Some foods and beverages do not need to be refrigerated and can be kept at room temperature. Coca Cola, for instance, self-reports that 71 percent of its greenhouse gas emissions are from refrigeration, which is unnecessary for safety or quality (Vermeulen, Campbell, and Ingram 2012). When cold storage is unavoidable, it can be improved based on the refrigerants used and the elimination of leaks in the system (Opio et al. 2013).

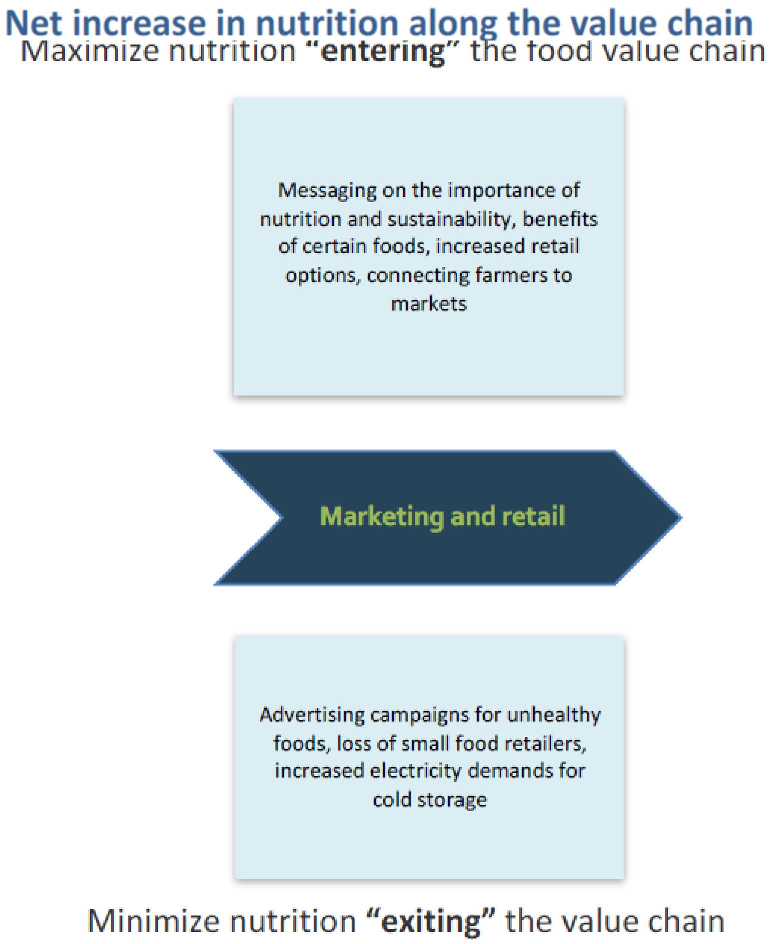
Aflatoxins in Food Processing and Storage

Climate change will increase aflatoxins at all stages of the value chain. Because aflatoxins are dangerous carcinogens at low levels and deadly food contaminants at high levels, it is critical to decrease their production and dispose of contaminated food. It is important to store foods, especially maize and groundnuts, in a way that minimizes aflatoxin production. Because aflatoxin production is highest in hot and humid environments, it can be decreased by thoroughly drying grains and legumes before storage. Storing these foodstuffs at cooler temperatures and lower humidity also decreases aflatoxin production, but this type of storage requires energy. Airtight hermetic storage can also be used to decrease the oxygen available and halt aflatoxin production. Other molds that do not produce aflatoxin can be introduced to compete with the aflatoxin-producing *Aspergillus* species. Another approach is to treat food with chemicals such as hydrogen peroxide, methanol, dimethylamine hydrochloride, and perchloric acid, but these chemical treatments may cause a decrease in protein in maize (Villers 2014).

Mitigation, Adaptation, and Trade-offs in Food Marketing and Retail

Figure 6.5 highlights the impacts of climate change on nutrition at the food retail and marketing point of the value chain.

Figure 6.5 Climate change and nutrition entry and exit points in food retail and marketing



Source: Adapted with permission from Fanzo et al. (2017).

Marketing to Address Environmental Impacts

Although some food marketing already addresses environmental impacts, it is key to increase environmental messaging so that consumers know their role in the food system and how to change their behavior. Consumers in high-income countries must change their consumption patterns in order to address climate change, as discussed later.

Parallel Arms of Food Retail

Multiple arms of food retail often exist in parallel. In low- and middle-income countries, small food retailers at local markets and individual farmer stands are critical for supplying food to rural and poorer populations. Unfortunately, these outlets often have little to no infrastructure, such as cold storage, increasing their risk for problems with food safety and food loss, especially in relation to the more nutritious animal-source foods, vegetables, and fruits. They also rely more on local food sources than do larger retailers and thus are more susceptible to changes in food availability and prices (Vermeulen, Campbell, and Ingram 2012).

Increased Market Access

Market access is key for the incomes of rural smallholder farmers, fishers, and pastoralists. In areas with greater density of small farms, such as in Africa south of the Sahara, farm networks can be used to increase market access (FAO 2016a). The ease of getting to markets is impacted by the infrastructure and transportation systems as well as the distance to the market. Markets also need to be better integrated, and agriculture needs to be more globalized (Vermeulen, Campbell, and Ingram 2012). Markets also provide opportunities for regional crop and livestock diversity to be dispersed to consumers, which can bolster dietary diversity.

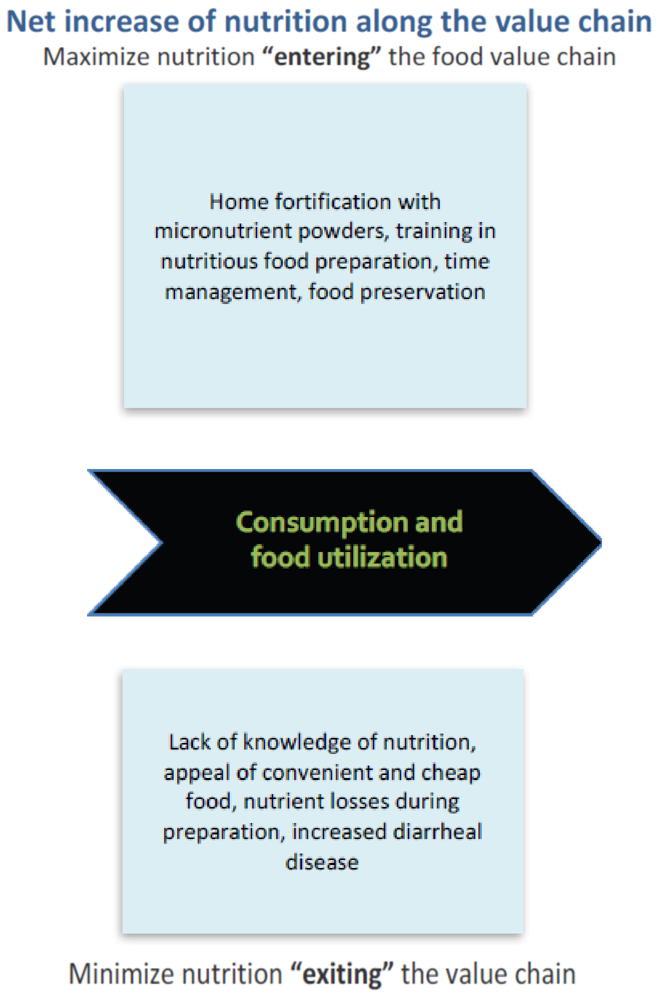
Decreased Food Loss

As discussed earlier, a tremendous amount of the world's food is wasted, with this loss happening at all points of the value chain. In high-income countries, most waste occurs at the retail and consumption stages, whereas in low- and middle-income countries, most of it occurs in production, transportation, and storage. In low-income countries, waste is exacerbated by social and cultural conditions, such as the differing roles played by men and women in the value chain. Women's difficulty in accessing resources, services, and income-generating activities impairs their productivity and efficiency in food production (FAO 2016a). Food waste decreases the amount of both calories and nutrients available, with the most nutritious foods also being the most perishable, including animal-source foods, vegetables, and fruits. Decreasing waste of these foods, including through increased access to cold storage in low- and middle-income countries, would be highly beneficial for food and nutrition security (Vermeulen, Campbell, and Ingram 2012).

Mitigation, Adaptation, and Trade-Offs in Consumption and Utilization

Consumption and utilization make up the final nexus point in the food value chain, a stage equally as important as the previous ones in mitigating and adapting to the impacts of climate change on nutrition. Figure 6.6 details the impacts of climate change on nutrition at the food consumption and utilization step.

Figure 6.6 Climate change and nutrition entry and exit points in food consumption and utilization



Source: Adapted with permission from Fanzo et al. (2017).

Sustainability in Dietary Recommendations

Promoting sustainability in dietary recommendations is an important mitigation technique. Bajželj and others (2014) projected that the adoption of healthy diets—defined as those that limit consumption of energy-rich foods such as livestock and sugar on the basis of nutritional evidence—would have positive impacts on both human and planetary health. Common features of healthy diets include a diversity of foods eaten, a balance between energy intake and expenditure, and the inclusion of minimally processed tubers and grains, along with unsalted seeds and nuts, legumes, fruits, vegetables, and in moderate quantities, meat and dairy. Small quantities of fish and aquatic products are included, and processed foods high in sugar, fat, or salt and low in micronutrients are heavily restricted (FAO 2016a).

If this dietary shift were adopted globally, it could potentially reduce the area needed for cropping by about 5 percent, the area for pasture by about 25 percent, and total greenhouse gas emissions by about 45 percent (Bajželj et al. 2014). These estimates are based on the projected decrease in enteric fermentation and manure emissions as well as carbon sequestration made possible by reverting some agricultural lands to unmanaged ecosystems. The implementation of healthy diets would require careful attention to regional and cultural preferences as well as crop suitability. Although some regions, namely industrialized ones, consume animal-source foods in excess of healthy levels and would experience health benefits from the shift to a healthy diet, livestock consumption is a critical means to improving nutrition in other populations (Bajželj et al. 2014; FAO 2016a). Additional challenges are discussed in greater detail below.

Meat Consumption

Managing meat consumption and production, which contributes to greenhouse gas emissions, can have a positive impact on mitigating climate change. For high-income countries, the emphasis is on reducing meat consumption, which would also improve health outcomes. Conversely, in low- and middle-income countries, meat consumption represents an opportunity to improve nutrition. The challenge for policy makers in these countries is to encourage consumption of animal-source foods for nutritionally vulnerable groups while simultaneously promoting improved livestock productivity, which would reduce livestock's carbon footprint and make their use of water and feed more efficient. Ultimately, the risk is that as low- and middle-income countries become wealthier, they will adopt the excessive meat consumption habits of high-income countries (GLOPAN 2015; FAO 2016a; Ranganathan et al. 2016).

Food Waste

Globally, the energy embedded in annual food losses is believed to be around 38 percent of the total energy consumed by the entire food chain, although the data on these percentages are not definitive. Food waste also contributes to global greenhouse gas emissions through disposal in landfills: the European Commission's Integrated Policy Platform identified the reduction of food waste as one of three key components required to limit the environmental impacts of agricultural production (cited in FAO 2011a). As with consumption of animal-source foods, the need to minimize food waste also differs by income status. As much as an estimated one-third of all food produced globally is not consumed. In high-income countries, food waste occurs mainly at the retail, preparation, cooking, and consumption stages of the food value chain, but in low-income countries, it occurs primarily at the production, storage, and distribution stages.

In Europe and North America, food waste is between 95 and 115 kilograms per capita per year. More than half of all the losses in these countries are caused by the deterioration of fresh produce. Other factors that contribute to waste include mismatched supply and demand, poor purchase planning, careless preparation, and leaving prepared food unconsumed. Rejection of foods that do not meet specific quality standards or are past the expiration date on the package label is another waste factor that is especially problematic in high-income countries. Reducing food waste is an important means of mitigation because when food is wasted, the energy embedded in that product is also wasted. In the United States, food losses account for about 2 percent of total annual energy consumption (FAO 2011a).

In low-income countries, food waste is lower but still a problem. In Africa south of the Sahara and in South Asia, food waste is between 6 and 11 kilograms per capita per year (FAO 2011a). Although these losses are much lower than in high-income countries, they still contribute to energy use and greenhouse gas emissions and, even more important, decrease farmer incomes, decrease food availability, and increase food prices for the rural and urban poor. Many people in low-income countries are food insecure or at risk of food insecurity and can benefit from even small increases in food availability and affordability. Food waste can be addressed by improving production, storage, processing, and infrastructure such as roads and electricity. Fresh produce is often wasted because processing facilities in low-income countries cannot process it. It is also wasted if cold storage or a sufficient transportation network is not available. Thus, food waste can also be addressed by better connecting farmers to markets and consumers. The FAO recommends selling food closer to consumers, such as through farm stands and markets (FAO 2011a).

Although food waste at the consumption level is primarily an issue for high-income countries, it should not be considered irrelevant for low- and middle-income countries. In emerging economies, food waste is primarily a problem during harvest and storage. However, in the last 20 years, many of these countries have experienced a change in eating habits as their incomes have grown and demographics have changed. Increased consumption of animal-source foods has been accompanied by obesity issues, often among the poorest populations, and rising food waste. As with meat consumption, the challenge for low- and middle-income countries is to improve nutrition outcomes while avoiding the pitfalls of negative environmental impacts and overconsumption faced by high-income nations (HLPE 2014).

Overconsumption

Addressing the overconsumption of calories around the globe is another pathway to mitigating the effects of climate change. Overconsumption leads to unnecessary use of land, water, and energy, and it carries unnecessary environmental impacts related to production. The world has seen a trend toward greater per capita consumption of calories over the last five decades; concurrently, the number of overweight and obese individuals is high and growing around the world: in 2013, 37 percent of adults over the age of 20 were overweight and 12 percent were obese. Though this issue has long been considered unique to high-income countries, the number of obese and overweight people is rising in emerging economies, especially among urban populations. Projections indicate that if consumption were reduced by 2 percent, the number of obese and overweight people would be halved, land use would decrease by 90 million hectares, and greenhouse gas emissions from agricultural production would decrease by 2 percent. The long-term mitigation effect is significant: sustaining these dietary changes over time would avert 19.9 billion tons of greenhouse gas emissions (Ranganathan et al. 2016).

Food Preparation

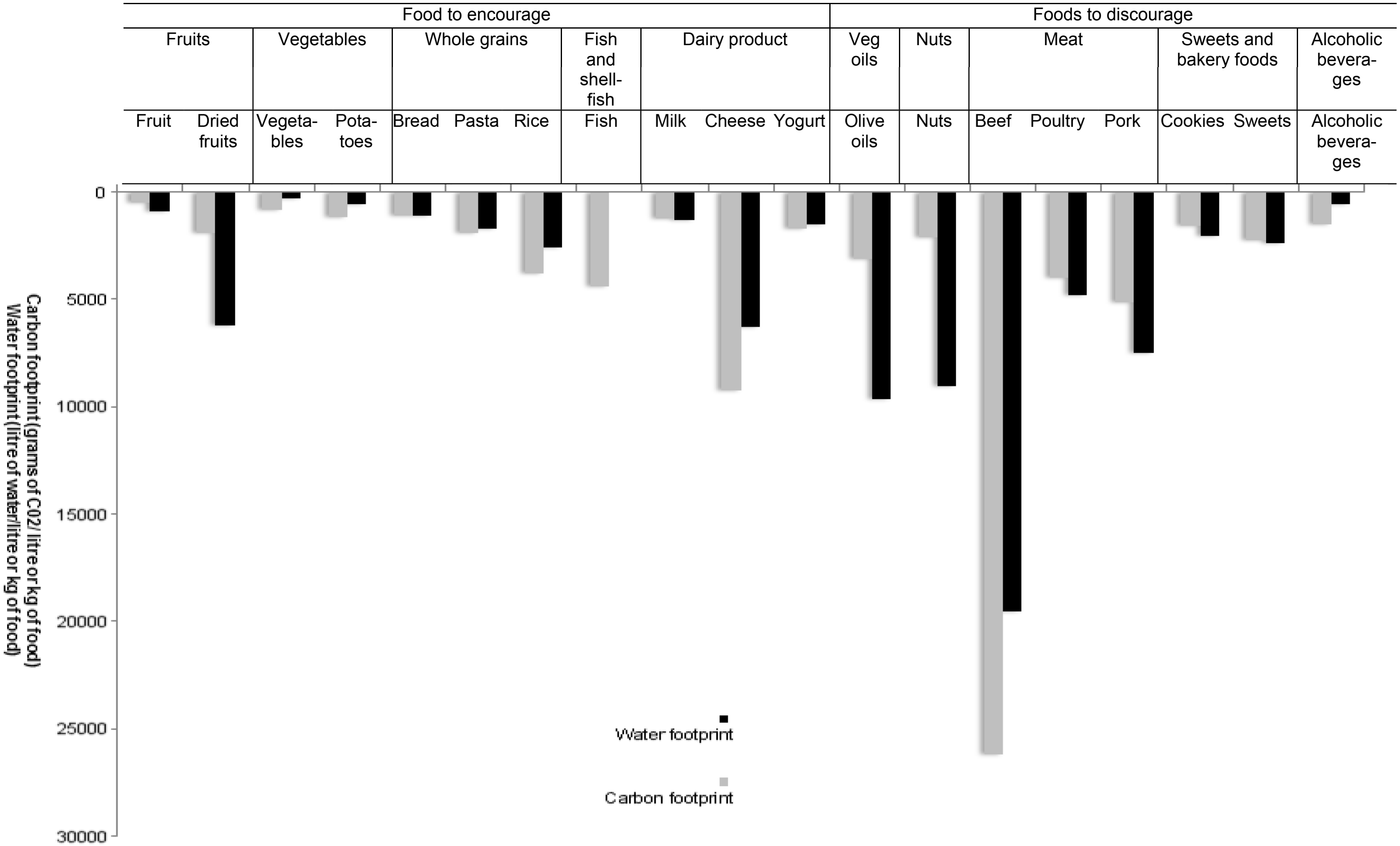
The way in which food is prepared in low- and middle-income countries can also mitigate the impacts of climate change. Around the world, an estimated 3 billion people rely on biomass for cooking (WHO 2016). In addition to the negative impacts of inefficient cooking on human health described earlier, this method of food preparation also carries deleterious implications for climate health. The burning of biomass is a significant contributor to emissions of greenhouse gases and other products of incomplete combustion that carry a high global warming potential (World Bank 2011). Another impact for the local and global environment lies in the unsustainable harvesting of biomass. When biomass is obtained from cutting down natural-growth trees, it reduces carbon dioxide sequestration potential, and when it is obtained from parts of plants or even dead wood, it depletes the soil and contributes to erosion. Shifting to more energy-efficient cooking methods decreases biomass use and has co-benefits for women, who, as the traditional collectors of biomass, are subsequently able to divert their time to other priorities and income-generating activities (IPCC 2011, World Bank 2011). The trade-offs of replacing energy-inefficient biomass with renewable resources for cooking include high initial equipment purchase costs and cultural preferences (World Bank 2011). In locations where this transition cannot be made, it is important to ensure that biomass is sustainably harvested through not cutting down natural-growth trees and through leaving a portion of the biomass to ensure soil health.

Trade-offs and Implementation

Changing how food is utilized and consumed is a powerful means of mitigating climate change and its impacts on nutrition. Projections of planetary and human well-being clearly indicate the positive results these changes might have, yet these shifts in utilization and consumption of food are rife with complex trade-offs and difficulties in implementation. Even if a large-scale shift to a globally healthy diet were accomplished, increases in population and accompanying food demand would likely exhaust the availability of suitable land, leading to agricultural expansion to less suitable or pristine land, such as through conversion of tropical forests to cropland (Bajželj et al. 2014). In the United States alone, a higher dietary share of fruits and vegetables would lead to an increase in water use by 10 percent, greenhouse gas emissions by 6 percent, and energy use by 38 percent (FAO 2016a). The healthy diet scenarios proposed by Bajželj and others (2014) would require a 30 percent reduction in global animal product intake relative to projected 2050 levels, and greater reductions in areas with higher intake, such as western Europe, all of which raises the question as to how such a tremendous change in dietary patterns can be effected (Kim et al. 2015).

It is not always about meat, either. Certain other foods also strain natural resources, such as water or land use. Downs and Fanzo (2015) showed that certain foods that make up the relatively plant-based, "sustainable," and cardioprotective Mediterranean diet have high water and carbon footprints (Figure 6.7), demonstrating that there are always trade-offs.

Figure 6.7 Water and carbon footprints of the components of a cardioprotective diet



Source: Adapted with permission from Downs and Fanzo (2015).
Note: Carbon footprint = grams of CO2 per liter or kilogram of food, based on the impact of the production of goods and services throughout the entire life cycle, expressed in emissions of carbon dioxide equivalents. Water footprint = liters of water per liter or kilogram of food, based on the amount of freshwater (green, blue, and gray) used to manufacture a product by totaling the water used at each stage of the production chain.

Implementing these changes at the consumer level would require disincentives for unhealthy behaviors: proposed initiatives include application of a carbon tax that accounts for livestock emissions, removal of subsidies and tax breaks for livestock production that artificially lower the price of animal products, support for developing plant-based meat alternatives, increase of plant-based options in federal meal programs, and expansion of behavior change programs such as Meatless Mondays (Bajželj et al. 2014; Kim et al. 2015). Evidence on how consumers make decisions about food indicates that these approaches will have to resonate beyond their rational choices and affect their unconscious, automatic decisions (Ranganathan et al. 2016). Other potential changes include addressing the livestock sector in climate mitigation policies and amending the current approach to diets, which bases health requirements on agricultural policies, to one that prioritizes health needs and shapes agriculture accordingly (Bajželj et al. 2014; FAO 2016a). Yet even these proposals contain ethical trade-offs and complexities: in the case of a tax on meat, a substantial tax is required to sway consumer behavior, but this price increase risks limiting low-income individuals' access to food (Ranganathan et al. 2016). Springmann, Mason-D'Croz, and colleagues (2017) found that the health benefits from tax-related reductions in obesity could outweigh the health losses from increased numbers of underweight people in three-quarters of all regions of the world.

Reductions in food waste at the consumer level can also be achieved through policy initiatives. The United Nations and numerous countries have already implemented detailed policy plans and monitoring mechanisms to halve food waste by 2030. Many of the plans already in place address the need for greater shelf life and improved date labeling for food. As with the goal of reducing animal-source food consumption, the need to reduce food waste is primarily aimed at those in high-income countries. Although most food waste in high-income countries is at the consumer level, most food waste in low- and middle-income countries occurs earlier in the value chain, as discussed earlier. Though low- and middle-income countries are not the target populations for these changes, dietary shifts in high-income countries have reverberating effects on human and planetary health elsewhere. Furthermore, these changes have the potential to serve as a guideline for sustainability as developing countries experience growing wealth and accompanying changes in consumption.

Early Warning Systems and Forecasting

In addition to mitigating the effects of climate change on nutrition, adaptation strategies are also needed to prepare for decreased yields, increased food prices, and price volatility. Early warning and forecasting of food security is one method of responding to the impacts of climate change on nutrition. Existing food security monitoring systems are organized around agricultural production monitoring; the market information system, which monitors domestic trade and sometimes international trade as well; the monitoring of vulnerable groups, which focuses on poverty; and food and nutritional surveillance systems, which, depending on the situation, monitor the health and nutritional status of populations. Focusing solely on the nutrition component of these systems, trend analyses, indirect and multiple indicators, and warning signals are used to track chronic, cyclic, and transitory food insecurity at the national, subnational, community, and household levels (FAO 2000).

Disease

Another adaptation technique involves addressing both infectious and noncommunicable disease to increase nutrient absorption and thereby decrease nutrient intake needs. As stated previously, increases in atmospheric carbon dioxide are expected to lower the availability of zinc, iron, and other nutrients in crops (Myers et al. 2014). This potential reduction in nutrient availability could exacerbate health burdens already experienced in low-income countries, especially in areas already subject to seasonal undernutrition (FAO 2016a). Diarrheal diseases, which are correlated with temperature increases, adversely affect the absorption of micronutrients (Wheeler and von Braun 2013). Though not directly influenced by climate change, environmental enteropathy likewise causes malabsorption and leads to malnutrition and stunting (Korpe and Petri 2012). Water scarcity, higher temperatures, and the resulting growth in pathogen exposure could potentially increase the health burdens of diarrhea by 10 percent by 2030 (FAO 2016a). An increase in foodborne pathogens, such as mycotoxins and cyanotoxins, is also correlated with the impacts of climate change and would have serious disease implications (FAO 2016a). Treatment of disease also converges with the mitigation pathway noted earlier of changing diets: the burden of noncommunicable disease can be reduced by limiting consumption of processed and red meat and increasing fruit and vegetable intake.

Mitigation, Adaptation, and Trade-offs in Services and Financing

Agriculture Insurance and Credit

Social protection services within agriculture are critical to provide education, technology, and money for farmers. The farmers most vulnerable to climate change are also the ones most disenfranchised from the financial system due to poverty, gender discrimination, and rural location. These farmers often have the lowest financial literacy; little to no credit history or collateral; and poor access to insurance, credit, and loans. It is critical to ensure that these farmers are reached through specific programs that are conscious of these barriers. Women are key players in agriculture, but they often do not have the same decision making power as men in their households and communities (FAO 2016a).

Crop insurance is a key way to protect farmers. Index-based insurance involves tying insurance to conditions such as heat waves, droughts, and average yields, and pays farmers when thresholds are exceeded. It provides the resources to adapt and maintain yields instead of reacting to losses after the fact. Insurance should be offered to all farmers but especially smallholder farmers and pastoralists, who are the most vulnerable to climate shocks and currently have the least access to insurance (FAO 2016a). There are, however, some unexpected negative effects. Antle (2010) argued that insurance removes the motivation for farmers to adapt, actually decreasing their productivity.

Farmers need resources to be able to implement new technology and practices to adapt to and mitigate climate change, but these resources require capital that is not always available. When farmers do not have the necessary capital, they have to make difficult financial decisions that often are necessary in the short term but may be detrimental in the long term. For example, farmers may sell livestock when they need the money, but such sales hurt their food and nutrition security as well as their future income.

Rural location makes access to credit more difficult. Credit is also less available to poor and women farmers, who may not have landownership or other capital to use as collateral, even though these are the farmers most in need. It is critical to ensure that women have access to insurance, credit, and loans (FAO 2016a).

Social Protection Services

Although social protection services within agriculture are critical, those in other sectors are just as important. Poverty reduction broadly increases agricultural production. Social protection services such as supplementary food, food vouchers, school meals, public works programs, and cash transfers are all valuable. Even when they are not explicitly meant to increase resilience to climate change, they still have this effect. In Zambia, cash transfers were found to have significant positive effects on the food security of households in the face of climate change. Although they were not sufficient to provide complete protection, they were still useful in increasing resilience and should be increased (Asfaw et al. 2016).

The effects of climate change resonate strongly at the production stage of the food value chain, as noted previously, yet they also indirectly influence food and nutrient access through impacts on household and individual incomes (Wheeler and Tiffin 2009). Transfers, both conditional and unconditional, help households manage shocks by providing food, cash, vouchers, or other resources during crisis periods. These support programs can also help support future resilience, as was the case with innovative resource transfers implemented by the FAO in Pakistan and the WFP in Kenya that provided resources in exchange for work on soil and water conservation programs (FAO 2013). Safety nets also directly support positive health outcomes by helping to prevent seasonal malnutrition in vulnerable communities (FAO 2013).

Public works programs and innovative risk-management tools are other forms of safety nets that promote positive nutrition outcomes. Public works programs can offer employment in times of need and thereby bolster household food security. Activities related to agriculture can also have significant impacts on crop yields and vegetation diversity. As a result, these public works programs can strengthen resilience against drought-induced food insecurity. As another example, weather index–based insurance is a labor-based safety net that protects beneficiaries from disruptions caused by climate events and expands access to insurance. Safety nets can also lead to important mitigation co-benefits: in Darfur, the WFP's Safe Access to Fuel and Energy (SAFE) program resulted in environmental gains as well as positive nutrition outcomes. The program, which trained women in environmental conservation and fuel-efficient cooking, resulted in a reduction in the use of wood for fuel as women adopted briquettes and fuel-efficient stoves, as well as an improvement in regional soil structure through reforestation and sustainable land management (FAO 2013). The Graduation approach, a multipronged initiative that provided self-employment activities through asset grants, training and support, life skills coaching, temporary cash for consumption, and access to savings accounts and health information, achieved improved food consumption and security after one year, benefits that largely outweighed the program's costs (Banerjee 2015).

Income Diversification

Most farmers, especially smallholders, rely on other sources of income in addition to farming. This income is critical for food purchasing because most farmers are also net purchasers of food (Vermeulen, Campbell, and Ingram 2012). When their incomes decrease, they cut out nutritious foods, including animal-source foods, vegetables, and fruits (GLOPAN 2015). As farming livelihoods are increasingly threatened from climate change, these off-farm sources of income will become even more important. Income diversification protects farmers from farm losses and price fluctuations (Vermeulen, Campbell, and Ingram 2012). However, women and rural farmers have fewer options for diversification. For instance, it may not be socially acceptable for women to take other jobs due to gender norms in some countries. Employment opportunities other than agriculture may be nonexistent in some rural communities. Women's empowerment can increase options for women to get credit and insurance as well as off-farm employment. Empowering women improves not only their lives and health but also their children's health. Rural development can improve conditions across the board as well as providing off-farm job opportunities (FAO 2016a).

Public Financing versus Market Forces

The question remains whether adaptation and mitigation should be tackled by international organizations and governments with funding for research as well as implementation of new technologies and practices, or whether it should rely on private companies through the use of market forces to generate a profit-based incentive. The public sector had a key role in the Green Revolution, funding the research and agricultural changes that were critical in increasing yields through land-grant university extension programs as well as through other institutions. Extension services provide information and training as well as human capital to help food producers adapt to climate change. These services can also heighten resilience for women, and they sometimes function as less formal initiatives, such as farmer field schools, that facilitate the sharing of information (HLPE 2012). It would seem obvious that in the face of such critical challenges and such high stakes, the public sector should again take the lead. However, some argue that the market will stimulate the needed response from the private sector (Antle 2010).

Limitations of Current Evidence

There is very little information about how to effectively mitigate and adapt to climate change in the food system at each step of the value chain in order to maximize nutrition, such as through increasing dietary diversity. Most of the research offers very little guidance on specific steps. We need research to determine evidence-based actions to achieve the desired outcomes. Hess and others (2014) looked at applying an evidence-based framework from the public health arena to climate change adaptation and found that a modified version would be effective but is limited by a current lack of evidence. They argued for increased evaluation of and reporting on current adaptation efforts (Hess et al. 2014). Already some work is being done in this area, such as the Strengthening Evidence-Based Climate Change Adaptations Policies project of the Food, Agriculture and Natural Resources Policy Analysis Network. Current work is heavily focused on food production. More of this work needs to be done on other points of the value chain besides just production.

The literature on the impacts of climate change on nutritional status of children and women is growing, but most studies are cross-sectional in nature, allowing only for associations and not for causality. Moreover, most studies either are not powered to detect results in subgroups, do not include important potential confounders, or utilize secondary data that were not meant to measure the potential effects of climate change on nutrition (Phalkey et al. 2015; Strand et al. 2011).

Despite these limitations, there are promising future avenues for solutions, such as geographic information analysis and other spatially oriented techniques to investigate malnutrition. Marx and others (2014) looked at the different approaches to such analysis in Africa south of the Sahara. Malnutrition data, they noted, are most commonly analyzed on a national or regional level and in terms of their relationship to climate, population, infrastructure, and agriculture. Eight of the nine studies that Marx and others (2014) reviewed investigated climate change and combined data on a spatial level to elucidate relationships. Marx and colleagues (2014) argued that poor data quality overall and a lack of data at the local and household levels are two current limitations. Others have asserted that analysis on a larger scale is more appropriate because household relationships are too complicated to be analyzed at the local or household level and because most interventions are implemented on a larger scale (Marx et al. 2014). Regardless, these techniques are valuable for analyzing complicated issues such as malnutrition that have many underlying interrelated determinants (Marx et al. 2014).

7. CONCLUSION AND RECOMMENDATIONS

Conclusions

The ramifications of climate change on human health are vast: agriculture, nutrition, diets, and health as a whole are all negatively affected. As noted in the abstract, this report is limited by its focus on poor rural farmers. Yet the adverse impacts of climate change are already being felt and will likely increase over time in a way that most severely affects all of the global poor. The relationship between climate and nutrition is complex. Climate is a potential driver of nutritional status, but climate is also affected by dietary choices, which also impact nutrition. Nutrition is determined by diet and, as discussed earlier, diet is a driving factor of greenhouse gas emissions. In addition to direct and indirect impacts on health as a whole, climate change influences nutritional status through the enabling, food, work and social, health, and living environments, ultimately leading to disrupted health behaviors and biological status, disease, diminished productivity, and mortality. In a vicious cycle, communities and countries without adequate means of mitigation and adaptation are in turn forced to make short-term decisions on food consumption, livelihoods, land use, water, energy use, and transportation that impair effective climate mitigation and potentially worsen planetary well-being.

In November 2016, the Conference of Parties 22 (COP22) convened to develop an implementation plan to achieve the priorities of the Paris Agreement. By the close of COP22, 111 countries representing more than three-fourths of global emissions had ratified the Paris Agreement and US$23 million had been pledged for the Climate Technology Centre and Network, which provides technical assistance and capacity building for developing countries in various sectors, including agriculture. This is a positive step forward, but undeniably more evidence-based research and action are urgently needed to understand, mitigate, and adapt to the ways in which climate change will impact food systems, food environments, diets, and nutritional outcomes.

The following recommendations offer guidance on key strategies to mitigate and adapt to the effects of climate change on nutrition. At the core of these recommendations is a focus on maximizing nutrition entering the food value chain and minimizing its exit points. The recommendations focus on the urban and rural poor in low- and middle-income countries because they will be most directly affected by climate change and least able to respond on their own. These suggestions also recognize and promote the important role women play in climate change mitigation and adaptation. It is also essential to recognize the trade-offs inherent to these strategies and to implement them in a way that first evaluates the unique needs and priorities of each situation.

Recommendations

1. Climate Change and Food Value Chain Inputs

Climate-smart and nutrition-sensitive agriculture is needed to maintain necessary levels of nutritious food production while minimizing the environmental effects of agriculture. Interventions in the inputs of food production, the earliest stage of the value chain, are key. Crop and livestock diversity, soil quality, and water access increase crop production and nutrition. Crop and livestock diversity also has the potential to increase dietary diversity.

Actions

- Increase access to varieties of seeds and livestock breeds that are diverse and resilient to variable weather conditions, pests, and diseases (governments, nongovernmental organizations [NGOs], private sector)
- Use agriculture extension programs to improve access to information and training about these varieties and breeds (governments, NGOs)
- Improve soil quality through the use of cover crops, crop rotation, organic fertilizers, and manure (governments, NGOs)
- Increase irrigation systems to protect crops and livestock from loss due to extreme weather events (governments, NGOs)

2. Climate Change and Food Production

Mitigation and adaptation strategies are needed to offset the impacts of climate change on food production. Integrated land-use policies both improve soil and water quality and protect agricultural land from the effects of climate change. Mixed crop and livestock systems improve the nutritional quality of food and minimize the impacts of livestock on climate. Services and financing such as risk-management tools, insurance, loans, and income diversification also help protect farmers.

Actions

- Invest in and provide education on integrated land-use policies and mixed crop and livestock systems (governments, NGOs)
- Expand access to services and financing to support farmers, including farmer risk-management tools, insurance, and loans (governments)

3. Climate Change and Postharvest Storage and Processing

Food storage and processing strategies that address food safety concerns, such as aflatoxins, while minimizing the need for cold storage and also preserving the nutritional value of foods, are key. These strategies also minimize food waste in low- and middle-income countries.

Actions

- Improve infrastructure, especially in rural areas, including roads, warehouses, and processing plants (governments, NGOs, private sector)
- Provide training on safe and health-promoting storage and processing techniques, such as drying (governments, NGOs)

4. Climate Change and Distribution, Marketing, and Retail

Market access is needed for rural smallholder farmers, fishers, and pastoralists through farm and livestock networks, market integration, and improved infrastructure and transportation. As in the postharvest storage and processing stage, food waste can be minimized and nutritional value protected through increasing retailers' access to cold storage and improving the connections between farmers and consumers. Public health campaigns around the world can promote an understanding of the need for incorporating sustainability into dietary guidelines.

Actions

- Improve retailer access to water, electricity, and cold storage (governments, NGOs)
- Create networks of food producers to increase market access and help limit food waste (NGOs)
- Improve transportation infrastructure in areas where the effects of climate change will limit people's ability to access markets (governments)

5. Climate Change and Food Consumption and Utilization

Social protection services are needed to protect the most vulnerable from long-term stresses and short-term shocks that threaten food security. Although nutritionally vulnerable populations may also need to increase their animal-source food consumption, overconsumption of these foods has negative consequences for human and planetary health. Energy-efficient methods of food preparation are also needed to improve human health and mitigate the effects of climate change.

Actions

- Expand access to social protection services including unconditional cash transfers and supplementary food allowances (governments, NGOs)
- Increase consumption of animal-source foods in low- and middle-income countries while educating the public about the health risks associated with overconsumption of these foods (governments, NGOs)
- Improve access to safe and energy-efficient cookstoves (governments, NGOs)

6. Climate Change and Undernutrition

Undernutrition can be exacerbated by the effects of climate change at all stages of the food value chain. In addition, disease is affected by climate and can, in turn, increase nutrient demands and reduce nutrient absorption. Dietary diversity and animal-source foods can be important tools for improving nutrition and health in nutritionally deficient populations.

Actions

- Increase access to healthcare for vulnerable populations, especially the rural poor, by increasing healthcare facilities and staff (governments, NGOs)
- Provide access to animal-source and fortified foods for nutritionally vulnerable populations (governments, NGOs)

7. Climate Change and Early Warning Systems

Improved early warning is needed for both extreme weather events and long-term shifts in temperature and precipitation patterns. Farmers and food producers need information about how to protect crops and stored food during extreme events and how to modify planting and harvesting schedules in response to changing weather patterns. Additionally, this information needs to be gender sensitive and reflect the needs of different populations.

Actions

- Provide training to producers on how to protect crops, store food, and otherwise prepare for extreme weather events (governments, NGOs)
- Improve early warning systems and increase farmers' access to them (governments, NGOs)

8. Evidence for and Inclusion of Nutrition in Climate Research

We currently have very little information on how to effectively mitigate and adapt to climate change in the food system at each step of the value chain. Additional research is needed to determine evidence-based steps to maximize nutrition in this context. Though work has been done on the food production stage, research needs to be expanded to address all stages in the food value chain.

Actions

- Conduct research, and collect and analyze data on how climate change affects the food system and how to maximize nutrition amid these effects (governments, research institutions, NGOs)

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