



7 FOOD SAFETY, NUTRITION, AND DISTRIBUTION

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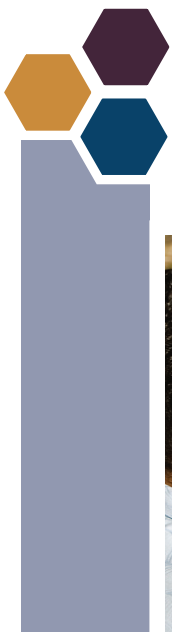
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7 FOOD SAFETY, NUTRITION, AND DISTRIBUTION



Key Findings

Increased Risk of Foodborne Illness

Key Finding 1: Climate change, including rising temperatures and changes in weather extremes, is expected to increase the exposure of food to certain pathogens and toxins [*Likely, High Confidence*]. This will increase the risk of negative health impacts [*Likely, Medium Confidence*], but actual incidence of foodborne illness will depend on the efficacy of practices that safeguard food in the United States [*High Confidence*].

Chemical Contaminants in the Food Chain

Key Finding 2: Climate change will increase human exposure to chemical contaminants in food through several pathways [*Likely, Medium Confidence*]. Elevated sea surface temperatures will lead to greater accumulation of mercury in seafood [*Likely, Medium Confidence*], while increases in extreme weather events will introduce contaminants into the food chain [*Likely, Medium Confidence*]. Rising carbon dioxide concentrations and climate change will alter incidence and distribution of pests, parasites, and microbes [*Very Likely, High Confidence*], leading to increases in the use of pesticides and veterinary drugs [*Likely, Medium Confidence*].

Rising Carbon Dioxide Lowers Nutritional Value of Food

Key Finding 3: The nutritional value of agriculturally important food crops, such as wheat and rice, will decrease as rising levels of atmospheric carbon dioxide continue to reduce the concentrations of protein and essential minerals in most plant species [*Very Likely, High Confidence*].

Extreme Weather Limits Access to Safe Foods

Key Finding 4: Increases in the frequency or intensity of some extreme weather events associated with climate change will increase disruptions of food distribution by damaging existing infrastructure or slowing food shipments [*Likely, High Confidence*]. These impediments lead to increased risk for food damage, spoilage, or contamination, which will limit availability of and access to safe and nutritious food depending on the extent of disruption and the resilience of food distribution infrastructure [*Medium Confidence*].

7.1 Introduction

A safe and nutritious food supply is a vital component of food security. Food security, in a public health context, can be summarized as permanent access to a sufficient, safe, and nutritious food supply needed to maintain an active and healthy lifestyle.¹

The impacts of climate change on food production, prices, and trade for the United States and globally have been widely examined, including in the U.S. Global Change Research Program (USGCRP) report, “Climate Change, Global Food Security, and the U.S. Food System,” in the most recent Intergovernmental Panel on Climate Change report, and elsewhere.^{1,2,3,4,5,6,7} An overall finding of the USGCRP report was that “climate change is very likely to affect global, regional, and local food security by disrupting food availability, decreasing access to food, and making utilization more difficult.”¹

This chapter focuses on some of the less reported aspects of food security, specifically, the impacts of climate change on food safety, nutrition, and distribution in the context of human health in the United States. While ingestion of contaminated seafood is discussed in this chapter, details on the exposure pathways of water related pathogens (for example, through recreational or drinking water) are discussed in Chapter 6: Water-Related Illness.

Systems and processes related to food safety, nutrition, and production are inextricably linked to their physical and biological environment.^{5,8} Although production is important, for most developed countries such as the United States, food shortages are uncommon; rather, nutritional quality and food safety are the primary health concerns.^{5,9} Certain populations, such as the poor, children, and Indigenous populations, may be more vulnerable to climate impacts on food safety, nutrition, and distribution (see also Ch. 9: Populations of Concern).

Farm to Table

The Potential Interactions of Rising CO₂ and Climate Change on Food Safety and Nutrition

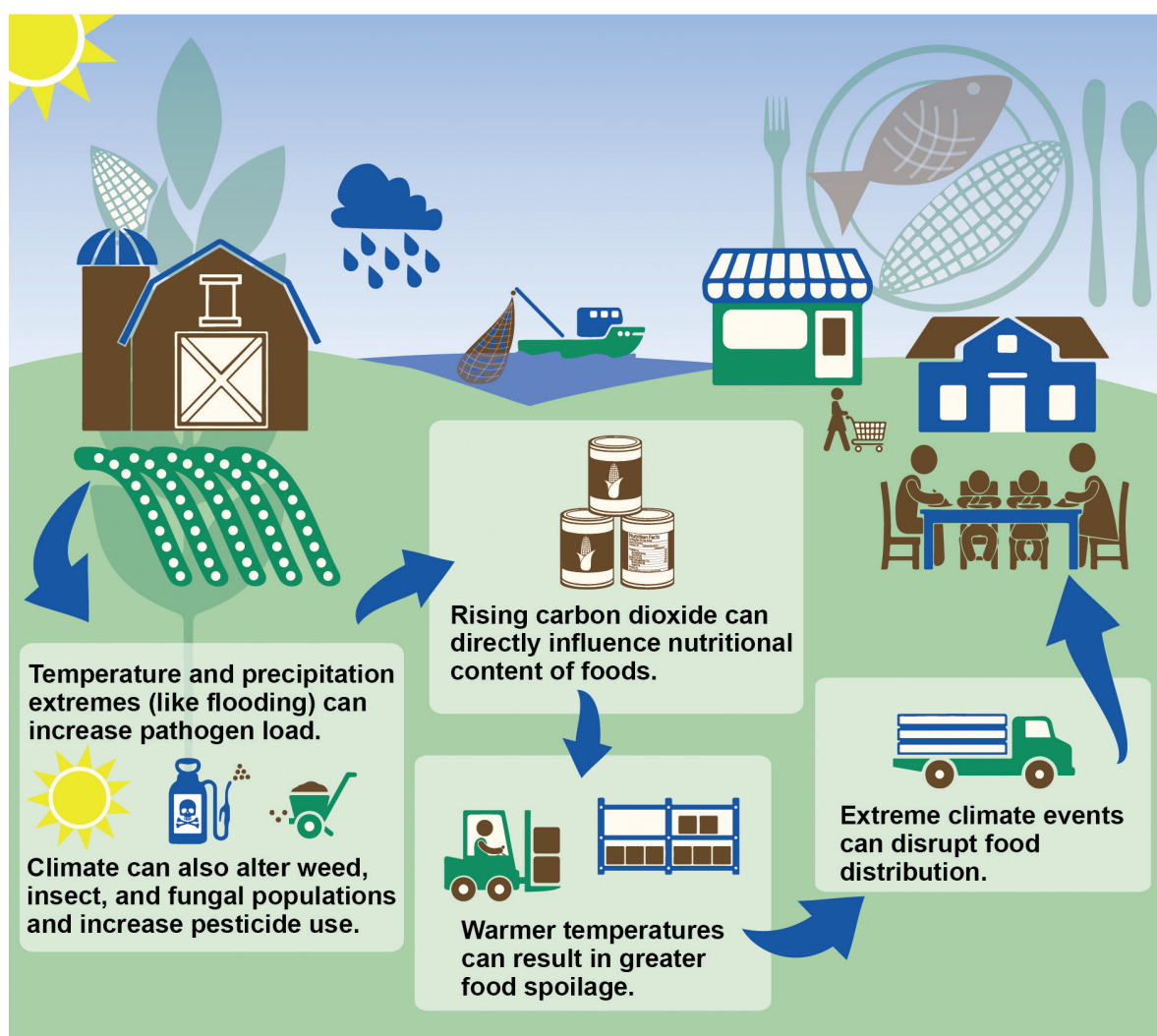


Figure 1: The food system involves a network of interactions with our physical and biological environments as food moves from production to consumption, or from “farm to table.” Rising CO₂ and climate change will affect the quality and distribution of food, with subsequent effects on food safety and nutrition.

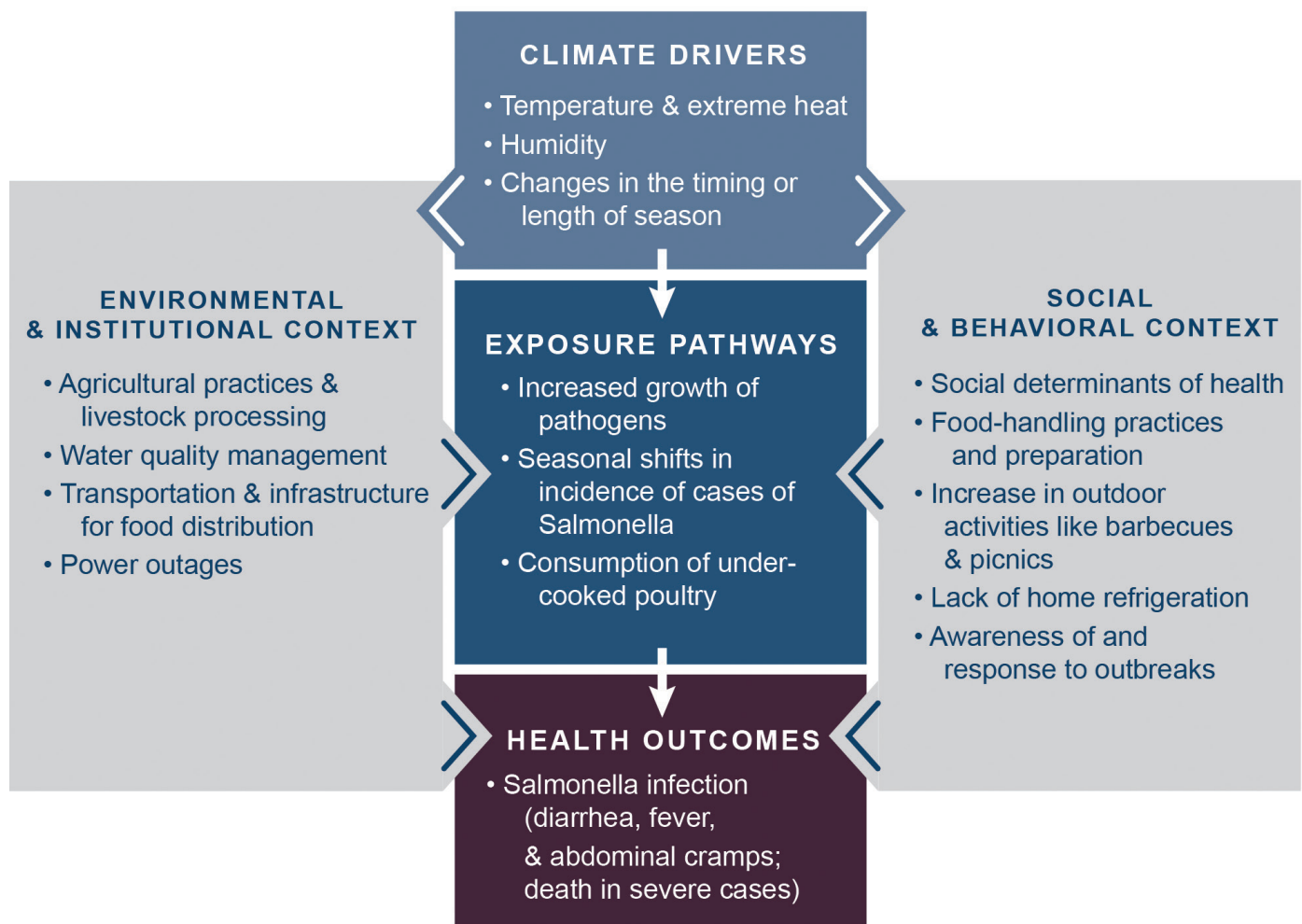
Climate Change and Health—*Salmonella*

Figure 2: This conceptual diagram for a *Salmonella* example illustrates the key pathways by which humans are exposed to health threats from climate drivers, and potential resulting health outcomes (center boxes). These exposure pathways exist within the context of other factors that positively or negatively influence health outcomes (gray side boxes). Key factors that influence vulnerability for individuals are shown in the right box, and include social determinants of health and behavioral choices. Key factors that influence vulnerability at larger scales, such as natural and built environments, governance and management, and institutions, are shown in the left box. All of these influencing factors can affect an individual's or a community's vulnerability through changes in exposure, sensitivity, and adaptive capacity and may also be affected by climate change. See Ch. 1: Introduction for more information.

There are two overarching means by which increasing carbon dioxide (CO₂) and climate change alter safety, nutrition, and distribution of food. The first is associated with rising global temperatures and the subsequent changes in weather patterns and extreme climate events.^{13, 14, 15} Current and anticipated changes in climate and the physical environment have consequences for contamination, spoilage, and the disruption of food distribution.

The second pathway is through the direct CO₂ “fertilization” effect on plant photosynthesis. Higher concentrations of CO₂ stimulate growth and carbohydrate production in some plants, but can lower the levels of protein and essential minerals in a number of widely consumed crops, including wheat, rice, and potatoes, with potentially negative implications for human nutrition.¹⁶

Terminology

Food Safety – Those conditions and measures necessary for food production, processing, storage, and distribution in order to ensure a safe, sound, wholesome product that is fit for human consumption.¹⁰

Foodborne Illness or Disease – Foodborne illness (sometimes called “food poisoning”) is a common public health problem. Each year, one in six Americans reports getting sick by consuming contaminated foods or beverages.¹¹ Foodborne disease is caused by ingestion of contaminated food. Many different disease-causing microbes, or pathogens, can contaminate foods, so there are many different foodborne infections. In addition, food contaminated by toxins or chemicals can also result in foodborne illness.¹²

7.2 Food Safety

Although the United States has one of the safest food supplies in the world,¹⁷ food safety remains an important public health issue. In the United States, the Centers for Disease Control and Prevention (CDC) estimate that there are 48 million cases of foodborne illnesses per year, with approximately 3,000 deaths.¹² As climate change drives changes in environmental variables such as ambient temperature, precipitation, and weather extremes (particularly flooding and drought), increases in foodborne illnesses are expected.^{18, 19}

Most acute illnesses are caused by foodborne viruses (specifically *noroviruses*), followed by bacterial pathogens (such as *Salmonella*; see Table 1). Of the common foodborne illnesses in the United States, most deaths are caused by *Salmonella*, followed by the parasite *Toxoplasma gondii*.^{20, 21, 22, 23} In addition, climate change impacts on the transport of chemical contaminants or accumulation of pesticides or heavy metals (such as mercury) in food, can also represent significant health threats in the food chain.^{22, 24, 25, 26, 27, 28}

How Climate Affects Food Safety

Climate already influences food safety within an agricultural system—prior to, during, and after the harvest, and during transport, storage, preparation, and consumption. Changes in climate factors, such as temperature, precipitation, and extreme weather are key drivers of pathogen introduction, food contamination, and foodborne disease, as well as changes in the level of exposure to specific contaminants and chemical residues for crops and livestock.^{29, 30, 31}

The impact of climate on food safety occurs through multiple pathways. Changes in air and water temperatures, weather-related changes, and extreme events can shift the seasonal and geographic occurrence of bacteria, viruses, pests, parasites, fungi, and other chemical contaminants.^{23, 30, 31, 32, 33} For example:

- Higher temperatures can increase the number of pathogens already present on produce³⁴ and seafood.^{35, 36}

Seasonality of Human Illnesses Associated With Foodborne Pathogens

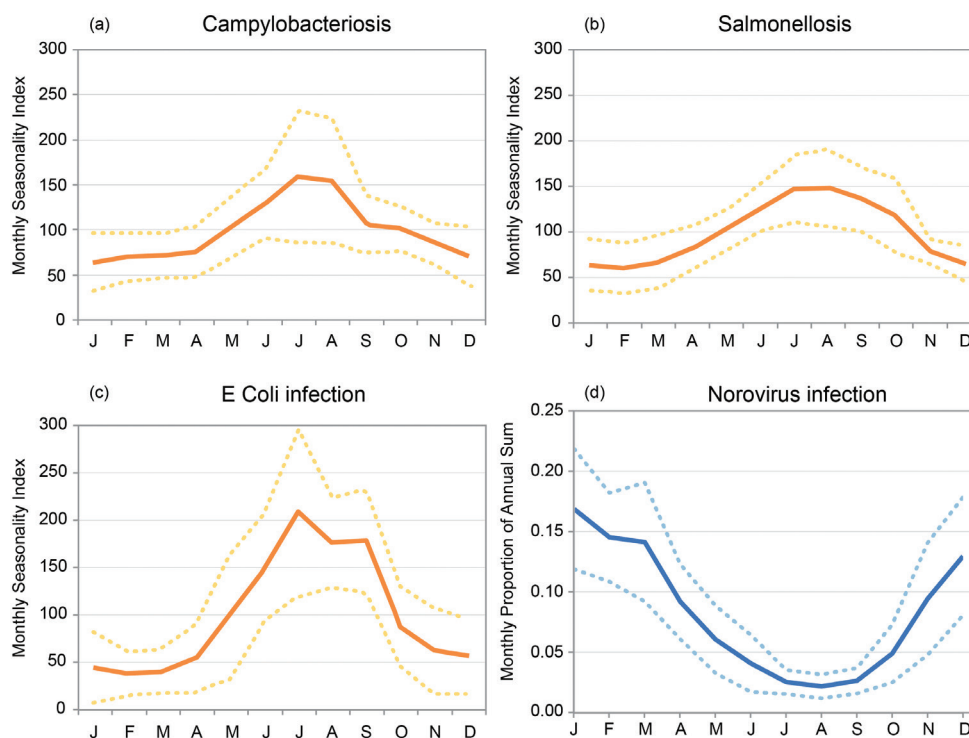



Figure 3: A review of the published literature from 1960 to 2010 indicates a summertime peak in the incidence of illnesses associated with infection from a) *Campylobacter*, b) *Salmonella*, and c) *Escherichia coli* (*E. coli*). For these three pathogens, the monthly seasonality index shown here on the y-axis indicates the global disease incidence above or below the yearly average, which is denoted as 100. For example, a value of 145 for the month of July for Salmonellosis would mean that the proportion of cases for that month was 45% higher than the 12 month average. Unlike these three pathogens, incidence of norovirus, which can be attained through food, has a wintertime peak. The y-axis of the norovirus incidence graph (d) uses a different metric than (a–c): the monthly proportion of the annual sum of norovirus cases in the northern hemisphere between 1997 and 2011. For example, a value of 0.12 for March would indicate that 12% of the annual cases occurred during that month). Solid line represents the average; confidence intervals (dashed lines) are plus and minus one standard deviation. (Figure sources: a, b, and c: adapted from Lal et al. 2012; d: Ahmed et al. 2013)^{49, 183}

Table 1. Foodborne Illness and Climate Change				
Foodborne Hazard	Symptoms	Estimated Annual Illness and Disease	Other Climate Drivers	Temperature/Humidity Relationship
Norovirus	Vomiting, non-bloody diarrhea with abdominal pain, nausea, aches, low grade fever	<ul style="list-style-type: none"> • 5,500,000 illnesses • 15,000 hospitalizations • 150 deaths 	Extreme weather events (such as heavy precipitation and flooding)	<p>Pathogens Favoring Colder/Dryer Conditions</p>  <p>Pathogens Favoring Warmer/Wetter Conditions</p>
Listeria monocytogene	Fever, muscle aches, and rarely diarrhea. Intensive infection can lead to miscarriage, stillbirth, premature delivery, or life-threatening infections (meningitis).	<ul style="list-style-type: none"> • 1,600 illnesses • 1,500 hospitalizations • 260 deaths 		
Toxoplasma	Minimal to mild illness with fever, serious illness in rare cases. Inflammation of the brain and infection of other organs, birth defects.	<ul style="list-style-type: none"> • 87,000 illnesses • 4,400 hospitalizations • 330 deaths 		
Campylobacter	Diarrhea, cramping, abdominal pain, nausea, and vomiting. In serious cases can be life-threatening.	<ul style="list-style-type: none"> • 850,000 illnesses • 8,500 hospitalizations • 76 deaths 	Changes in the timing or length of seasons, precipitation and flooding	
Salmonella spp. (non typhoidal)	Diarrhea, fever, and abdominal cramps; in severe cases death.	<ul style="list-style-type: none"> • 1,000,000 illnesses • 19,000 hospitalizations • 380 deaths 	Extreme weather events, changes in the timing or length of seasons	
Vibrio vulnificus and parahaemolyticus	When ingested: watery diarrhea often with abdominal cramping, nausea, vomiting, fever and chills. Can cause liver disease. When exposed to an open wound: infection of the skin.	<ul style="list-style-type: none"> • 35,000 illnesses • 190 hospitalizations • 40 deaths 	Sea surface temperature, extreme weather events	
Escherichia coli (E coli)	<i>E. coli</i> usually causes mild diarrhea. More severe pathogenic types, such as enterohemorrhagic <i>E. Coli</i> (EHEC), are associated with hemolytic uremic syndrome (a toxin causing destruction of red blood cells, leading to kidney failure).	<ul style="list-style-type: none"> • 200,000 illnesses • 2,400 hospitalizations • 20 deaths 	Extreme weather events, changes in the timing or length of seasons	

Estimated annual number of foodborne illnesses and deaths in the United States. (Adapted from Scallan et al. 2011; Akil et al. 2014; Kim et al. 2015; Lal et al. 2012)^{20, 48, 49, 80}

- Bacterial populations can increase during food storage which, depending on time and temperature, can also increase food spoilage rates.³⁷
- Sea surface temperature is directly related to seafood exposure to pathogens (see Ch. 6: Water-Related Illness).^{38, 39, 40}
- Precipitation has been identified as a factor in the contamination of irrigation water and produce,^{30, 31, 33, 41} which has been linked to foodborne illness outbreaks.^{42, 43}
- Extreme weather events like dust storms or flooding can introduce toxins to crops during development (see Ch. 4: Extreme Events).⁴⁴
- Changing environmental conditions and soil properties may result in increases in the incidence of heavy metals in the food supply.^{45, 46, 47}

Climate Impacts on Pathogen Prevalence

While climate change affects the prevalence of pathogens harmful to human health, the extent of exposure and resulting illness will depend on individual and institutional sensitivity and adaptive capacity, including human behavior and the effectiveness of food safety regulatory, surveillance, monitoring, and communication systems.

Rising Temperature and Humidity

Climate change will influence the fate, transport, transmission, viability, and multiplication rate of pathogens in the food chain. For example, increases in average global temperatures and humidity will lead to changes in the geographic range, seasonal occurrence, and survivability of certain pathogens.^{9, 48, 49, 50}

Ongoing changes in temperature and humidity will not affect all foodborne pathogens equally (Table 1). The occurrence of some pathogens, such as *Salmonella*, *Escherichia coli* (*E. coli*), and *Campylobacter*, could increase with climate change be-

cause these pathogens thrive in warm, humid conditions. For example, *Salmonella* on raw chicken will double in number approximately every hour at 70°F, every 30 minutes at 80°F, and every 22 minutes at 90°F.^{51, 52}

There is a summertime peak in the incidence of illnesses associated with these specific pathogens (see Figure 3).^{18, 48, 53,}

⁵⁴ This peak may be related not only to warmer temperatures favoring pathogen growth but also to an increase in outdoor activities, such as barbecues and picnics. Risk for foodborne illness is higher when food is prepared outdoors where the safety controls that a kitchen provides—thermostat-con-

trolled cooking, refrigeration, and washing facilities—are usually not available.^{5, 18, 19, 48, 55, 56}

Norovirus, the most common cause of stomach flu, can be transmitted by consumption of contaminated food. Although norovirus generally has a winter seasonal peak (see Figure 3), changing climate parameters, particularly temperature and rainfall, may influence its incidence and spread. Overall, localized climate impacts could improve health outcomes (fewer cases during warmer winters) or worsen them (elevated transmission during floods), such that projected trends in overall health outcomes for norovirus remain unclear.^{48, 57}

Rising ocean temperatures can increase the risk of pathogen exposure from ingestion of contaminated seafood. For example, significantly warmer coastal waters in Alaska from 1997 to 2004 were associated with an outbreak in 2004 of *Vibrio parahaemolyticus*, a bacterium that causes gastrointestinal illnesses when contaminated seafood is ingested.⁵⁸ *Vibrio parahaemolyticus* is one of the leading causes of seafood-related gastroenteritis in the United States and is associated with the consumption of raw oysters harvested from warm-water estuaries.⁵⁹ Similarly, the emergence of a related bacterium, *Vibrio vulnificus*, may also be associated with high water temperatures.⁴⁰ While increasing average water temperatures were implicated in a 2004 outbreak,⁵⁸ ambient air temperature also affects pathogen levels of multiple species of *Vibrio* in shellfish.^{35, 36} For example, *Vibrio vulnificus* may increase 10- to 100-fold when oysters are stored at ambient temperatures for ten hours before refrigeration.⁶⁰ Increases in ambient ocean water and air temperatures would accelerate *Vibrio* growth in shellfish, potentially necessitating changes in post-harvest controls to minimize the increased risk of exposure. (For more

information on *Vibrio* and other water-related pathogens, including contamination of recreational and drinking water, see Ch. 6: Water-Related Illness).

Finally, climate change is projected to result in warmer winters, earlier springs, and an

increase in the overall growing season in many regions.^{61, 62}

While there are potential food production benefits from such changes, warmer and longer growing seasons could also alter the timing and occurrence of pathogen transmissions in food and the chance of human exposure.^{63, 64, 65}

Extreme Events

In addition to the effects of increasing average temperature and humidity on pathogen survival and growth, increases in temperature and precipitation extremes can contribute to changes in pathogen transmission, multiplication, and survivability. More frequent and severe heavy rainfall events can in-

Climate change will influence the fate, transport, transmission, viability, and multiplication rate of pathogens in the food chain.

Crops Susceptible to Mycotoxin Infections



Climate change will expand the geographical range where mold growth and mycotoxin production occur.^{9, 32, 37, 75} Corn, a major U.S. crop, is especially susceptible to mold growth and mycotoxin production.⁸¹ Human dietary exposure to these toxins has resulted in illness and death in tropical regions, or where their presence remains unregulated.⁸² In the United States, regulations are designed to prevent mycotoxins entering the food supply.

Aflatoxins (naturally occurring mycotoxins found in corn) are known carcinogens and can also cause impaired development in children, immune suppression, and, with severe exposure, death.^{82, 83, 84} Recent models show that aflatoxin contamination in corn may increase with climate change in Europe.⁸⁵ Other commodities susceptible to contamination by mycotoxins include peanuts, cereal grains, and fruit.³⁷

crease infection risk from most pathogens, particularly when it leads to flooding.⁶⁶ Flooding, and other weather extremes, can increase the incidence and levels of pathogens in food production, harvesting, and processing environments. Groundwater and surface water used for irrigation, harvesting, and washing can be contaminated with runoff or flood waters that carry partially or untreated sewage, manure, or other wastes containing foodborne contaminants.^{55, 67, 68, 69, 70, 71} The level of *Salmonella* in water is elevated during times of monthly maximum precipitation in the summer and fall months;^{56, 72} consequently the likelihood of *Salmonella* in water may increase in regions experiencing increased total or heavy precipitation events.

Water is also an important factor in food processing. Climate and weather extremes, such as flooding or drought, can reduce water quality and increase the risk of pathogen transfer during the handling and storage of food following harvest.⁹

The direct effect of drought on food safety is less clear. Dry conditions can pose a risk for pathogen transmission due to reduced water quality, increased risk of runoff when rains

do occur, and increased pathogen concentration in reduced water supplies if such water is used for irrigation, food processing, or livestock management.^{29, 31, 55, 73} Increasing drought generally leads to an elevated risk of exposure to pathogens such as norovirus and *Cryptosporidium*.⁶⁶ However, drought and extreme heat events could also decrease the survivability of certain foodborne pathogens, affecting establishment and transmission, and thus reducing human exposure.^{66, 74}

Mycotoxins and Phycotoxins

Mycotoxins are toxic chemicals produced by molds that grow on crops prior to harvest and during storage. Prior to harvest, increasing temperatures and drought can stress plants, making them more susceptible to mold growth.⁷⁵ Warm and moist conditions favor mold growth directly and affect the biology of insect vectors that transmit molds to crops. Post-harvest contamination is also affected by environmental parameters, including extreme temperatures and moisture. If crops are not dried and stored at low humidity, mold growth and mycotoxin production can increase to very high levels.^{76, 77}

Phycotoxins are toxic chemicals produced by certain harmful freshwater and marine algae that may affect the safety of drinking water and shellfish or other seafood. For example, the alga responsible for producing ciguatera toxin (the toxin that causes the illness known as ciguatera fish poisoning) thrives in warm water (see also Ch. 6: Water-Related Illness). Projected increases in sea surface temperatures may expand the endemic range of ciguatera-producing algae and increase ciguatera fish poisoning incidence following ingestion.⁷⁸ Predicted increases in sea surface temperature of 4.5° to 6.3°F (2.5° to 3.5°C) could yield increases in ciguatera fish poisoning cases of 200% to 400%.⁷⁹



Crop dusting of a corn field in Iowa.

Once introduced into the food chain, these poisonous toxins can result in adverse health outcomes, with both acute and chronic effects. Current regulatory laws and management strategies safeguard the food supply from mycotoxins and phycotoxins; however, increases in frequency and range of their prevalence may increase the vulnerability of the food safety system.

Climate Impacts on Chemical Contaminants

Climate change will affect human exposure to metals, pesticides, pesticide residues, and other chemical contaminants. However, resulting incidence of illness will depend on the genetic predisposition of the person exposed, type of contaminant, and extent of exposure over time.⁸⁶

Metals and Other Chemical Contaminants

There are a number of environmental contaminants, such as polychlorinated biphenyls, persistent organic pollutants, dioxins, pesticides, and heavy metals, which pose a human health risk when they enter the food chain. Extreme events may facilitate the entry of such contaminants into the food chain, particularly during heavy precipitation and flooding.^{45, 46, 47} For example, chemical contaminants in floodwater following Hurricane Katrina included spilled oil, pesticides, heavy metals, and hazardous waste.^{47, 87}

Methylmercury is a form of mercury that can be absorbed into the bodies of animals, including humans, where it can have adverse neurological effects. Elevated water temperatures may lead to higher concentrations of methylmercury in

fish and mammals.^{88, 89} This is related to an increase in metabolic rates and increased mercury uptake at higher water temperatures.^{28, 90, 91} Human exposure to dietary mercury is influenced by the amount of mercury ingested, which can vary with the species, age, and size of the fish. If future fish consumption patterns are unaltered, increasing ocean temperature would likely increase mercury exposure in human diets. Methylmercury exposure can affect the development of children, particularly if exposed in utero.⁹²

Pesticides

Climate change is likely to exhibit a wide range of effects on the biology of plant and livestock pests (weeds, insects, and microbes). Rising minimum winter temperatures and longer growing seasons are very likely to alter pest distribution and populations.^{93, 94, 95} In addition, rising average temperature and CO₂ concentration are also likely to increase the range and distribution of pests, their impact, and the vulnerability of host plants and animals.^{3, 96, 97}

Pesticides are chemicals generally regulated for use in agriculture to protect plants and animals from pests; chemical management is the primary means for agricultural pest control in the United States and most developed countries. Because climate and CO₂ will intensify pest distribution and populations,^{98, 99} increases in pesticide use are expected.^{100, 101} In addition, the efficacy of chemical management may be reduced in the context of climate change. This decline in efficacy can reflect CO₂-induced increases in the herbicide tolerance of certain weeds or climate-induced shifts in invasive weed, insect,

Impacts of Rising CO₂ on the Nutritional Value of Crops

Protein. Protein content of major food crops is very likely to decline significantly as atmospheric CO₂ concentrations increase to between 540 and 960 parts per million (ppm),^{129, 134, 135, 137} the range projected by the end of this century (see description of Representative Concentration Pathways in Appendix 1: Technical Support Document).¹⁴ Current atmospheric concentrations of CO₂ are approximately 400 ppm.¹³⁸

Minerals and trace elements. Rising CO₂ levels are very likely to lower the concentrations of essential micro- and macroelements such as iron, zinc, calcium, magnesium, copper, sulfur, phosphorus, and nitrogen in most plants (including major cereals and staple crops).^{16, 128, 132, 133, 139, 140}

Ratio of major macronutrients (carbohydrates to protein). It is very likely that rising CO₂ will alter the relative proportions of major macronutrients in many crops by increasing carbohydrate content (starch and sugars) while at the same time decreasing protein content.¹⁶ An increase in dietary carbohydrates-to-protein ratio can have unhealthy effects on human metabolism and body mass.^{136, 141, 142, 143}



Wheat grown in southeast Washington state, August, 2008.

and plant pathogen populations^{100, 102, 103, 104, 105, 106, 107, 108} as well as climate-induced changes that enhance pesticide degradation or affect coverage.^{108, 109}

Increased pest pressures and reductions in the efficacy of pesticides are likely to lead to increased pesticide use, contamination in the field, and exposure within the food chain.¹¹⁰ Increased exposure to pesticides could have implications for human health.^{5, 29, 44} However, the extent of pesticide use and potential exposure may also reflect climate change induced choices for crop selection and land use.

Pesticide Residues

Climate change, especially increases in temperature, may be important in altering the transmission of vector-borne diseases in livestock by influencing the life cycle, range, and reproductive success of disease vectors.^{8, 65} Potential changes in veterinary practices, including an increase in the use of parasiticides and other animal health treatments, are likely to be adopted to maintain livestock health in response to climate-induced changes in pests, parasites, and microbes.^{5, 23, 110} This could increase the risk of pesticides entering the food chain or lead to evolution of pesticide resistance, with subsequent implications for the safety, distribution, and consumption of livestock and aquaculture products.^{111, 112, 113}

Climate change may affect aquatic animal health through temperature-driven increases in disease.¹¹⁴ The occurrence of increased infections in aquaculture with rising temperature has been observed for some diseases (such as *Ichthyophthirius multifiliis* and *Flavobacterium columnare*)¹¹⁵ and is likely to result in greater use of aquaculture drugs.⁷⁶

7.3 Nutrition

While sufficient *quantity* of food is an obvious requirement for food security, food *quality* is essential to fulfill basic nutritional needs. Globally, chronic dietary deficiencies of micronutrients such as vitamin A, iron, iodine, and zinc contribute to “hidden hunger,” in which the consequences of the micronutrient insufficiency may not be immediately visible or easily observed. This type of micronutrient deficiency constitutes one of the world’s leading health risk factors and adversely affects metabolism, the immune system, cognitive development and maturation—particularly in children. In addition, micronutrient deficiency can exacerbate the effects of diseases and can be a factor in prevalence of obesity.^{116, 117, 118, 119, 120, 121}

In developed countries with abundant food supplies, like the United States, the health burden of malnutrition may not be intuitive and is often underappreciated. In the United States, although a number of foods are supplemented with nutrients, it is estimated that the diets of 38% and 45% of the population fall below the estimated average requirements for calcium and magnesium, respectively.¹²² Approximately 12% of the population is at risk for zinc deficiency, including perhaps as much as 40% of the elderly.¹²³ In addition, nutritional deficiencies of magnesium, iron, selenium, and other essential micronutrients can occur in overweight and obese individuals, whose diets might reflect excessive intake of calories and refined carbohydrates but insufficient intake of vitamins and essential minerals.^{119, 124, 125, 126}

Effects of Carbon Dioxide on Protein and Minerals

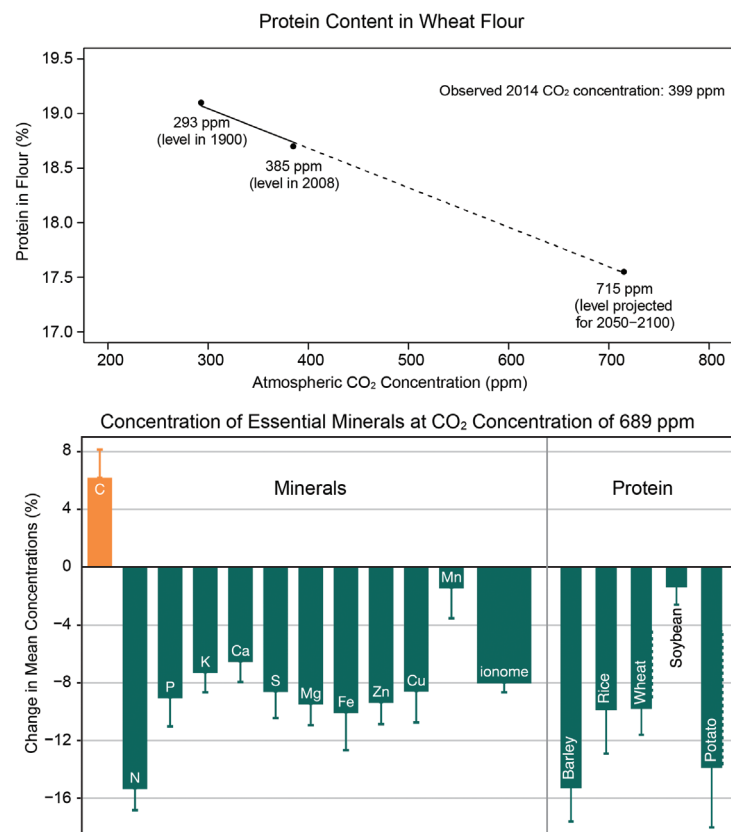


Figure 4: Direct effect of rising atmospheric carbon dioxide (CO₂) on the concentrations of protein and minerals in crops. The top figure shows that the rise in CO₂ concentration from 293 ppm (at the beginning of the last century) to 385 ppm (global average in 2008) to 715 ppm (projected to occur by 2100 under the RCP8.5 and RCP6.0 pathways),¹⁸⁴ progressively lowers protein concentrations in wheat flour (the average of four varieties of spring wheat). The lower figure—the average effect on 125 plant species and cultivars—shows that a doubling of CO₂ concentration from preindustrial levels diminishes the concentration of essential minerals in wild and crop plants, including ionome (all the inorganic ions present in an organism) levels, and also lowers protein concentrations in barley, rice, wheat and potato. (Figure source: Experimental data from Ziska et al. 2004 (top figure), Taub et al. 2008, and Loladze 2014 (bottom figure)).^{16, 129, 134}

How Rising CO₂ Affects Nutrition

Though rising CO₂ stimulates plant growth and carbohydrate production, it reduces the nutritional value (protein and minerals) of most food crops (Figure 4).^{16, 127, 128, 129, 130, 131, 132, 133} This direct effect of rising CO₂ on the nutritional value of crops represents a potential threat to human health.^{16, 133, 134, 135, 136}

Protein

As CO₂ increases, plants need less protein for photosynthesis, resulting in an overall decline in protein concentration in plant tissues.^{134, 135} This trend for declining protein levels is evident for wheat flour derived from multiple wheat varieties when grown under laboratory conditions simulating the observed increase in global atmospheric CO₂ concentration since 1900.¹²⁹ When grown at the CO₂ levels projected for 2100 (540–958 ppm), major food crops, such as barley, wheat, rice, and potato, exhibit 6% to 15% lower protein concentrations relative to ambient levels (315–400 ppm).^{16, 134, 135} In contrast, protein content is not anticipated to decline significantly for corn or sorghum.¹³⁵

While protein is an essential aspect of human dietary needs, the projected human health impacts of a diet including plants with reduced protein concentration from increasing CO₂ are not well understood and may not be of considerable threat in the United States, where dietary protein deficiencies are uncommon.

Micronutrients

The ongoing increase in atmospheric CO₂ is also very likely to deplete other elements essential to human health (such as calcium, copper, iron, magnesium, and zinc) by 5% to 10% in most plants.¹⁶ The projected decline in mineral concentrations in crops has been attributed to at least two distinct effects of elevated CO₂ on plant biology. First, rising CO₂ increases carbohydrate accumulation in plant tissues, which can, in turn, dilute the content of other nutrients, including minerals. Second, high CO₂ concentrations reduce plant demands for water, resulting in fewer nutrients being drawn into plant roots.^{133, 144, 145}

The ongoing increase in CO₂ concentrations reduces the amount of essential minerals per calorie in most crops, thus reducing nutrient density. Such a reduction in crop quality may aggravate existing nutritional deficiencies, particularly for populations with pre-existing health conditions (see Ch. 9: Populations of Concern).

Carbohydrate-to-Protein Ratio

Elevated CO₂ tends to increase the concentrations of carbohydrates (starch and sugars) and reduce the concentrations of protein.¹³⁴ The overall effect is a significant increase in the ratio of carbohydrates to protein in plants exposed to increasing CO₂.¹⁶ There is growing evidence that a dietary increase in this ratio can adversely affect human metabolism¹⁴³ and body composition.¹⁴¹

7.4 Distribution and Access

A reliable and resilient food distribution system is essential for access to a safe and nutritious food supply. Access to food is characterized by transportation and availability, which are defined by infrastructure, trade management, storage requirements, government regulation, and other socioeconomic factors.¹⁴⁶

The shift in recent decades to a more global food market has resulted in a greater dependency on food transport and distribution, particularly for growing urban populations. Consequently, any climate-related disturbance to food distribution and transport may have significant impacts not only on safety and quality but also on food access. The effects of climate change on each of these interfaces will differ based on geographic, social, and economic factors.⁴ Ultimately, the outcome of climate-related disruptions and damages to the food transportation system will be strongly influenced by the resilience of the system, as well as the adaptive capacity of individuals, populations, and institutions.

How Extreme Events Affect Food Distribution and Access

Projected increases in the frequency or severity of some extreme events will interrupt food delivery, particularly for vulnerable transport routes.^{13, 15, 147, 148} The degree of disruption is related to three factors: a) popularity of the transport pathway, b) availability of alternate routes, and c) timing or seasonality of the extreme event.¹⁴⁹ As an example, the food transportation system in the United States frequently moves large volumes of grain by water. In the case of an extreme weather event affecting a waterway, there are few, if any, alternate pathways for transport.¹⁵⁰ This presents an especially relevant risk to food access if an extreme event, like flooding or drought, coincides with times of agricultural distribution, such as the fall harvest.

Immediately following an extreme event, food supply and safety can be compromised.^{150, 151, 152} Hurricanes or other storms can disrupt food distribution infrastructure, damage food supplies,⁷ and limit access to safe and nutritious food, even in areas not directly affected by such events (see also Ch. 4: Extreme Events).¹⁵³ For example, the Gulf Coast transportation network is vulnerable to storm surges of 23 feet.¹⁵⁴ Following Hurricane Katrina in 2005, where storm surges of 25 to 28 feet were recorded along parts of the Gulf Coast, grain transportation by rail or barge was severely slowed due to physical damage to infrastructure and the displacement of employees.^{151, 155} Barriers to food transport may also affect food markets, reaching consumers in the form of increased food costs.¹⁵⁶

The risk for food spoilage and contamination in storage facilities, supermarkets, and homes is likely to increase due to the impacts of extreme weather events, particularly those that result in power outages, which may expose food to ambient tem-

Case Study: Extreme Drought and the Mississippi River, 2012



Low water conditions on Mississippi River near St. Louis, MO, on December 5, 2012. Photo source: St. Louis District, U.S. Army Corps of Engineers.

The summer (June through August) of 2012 was the second hottest on record for the contiguous United States.¹⁵⁹ High temperatures and a shortage of rain led to one of the most severe summer droughts the nation has seen and posed serious impacts to the Mississippi River watershed, a major transcontinental shipping route for Midwestern agriculture.^{160, 161} This drought resulted in significant food and economic losses due to reductions in barge traffic, the volume of goods carried, and the number of Americans employed by the tugboat industry.¹⁶² The 2012 drought was immediately followed by flooding throughout the Mississippi in the spring of 2013, which also resulted in disruptions of barge traffic and food transport. These swings in precipitation, from drought to flooding, are consistent with projected increases in the frequency or severity of some types of extreme weather under continued climate change.^{7, 62, 152}

Mississippi River Level at St. Louis, Missouri

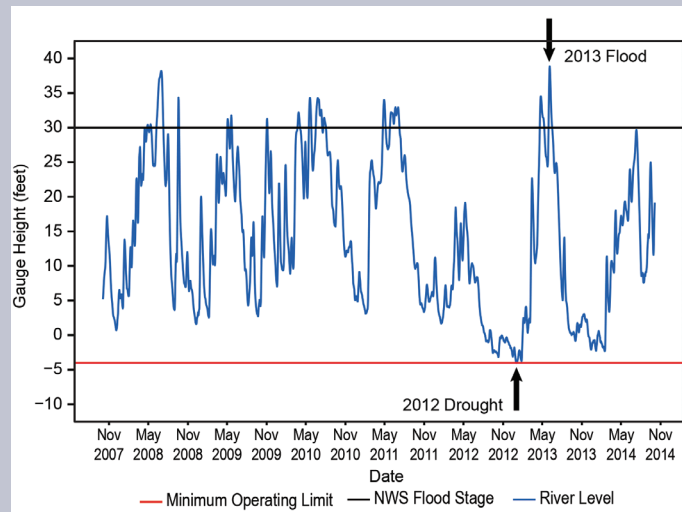


Figure 5: Mississippi River gauge height at St. Louis, MO, from October 2007 through October 2014 showing low water conditions during the 2012 drought and water levels above flood stage in 2013. (Figure source: adapted from USGS 2015)¹⁸⁵

peratures inadequate for safe storage.¹⁵² Storm-related power grid disruptions have steadily increased since 2000.¹⁵⁷ Between 2002 and 2012, extreme weather caused 58% of power outage events, 87% of which affected 50,000 or more customers.¹⁵⁷ Power outages are often linked to an increase in illness. For example, in August of 2003, a sudden power outage affected over 60 million people in the northeastern United States and Canada. New York City's Department of Health and Mental Hygiene detected a statistically significant citywide increase in diarrheal illness resulting from consumption of spoiled foods due to lost refrigeration capabilities.¹⁵⁸

7.5 Populations of Concern

Climate change, combined with other social, economic, and political conditions, may increase the vulnerability of many different populations to food insecurity or food-related illness.¹⁶³ However, not all populations are equally vulnerable.^{7, 62} Infants and young children, pregnant women, the elderly, low-income populations, agricultural workers, and those with weakened immune systems or who have underlying medical conditions are more susceptible to the effects of climate change on food safety, nutrition, and access.

Children may be especially vulnerable because they eat more food by body weight than adults, and do so during important stages of physical and mental growth and development. Children are also more susceptible to severe infection or complications from *E. coli* infections, such as hemolytic uremic syndrome.^{164, 165, 166} Agricultural field workers, especially pesticide applicators, may experience increased exposure as pesticide applications increase with rising pest loads, which could also lead to higher pesticide levels in the children of these field workers.^{167, 168} People living in low-income urban areas, those with limited access to supermarkets,^{169, 170} and the elderly may have difficulty accessing safe and nutritious food after disruptions associated with extreme weather events. Climate change will also affect U.S. Indigenous peoples' access to both wild and cultivated traditional foods associated with their nutrition, cultural practices, local economies, and community health¹⁷¹ (see also Ch. 6 Water-Related Illness and Ch. 9: Populations of Concern). All of the health impacts described in this chapter can have significant consequences on mental health and well-being (see Ch. 8 Mental Health).

7.6 Emerging Issues

Climate and food allergies. Food allergies in the United States currently affect between 1% and 9% of the population,¹⁷² but have increased significantly among children under age 18 since 1997.¹⁷³ Rising CO₂ levels can reduce protein content and alter protein composition in certain plants, which has the potential to alter allergenic sensitivity. For example, rising CO₂ has been shown to increase the concentration of the *Amb a 1* protein—the allergenic protein most associated with ragweed pollen.¹⁷⁴ However, at present, the question of how rising levels of CO₂ and climate change affect allergenic properties of food is uncertain and requires more research.¹⁷⁵

Heavy metals. Arsenic and other heavy metals occur naturally in some groundwater sources.¹⁷⁶ Climate change can exacerbate drought and competition for water, resulting in the use of poorer-quality water sources.^{177, 178} Because climate and rising CO₂ levels can also influence the extent of water loss through the crop canopy, poorer water quality could lead to changes in the concentrations of arsenic and potentially other heavy metals (like cadmium and selenium) in plant tissues. Additional information is needed to determine how rising levels of CO₂ and climate change affect heavy metal accumulation in food and the consequences for human exposure.

Zoonosis and livestock. Zoonotic diseases, which are spread from animals to humans, can be transmitted through direct contact with an infected animal or through the consumption of contaminated food or water. Climate change could potentially increase the rate of zoonoses, through environmental change that alters the biology or evolutionary rate of disease vectors or the health of animal hosts. The impact of rising levels of CO₂ and climate change on the transmission of disease through zoonosis remains a fundamental issue of potential global consequence.

Foodborne pathogen contamination of fresh produce by insect vectors. Climate change will alter the range and distribution of insects and other microorganisms that can transmit bacterial pathogens such as *Salmonella* to fresh produce.^{179, 180, 181} Additional information is needed regarding the role of climate change on the transmission to and development of food pathogens through insect vectors.

7.7 Research Needs

In addition to the emerging issues identified above, the authors highlight the following potential areas for additional scientific and research activity on food safety, nutrition and distribution, based on their review of the literature. Understanding climate change impacts in the context of the current food safety infrastructure will be improved by enhanced surveillance of foodborne diseases and contaminant levels, improved understanding of CO₂ impacts on nutritional quality of food, and more accurate models of the impacts of extreme events on food access and delivery.

Future assessments can benefit from research activities that:

- synthesize and assess efforts to identify and respond to current and projected food safety concerns and their impacts on human health within the existing and future food safety infrastructure;
- develop, test, and expand integrated assessment models to enhance understanding of climate and weather variability, particularly extreme events, and the role of human responses, including changes in farming technology and management, on health risks within the food chain; and
- examine the impacts of rising CO₂ and climate change on human and livestock nutritional needs, as well as the impacts of changing nutritional sources on disease vulnerability.¹

Supporting Evidence

PROCESS FOR DEVELOPING CHAPTER

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at several workshops, teleconferences, and email exchanges. The authors considered inputs and comments submitted by the public, the National Academies of Sciences, and Federal agencies. For additional information on the overall report process, see Appendices 2 and 3. The author team also engaged in targeted consultations during multiple exchanges with contributing authors, who provided additional expertise on subsets of the Traceable Accounts associated with each Key Finding.

Because the impacts of climate change on food production, prices, and trade for the United States and globally have been widely examined elsewhere, including in the most recent report from the Intergovernmental Panel on Climate Change,^{2, 3, 4, 5, 6, 7} this chapter focuses only on the impacts of climate change on food safety, nutrition, and distribution in the context of human health in the United States. Many nutritional deficiencies and food-related illnesses are of critical importance globally, particularly those causing diarrheal epidemics or mycotoxin poisoning, and affect U.S. interests abroad; but the primary focus of this chapter is to address climate impacts on the food safety concerns most important in the United States. Thus, the literature cited in this chapter is specific to the United States or of demonstrated relevance to developed countries. The placement of health threats from seafood was determined based on pre- and post-ingestion risks: while ingestion of contaminated seafood is discussed in this chapter, details on the exposure pathways of water-related pathogens (for example, through recreational or drinking water) are discussed in Chapter 6: Water-Related Illness.

KEY FINDING TRACEABLE ACCOUNTS

Increased Risk of Foodborne Illness

Key Finding 1: Climate change, including rising temperatures and changes in weather extremes, is expected to increase the exposure of food to certain pathogens and toxins [*Likely, High Confidence*]. This will increase the risk of negative health impacts [*Likely, Medium Confidence*], but actual incidence of foodborne illness will depend on the efficacy of practices that safeguard food in the United States [*High Confidence*].

Description of evidence base

Multiple lines of research have shown that changes in weather extremes, such as increased extreme precipitation (leading to flooding and runoff events), can result in increased microbial and chemical contamination of crops and water in agricultural environments, with increases in human exposure.^{55, 56, 72} During

times of drought, plants become weaker and more susceptible to stress, which can result in mold growth and mycotoxin production if plants are held in warm, moist environments.^{32, 75}

While studies that link climate change to specific outbreaks of foodborne illness are limited, numerous studies have documented that many microbial foodborne illnesses increase with increasing ambient temperature.^{18, 19} There is very strong evidence that certain bacteria grow more rapidly at higher temperatures and can increase the prevalence of pathogens and toxins in food.^{32, 34, 54} Case studies have demonstrated that lack of refrigerated storage, particularly during very warm weather, leads to increases in microbial growth and higher exposure to pathogens.^{5, 18, 19, 48, 60}

Major uncertainties

Concentrations of pathogens and toxins in food are expected to increase, resulting in an increase in the risk of human exposure to infectious foodborne pathogens and toxins. However, the number or severity of foodborne illnesses due to climate change is uncertain. Much of this uncertainty is due to having controls in place to protect public health. For example, contaminated crops are likely to be destroyed before consumption, and certain pathogens in food, like mycotoxins, are highly regulated in the United States. Consequently, the extent of exposure and foodborne illness will depend on regulatory, surveillance, monitoring, and communication systems, and on how, and to what extent, climate change alters these adaptive capacities. Furthermore, for certain pathogens, it is not yet clear whether the impact of climate change on a pathogen will be positive or negative. For example, climate change could lead to fewer cases of norovirus infection in the winter, but worsening health outcomes are also possible due to elevated transmission of norovirus during floods. Similarly drought can reduce water quality, increase runoff, and increase pathogen concentration, but can also decrease the survivability of certain foodborne pathogens.

Assessment of confidence and likelihood based on evidence

There is **high confidence** that rising temperature and increases in flooding, runoff events, and drought will **likely** lead to increases in the occurrence and transport of pathogens in agricultural environments, which will increase the risk of food contamination and human exposure to pathogens and toxins. However, the actual prevalence of disease will depend on the response of regulatory systems and, for certain pathogens, the relative importance of multiple climate drivers with opposing impacts on exposure. Thus there is **medium confidence** that these impacts of climate change on exposure to pathogens and toxins will **likely** lead to negative health outcomes. There is a **high confidence** that the actual incidence of foodborne illness will depend on the efficacy of practices that safeguard food in the United States.

Chemical Contaminants in the Food Chain

Key Finding 2: Climate change will increase human exposure to chemical contaminants in food through several pathways [*Likely, Medium Confidence*]. Elevated sea surface temperatures will lead to greater accumulation of mercury in seafood [*Likely, Medium Confidence*], while increases in extreme weather events will introduce contaminants into the food chain [*Likely, Medium Confidence*]. Rising carbon dioxide concentrations and climate change will alter incidence and distribution of pests, parasites, and microbes [*Very Likely, High Confidence*], leading to increases in the use of pesticides and veterinary drugs [*Likely, Medium Confidence*].

Description of evidence base

There are a number of established pathways by which climate change will intensify chemical contaminants within the food chain. Multiple studies have shown that increases in ocean temperatures are likely to increase the potential for mercury exposure, likely due to the increased uptake and concentration of mercury in fish and mammals at higher metabolic rates associated with warmer ambient temperatures.^{28, 88, 89, 90} Another pathway includes extreme weather events, which can move chemical contaminants such as lead into agricultural fields and pastures (as well as into drinking or recreational water sources—see Chapter 6: Water-Related Illness).^{45, 46, 87} A final pathway is through rising minimum winter temperatures and longer growing seasons, which will very likely alter pest distribution and populations. A large body of literature shows that temperature, carbon dioxide (CO₂) concentrations, and water availability are also likely to affect pest development, number of pest generations per year, changes in pest range, rate of infestation, and host plant and animal susceptibility.^{3, 50, 76, 96, 97} Empirical models and an analysis of long-term in situ data indicate that rising temperatures will result in increased pest pressures.^{100, 101, 105} These changes are expected to result in increased use of pesticides,^{100, 102} which can lead to increased human exposure.⁸⁶

Major uncertainties

Each of the pathways described in the evidence base has variable levels of uncertainty associated with each step of the exposure pathway.¹¹⁰ For all these pathways, projecting the specific consequences on human health in the United States is challenging, due to the variability in type of pathogen or contaminant, time and duration of exposures, individual sensitivity (for example, genetic predisposition) and individual or institutional adaptive capacity. While increasing exposure to chemicals will exacerbate potential health risks, the nature of those risks will depend on the specific epidemiological links between exposure and human health as well as availability and access to health services. Resulting incidence of illness will depend on the genetic predisposition of the person exposed, type of contaminant, and extent of exposure over time.⁸⁶

Assessment of confidence and likelihood based on evidence

Although it is *likely* that climate change will increase human exposure to chemical contaminants, the specific pathway(s) of exposure have varying levels of uncertainty associated with them and hence there is *medium confidence* regarding the overall extent of exposure. This chapter focuses on three such pathways. First, it is *likely* that elevated sea surface temperatures will result in increased bioaccumulation of mercury in seafood, but there is *medium confidence* regarding human illness because rates of accumulation and exposure vary according to the type of seafood ingested, and because of the role of varying individual sensitivity and individual or institutional adaptive capacity (particularly behavioral choices). Similarly, it is *likely* that extreme events will increase contaminants into agricultural soil and the food chain. However, there is *medium confidence* regarding exposure because the specific nature of the contaminant and the food source will vary, and because the extent of exposure will depend on risk management, communication of public health threats, and the effectiveness of regulatory, surveillance, and monitoring systems within the current food safety network. There is *high confidence* that it is *very likely* that rising CO₂ and climate change will alter pest incidence and distribution. There is *medium confidence* that such changes in incidence and distribution are *likely* to increase chemical management and the use of veterinary drugs in livestock. However, in all these pathways, the specific consequences on human health in the United States are uncertain, due primarily to the variability in type of pathogen or contaminant, time and duration of exposures, individual sensitivity (for example, genetic predisposition), and individual or institutional adaptive capacity.

Rising Carbon Dioxide Lowers Nutritional Value of Food

Key Finding 3: The nutritional value of agriculturally important food crops, such as wheat and rice, will decrease as rising levels of atmospheric carbon dioxide continue to reduce the concentrations of protein and essential minerals in most plant species [*Very Likely, High Confidence*].

Description of evidence base

The nutritional response of crops to rising carbon dioxide is well documented, particularly among C₃ cereals such as rice and wheat, which make up the bulk of human caloric input. C₃ species are about 95% of all plant species and represent those species most likely to respond to an increase in atmospheric CO₂ concentrations.

There is strong evidence and consensus that protein concentrations in plants strongly correlate with nitrogen concentrations. CO₂-induced declines in nitrogen concentrations have been observed in nearly a hundred individual studies and several meta-analyses.^{16, 133, 137, 139, 140} A meta-analysis of the effect of CO₂ on protein by crop covers

228 observations on wheat, rice, soybeans, barley and potato,¹³⁴ and was recently repeated for the United States, Japan, and Australia,¹³⁵ covering 138 mean observations on nitrogen/protein in wheat, rice, peas, maize, and sorghum. There is very strong evidence that rising CO₂ reduces protein content in non-leguminous C₃ crops, including wheat, rice, potato, and barley. There is also good agreement across studies that the ongoing increase in CO₂ elevates the overall carbohydrate content in C₃ plants.¹⁶

Another meta-analysis quantifies the role of increasing CO₂ in altering the ionome (the mineral nutrient and trace element composition of an organism) of plants, including major crops.¹⁶ This meta-analysis of 7,761 observations indicates that increasing CO₂ also significantly reduces the mineral concentrations (calcium, magnesium, iron, zinc, copper, sulfur, potassium, and phosphorus) in C₃ plants, including grains and edible parts of other crops, while also substantially increasing the ratio of total non-structural carbohydrates (starch and sugars) to minerals and to protein.

Furthermore, these studies show the quality of current crops to be lower relative to the crops raised in the past with respect to protein and minerals.^{16,134} Direct experimental evidence shows that protein concentrations in wheat flour progressively declined with rising CO₂ concentrations representing levels in 1900 (approximately 290 ppm), 2008 (approximately 385 ppm), and the CO₂ concentrations projected to occur later in this century (approximately 715 ppm).¹²⁹

Major uncertainties

While the general response and the direction in the change of crop quality is evident; there is uncertainty in the extent of variation in both protein and ionome among different crop varieties. There is little evidence regarding the CO₂ effects on complex micronutrients such as carotenoids (vitamin A, lutein, and zeaxanthin). Although protein, micronutrients, and ratio of carbohydrates to protein are all essential aspects of human dietary needs, the projected human health impacts of nutritional changes with increasing CO₂ are still being evaluated. There remains a high level of uncertainty regarding how reductions in crop quality affect human nutrition by contributing to or aggravating existing chronic dietary deficiencies and obesity risks, particularly in the United States where dietary protein deficiencies are uncommon.

Assessment of confidence and likelihood based on evidence

Based on the evidence, there is **high confidence** that the rapid increase in atmospheric CO₂ has resulted in a reduction in the level of protein and minerals relative to the amount of carbohydrates present for a number of important crop species (including a number of globally important cereals such as wheat, barley and rice), and will **very likely** continue to do so as atmospheric CO₂ concentration continues to rise.

Extreme Weather Limits Access to Safe Foods

Key Finding 4: Increases in the frequency or intensity of some extreme weather events associated with climate change will increase disruptions of food distribution by damaging existing infrastructure or slowing food shipments [*Likely, High Confidence*]. These impediments lead to increased risk for food damage, spoilage, or contamination, which will limit availability of and access to safe and nutritious food, depending on the extent of disruption and the resilience of food distribution infrastructure [*Medium Confidence*].

Description of evidence base

It is well documented in assessment literature that climate models project an increase in the frequency and intensity of some extreme weather events.^{14,15} Because the food transportation system moves large volumes at a time, has limited alternative routes, and is dependent on the timing of the growing and harvest seasons, it is likely that the projected increase in the frequency and intensity of extreme weather events^{13,14} will also increase the frequency of food supply chain disruptions (including risks to food availability and access)^{147,148,149,150,151,152,156} and the risk for food spoilage and contamination.^{152,163} Recent extreme events have demonstrated a clear linkage to the disruption of food distribution and access.^{151,161} Case studies show that such events, particularly those that result in power outages, may also expose food to temperatures inadequate for safe storage,¹⁵² with increased risk of illness. For example, New York City's Department of Health and Mental Hygiene detected a statistically significant citywide increase in diarrheal illness resulting from consumption of spoiled foods due to lost refrigeration capabilities after a 2003 power outage.¹⁵⁸

Major uncertainties

The extent to which climate-related disruptions to the food distribution system will affect food supply, safety, and human health, including incidences of illnesses, remains uncertain. This is because the impacts of any one extreme weather event are determined by the type, severity, and intensity of the event, the geographic location in which it occurs, infrastructure resiliency, and the social vulnerabilities or adaptive capacity of the populations at risk.

Assessment of confidence and likelihood based on evidence

Given the evidence base and current uncertainties, there is **high confidence** that projected increases in the frequency and severity of extreme events will **likely** lead to damage of existing food supplies and disruptions to food distribution infrastructure. There is **medium confidence** that these damages and disruptions will increase risk for food damage, spoilage, or contamination, which will limit availability and access to safe and nutritious foods because of uncertainties surrounding the extent of the disruptions and individual, community, or institutional sensitivity to impacts. There are

further uncertainties surrounding how the specific dynamics of the extreme event, such as the geographic location in which it occurs, as well as the social vulnerabilities or adaptive capacity of the populations at risk, will impact human health.

DOCUMENTING UNCERTAINTY

See Appendix 4: Documenting Uncertainty for more information on assessments of confidence and likelihood used in this report.

Confidence Level	Likelihood
Very High	Very Likely
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	≥ 9 in 10
High	Likely
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	≥ 2 in 3
Medium	As Likely As Not
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	≈ 1 in 2
Low	Unlikely
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts	≤ 1 in 3
	Very Unlikely
	≤ 1 in 10

PHOTO CREDITS

Pg. 189—Farmer holding wheat: © Dan Lamont/Corbis

Pg. 190—Family enjoying outdoor grilling party: © Hill Street Studios/Blend Images/Corbis

Pg. 196—Helicopter crop dusting: © Lucas Payne/AgStock Images/Corbis

Pg. 197—Farmer holding wheat: © Dan Lamont/Corbis

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