7 FOOD SAFETY, NUTRITION, AND DISTRIBUTION

Lead Authors

Lewis Ziska
U.S. Department of Agriculture

Allison Crimmins*
U.S. Environmental Protection Agency

Contributing Authors

Allan Auclair
U.S. Department of Agriculture

Stacey DeGrasse
U.S. Food and Drug Administration

Jada F. Garofalo
Centers for Disease Control and Prevention

Ali S. Khan
University of Nebraska Medical Center

Irakli Loladze
Bryan College of Health Sciences

Adalberto A. Pérez de León
U.S. Department of Agriculture

Allan Showler
U.S. Department of Agriculture

Jeanette Thurston
U.S. Department of Agriculture

Isabel Walls
U.S. Department of Agriculture

Acknowledgements: Steve Gendel, Formerly of the U.S. Food and Drug Administration

Recommended Citation: Ziska, L., A. Crimmins, A. Auclair, S. DeGrasse, J.F. Garofalo, A.S. Khan, I. Loladze, A.A. Pérez de León, A. Showler, J. Thurston, and I. Walls, 2016: Ch. 7: Food Safety, Nutrition, and Distribution. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment.* U.S. Global Change Research Program, Washington, DC, 189–216. http://dx.doi.org/10.7930/J0ZP4417

On the web: health2016.globalchange.gov

**Chapter Coordinators*

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 CO_2 and Climate Change on Food Safety and Nutrition

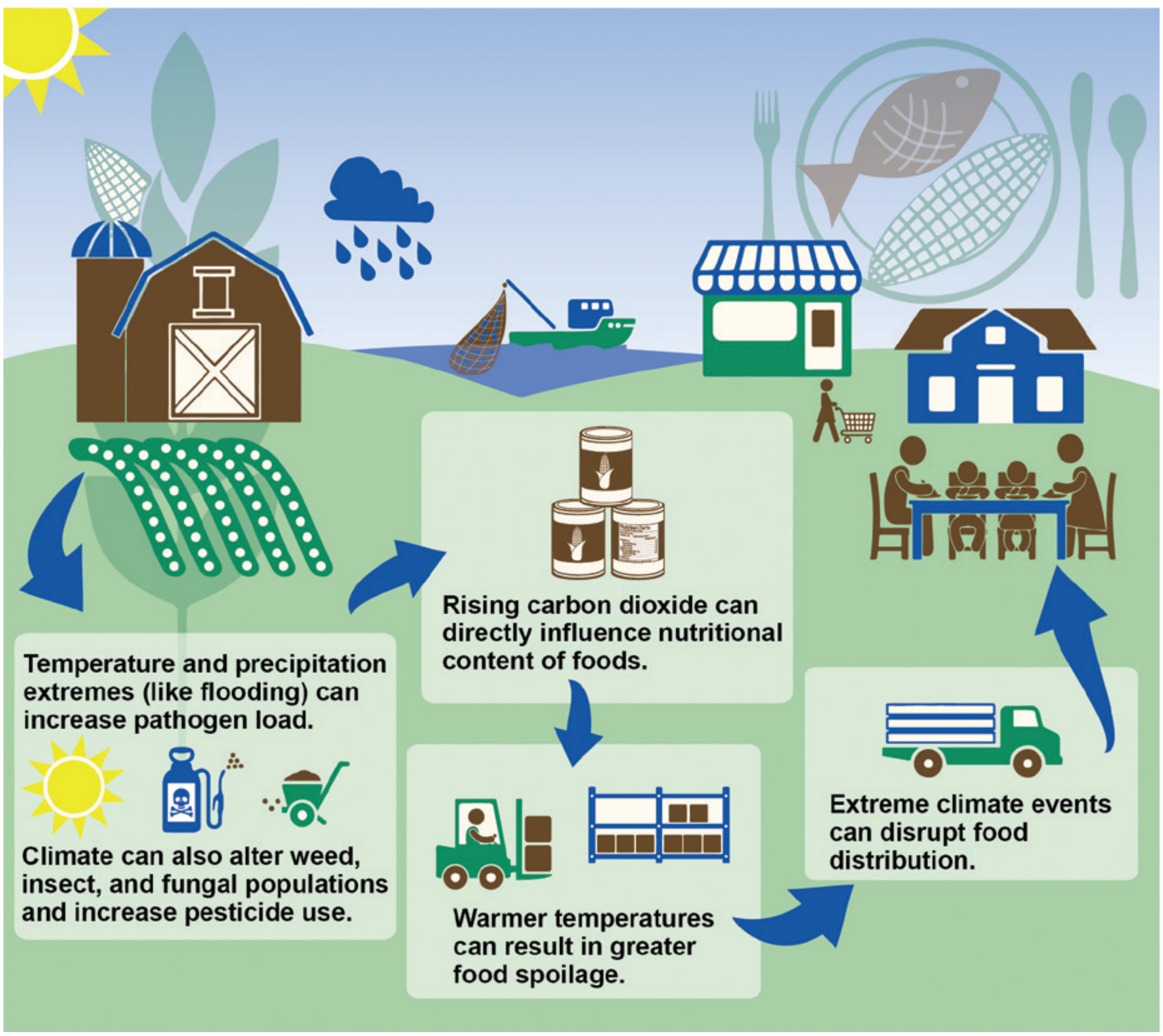

Figure 1: The food system involves a network of interactions with our physical and biological environments as food moves from production to consumption, or from "farm to table." Rising CO_2 and climate change will affect the quality and distribution of food, with subsequent effects on food safety and nutrition.

Climate Change and Health—*Salmonella*

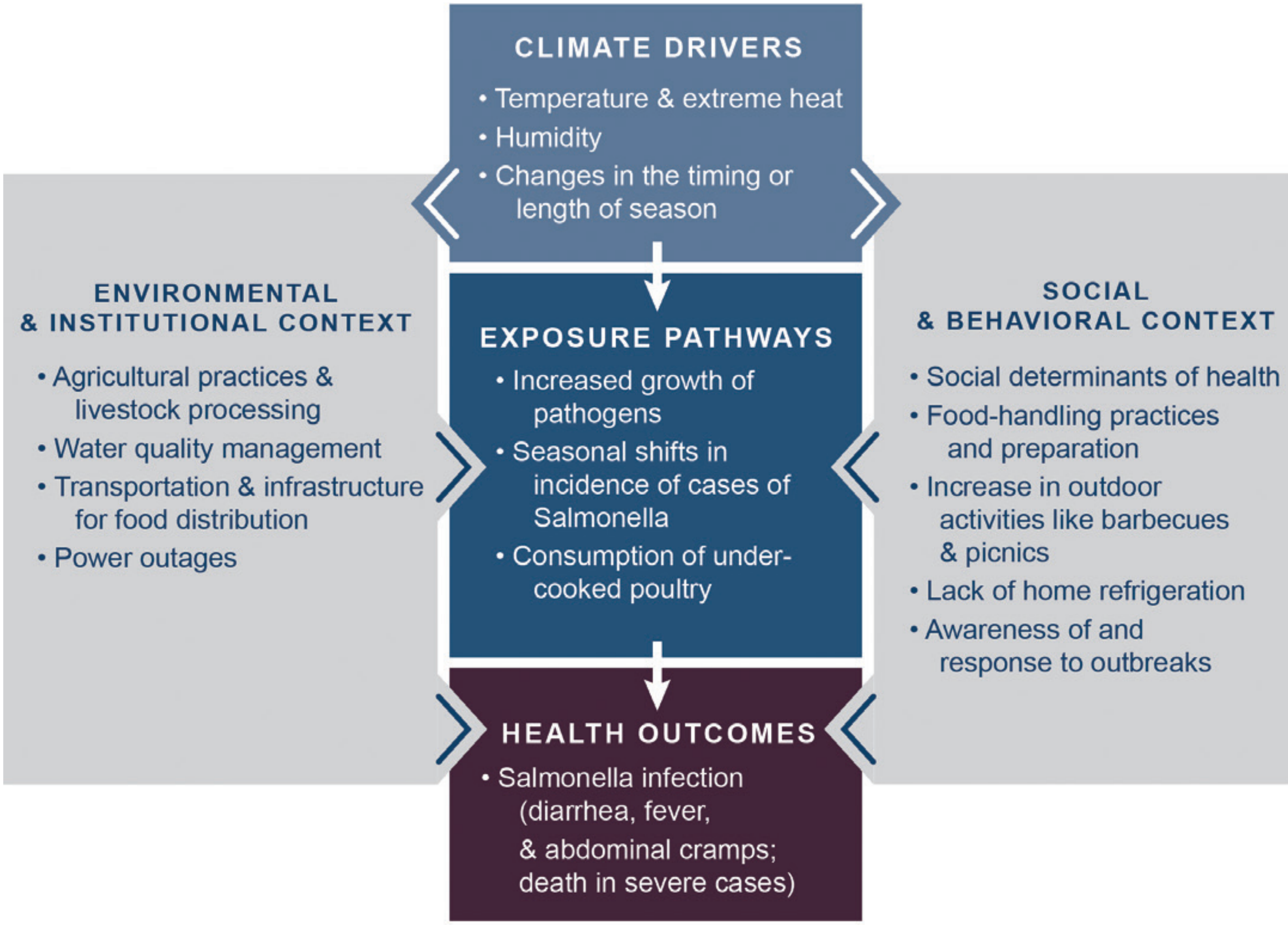

Figure 2: This conceptual diagram for a *Salmonella* example illustrates the key pathways by which humans are exposed to health threats from climate drivers, and potential resulting health outcomes (center boxes). These exposure pathways exist within the context of other factors that positively or negatively 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 (CO_2) 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 CO_2 "fertilization" effect on plant photosynthesis. Higher concentrations of CO_2 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 produce[34] and seafood.[35, 36]

Seasonality of Human Illnesses Associated With Foodborne Pathogens

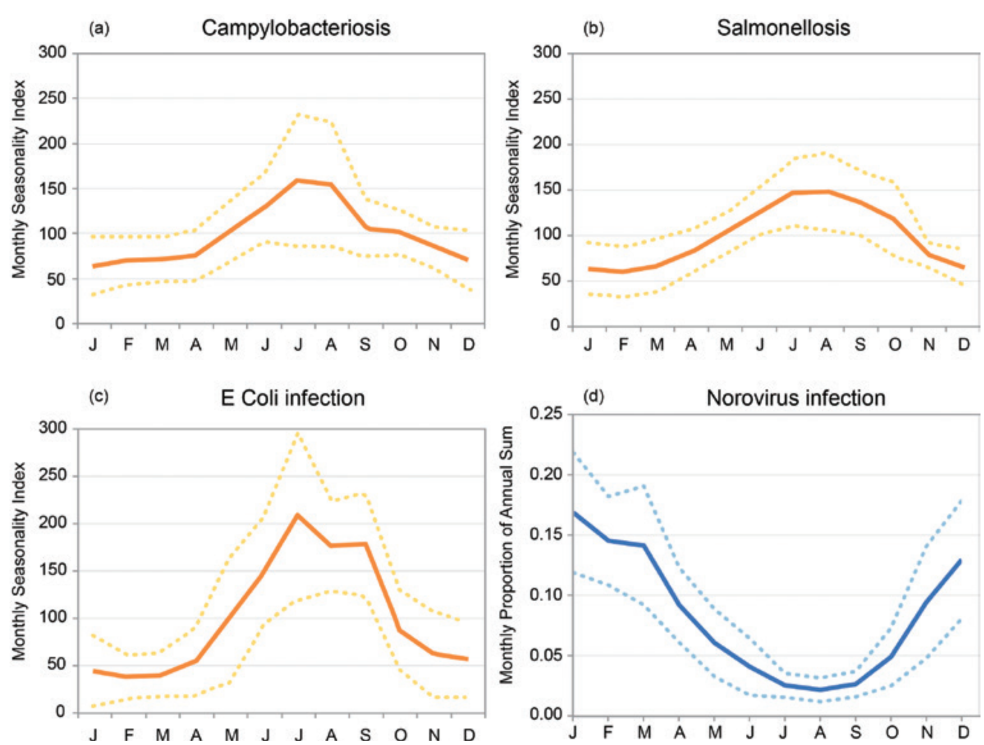

Figure 3: A review of the published literature from 1960 to 2010 indicates a summertime peak in the incidence of illnesses associated with infection from a) *Campylobacter*, b) *Salmonella*, and c) *Escherichia coli* (*E. coli*). For these three pathogens, the monthly seasonality index shown here on 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	• 5,500,000 illnesses • 15,000 hospitalizations • 150 deaths	Extreme weather events (such as heavy precipitation and flooding)	**Pathogens Favoring Colder/ Dryer Conditions**
Listeria monocytogene	Fever, muscle aches, and rarely diarrhea. Intensive infection can lead to miscarriage, stillbirth, premature delivery, or life-threatening infections (meningitis).	• 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.	• 87,000 illnesses • 4,400 hospitalizations • 330 deaths		
Campylobacter	Diarrhea, cramping, abdominal pain, nausea, and vomiting. In serious cases can be life-threatening.	• 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.	• 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.	• 35,000 illnesses • 190 hospitalizations • 40 deaths	Sea surface temperature, extreme weather events	
***Escherichia coli* (*E coli*)**	*E. coli* usually causes mild diarrhea. More severe pathogenic types, such as enterohemorrhagic *E. Coli* (EHEC), are associated with hemolytic uremic syndrome (a toxin causing destruction of red blood cells, leading to kidney failure).	• 200,000 illnesses • 2,400 hospitalizations • 20 deaths	Extreme weather events, changes in the timing or length of seasons	**Pathogens Favoring Warmer/ Wetter Conditions**

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]

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

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 because 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-controlled 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-

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 ciguatoxin (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 ciguatoxin-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 CO_2 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 CO_2 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 CO_2-induced increases in the herbicide tolerance of certain weeds or climate-induced shifts in invasive weed, insect,

Impacts of Rising CO_2 on the Nutritional Value of Crops

Protein. Protein content of major food crops is very likely to decline significantly as atmospheric CO_2 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 CO_2 are approximately 400 ppm.[138]

Minerals and trace elements. Rising CO_2 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]

Wheat grown in southeast Washington state, August, 2008.

Ratio of major macronutrients (carbohydrates to protein). It is very likely that rising CO_2 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] 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

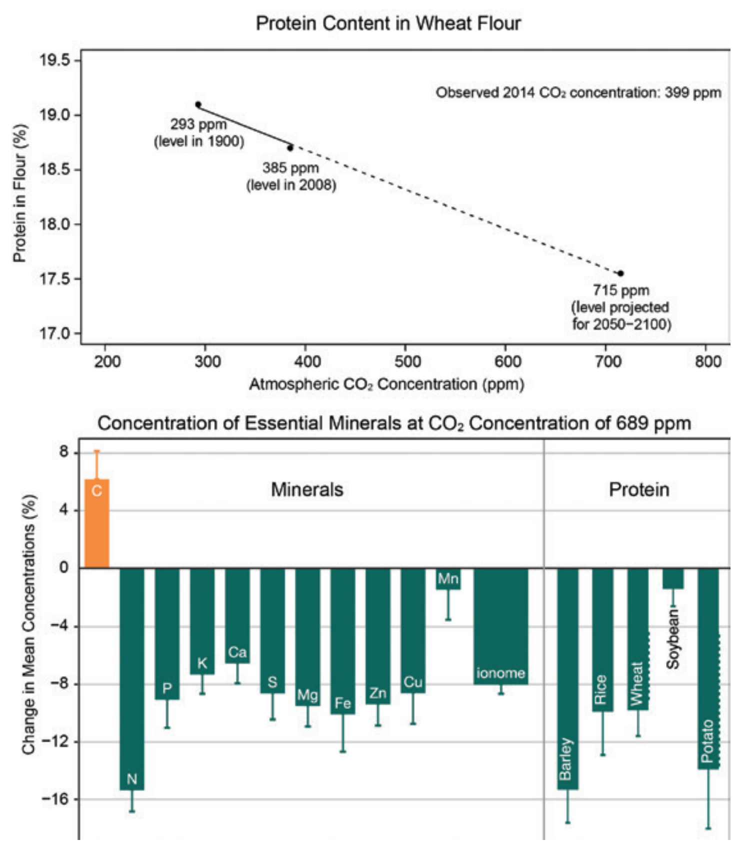

Figure 4: Direct effect of rising atmospheric carbon dioxide (CO_2) on the concentrations of protein and minerals in crops. The top figure shows that the rise in CO_2 concentration from 293 ppm (at the beginning of the last century) to 385 ppm (global average in 2008) to 715 ppm (projected to occur by 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 CO_2 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 CO_2 Affects Nutrition

Though rising CO_2 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 CO_2 on the nutritional value of crops represents a potential threat to human health.[16, 133, 134, 135, 136]

Protein

As CO_2 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 CO_2 concentration since 1900.[129] When grown at the CO_2 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 CO_2 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 CO_2 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 CO_2 on plant biology. First, rising CO_2 increases carbohydrate accumulation in plant tissues, which can, in turn, dilute the content of other nutrients, including minerals. Second, high CO_2 concentrations reduce plant demands for water, resulting in fewer nutrients being drawn into plant roots.[133, 144, 145]

The ongoing increase in CO_2 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 CO_2 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 CO_2.[16] There is growing evidence that a dietary increase in this ratio can adversely affect human metabolism[143] 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.

Mississippi River Level at St. Louis, Missouri

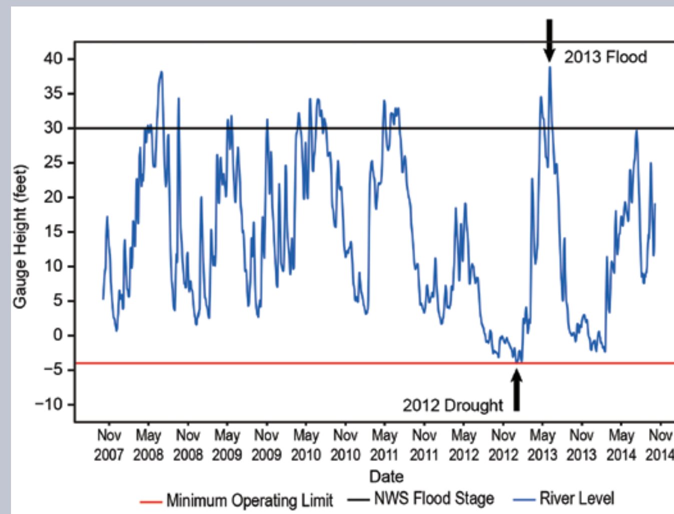

Figure 5: Mississippi River gauge height at St. Louis, MO, from October 2007 through October 2014 showing low water conditions during the 2012 drought and water levels above flood stage in 2013. (Figure source: adapted from USGS 2015)[185]

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]

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 health[171] (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 CO_2 levels can reduce protein content and alter protein composition in certain plants, which has the potential to alter allergenic sensitivity. For example, rising CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 (CO_2) 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 Unites 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 CO_2 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 Unites 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 C_3 cereals such as rice and wheat, which make up the bulk of human caloric input. C_3 species are about 95% of all plant species and represent those species most likely to respond to an increase in atmospheric CO_2 concentrations.

There is strong evidence and consensus that protein concentrations in plants strongly correlate with nitrogen concentrations. CO_2-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 CO_2 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 CO_2 reduces protein content in non-leguminous C_3 crops, including wheat, rice, potato, and barley. There is also good agreement across studies that the ongoing increase in CO_2 elevates the overall carbohydrate content in C_3 plants.[16]

Another meta-analysis quantifies the role of increasing CO_2 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 CO_2 also significantly reduces the mineral concentrations (calcium, magnesium, iron, zinc, copper, sulfur, potassium, and phosphorus) in C_3 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 CO_2 concentrations representing levels in 1900 (approximately 290 ppm), 2008 (approximately 385 ppm), and the CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Likelihood
Very Likely
≥ 9 in 10
Likely
≥ 2 in 3
As Likely As Not
≈ 1 in 2
Unlikely
≤ 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

References

1. Brown, M.E., J.M. Antle, P. Backlund, E.R. Carr, W.E. Easterling, M.K. Walsh, C. Ammann, W. Attavanich, C.B. Barrett, M.F. Bellemare, V. Dancheck, C. Funk, K. Grace, J.S.I. Ingram, H. Jiang, H. Maletta, T. Mata, A. Murray, M. Ngugi, D. Ojima, B. O'Neill, and C. Tebaldi, 2015: Climate Change, Global Food Security and the U.S. Food System. 146 pp. U.S. Global Change Research Program. http://www.usda.gov/oce/climate_change/FoodSecurity2015Assessment/FullAssessment.pdf

2. Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso, 2014: Food security and food production systems. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 485-533. http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap7_FINAL.pdf

3. Chakraborty, S. and A.C. Newton, 2011: Climate change, plant diseases and food security: An overview. *Plant Pathology,* **60,** 2-14. http://dx.doi.org/10.1111/j.1365-3059.2010.02411.x

4. Gregory, P.J., J.S.I. Ingram, and M. Brklacich, 2005: Climate change and food security. *Philosophical Transactions of the Royal Society B: Biological Sciences,* **360,** 2139-2148. http://dx.doi.org/10.1098/rstb.2005.1745

5. Lake, I.R., L. Hooper, A. Abdelhamid, G. Bentham, A.B.A. Boxall, A. Draper, S. Fairweather-Tait, M. Hulme, P.R. Hunter, G. Nichols, and K.W. Waldron, 2012: Climate change and food security: Health impacts in developed countries. *Environmental Health Perspectives,* **120,** 1520-1526. http://dx.doi.org/10.1289/ehp.1104424

6. Walthall, C., P. Backlund, J. Hatfield, L. Lengnick, E. Marshall, M. Walsh, S. Adkins, M. Aillery, E.A. Ainsworth, C. Amman, C.J. Anderson, I. Bartomeus, L.H. Baumgard, F. Booker, B. Bradley, D.M. Blumenthal, J. Bunce, K. Burkey, S.M. Dabney, J.A. Delgado, J. Dukes, A. Funk, K. Garrett, M. Glenn, D.A. Grantz, D. Goodrich, S. Hu, R.C. Izaurralde, R.A.C. Jones, S.-H. Kim, A.D.B. Leaky, K. Lewers, T.L. Mader, A. McClung, J. Morgan, D.J. Muth, M. Nearing, D.M. Oosterhuis, D. Ort, C. Parmesan, W.T. Pettigrew, W. Polley, R. Rader, C. Rice, M. Rivington, E. Rosskopf, W.A. Salas, L.E. Sollenberger, R. Srygley, C. Stöckle, E.S. Takle, D. Timlin, J.W. White, R. Winfree, L. Wright-Morton, and L.H. Ziska, 2012: Climate Change and Agriculture in the United States: Effects and Adaptation. USDA Technical Bulletin 1935, 186 pp. U.S. Department of Agriculture, Washington, D.C. http://www.usda.gov/oce/climate_change/effects_2012/CC%20and%20Agriculture%20Report%20(02-04-2013)b.pdf

7. IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (Eds.), 1132 pp. Cambridge University Press, Cambridge, UK and New York, NY. http://www.ipcc.ch/report/ar5/wg2/

8. IOM, 2012: *Improving Food Safety Through a One Health Approach: Workshop Summary*. Choffnes, E.R., D.A. Relman, L. Olsen, R. Hutton, and A. Mack, Eds. Institute of Medicine. The National Academies Press, Washington, D.C., 418 pp. http://dx.doi.org/10.17226/13423

9. Jaykus, L., M. Woolridge, J.M. Frank, M. Miraglia, A. McQuatters-Gollop, C. Tirado, R. Clarke, and M. Friel, 2008: Climate Change: Implications for Food Safety. 49 pp. Food and Agriculture Organisation of the United Nations. http://www.fao.org/docrep/010/i0195e/i0195e00.HTM

10. FAO, 2014: Definitions of Purposes of the Codex Alimentarius. Food and Agriculture Organization of the United Nations. http://www.fao.org/docrep/005/y2200e/y2200e07.htm

11. CDC, 2014: CDC Estimates of Foodborne Illness in the United States. Centers for Disease Control and Prevention, Atlanta, GA. http://www.cdc.gov/foodborneburden/2011-foodborne-estimates.html

12. CDC, 2015: Food Safety: Foodborne Germs and Illnesses. Centers for Disease Control and Prevention, Atlanta, GA. http://www.cdc.gov/foodsafety/foodborne-germs.html

13. IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (Eds.), 582 pp. Cambridge University Press, Cambridge, UK and New York, NY. http://ipcc-wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf

14. IPCC, 2013: Summary for policymakers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1–30. http://dx.doi.org/10.1017/CBO9781107415324.004

15. Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, D.C., 19-67. http://dx.doi.org/10.7930/J0KW5CXT

16. Loladze, I., 2014: Hidden shift of the ionome of plants exposed to elevated CO2 depletes minerals at the base of human nutrition. *eLife,* **3,** e02245. http://dx.doi.org/10.7554/eLife.02245

17. Curtis, D., A. Hill, A. Wilcock, and S. Charlebois, 2014: Foodborne and waterborne pathogenic bacteria in selected Organisation for Economic Cooperation and Development (OECD) countries. *Journal of Food Science,* **79,** R1871-R1876. http://dx.doi.org/10.1111/1750-3841.12646

18. Kovats, R.S., S.J. Edwards, S. Hajat, B.G. Armstrong, K.L. Ebi, and B. Menne, 2004: The effect of temperature on food poisoning: A time-series analysis of salmonellosis in ten European countries. *Epidemiology and Infection,* **132,** 443-453. http://dx.doi.org/10.1017/s0950268804001992

19. USDA, 2013: Foodborne Illness Peaks in Summer-Why? United States Department of Agriculture, Food Safety and Inspection Service. http://www.fsis.usda.gov/wps/portal/fsis/topics/food-safety-education/get-answers/food-safety-fact-sheets/foodborne-illness-and-disease/foodborne-illness-peaks-in-summer/ct_index

20. Scallan, E., P.M. Griffin, F.J. Angulo, R.V. Tauxe, and R.M. Hoekstra, 2011: Foodborne illness acquired in the United States: Unspecified agents. *Emerging Infectious Diseases,* **17,** 16-22. http://dx.doi.org/10.3201/eid1701.P21101

21. Scallan, E., R.M. Hoekstra, F.J. Angulo, R.V. Tauxe, M.A. Widdowson, S.L. Roy, J.L. Jones, and P.M. Griffin, 2011: Foodborne illness acquired in the United States: Major pathogens. *Emerging Infectious Diseases,* **17,** 7-15. http://dx.doi.org/10.3201/eid1701.P11101

22. Painter, J.A., R.M. Hoekstra, T. Ayers, R.V. Tauxe, C.R. Braden, F.J. Angulo, and P.M. Griffin, 2013: Attribution of foodborne illnesses, hospitalizations, and deaths to food commodities by using outbreak data, United States, 1998–2008. *Emerging Infectious Diseases,* **19,** 407-415. http://dx.doi.org/10.3201/eid1903.111866

23. Utaaker, K.S. and L.J. Robertson, 2015: Climate change and foodborne transmission of parasites: A consideration of possible interactions and impacts for selected parasites. *Food Research International,* **68,** 16-23. http://dx.doi.org/10.1016/j.foodres.2014.06.051

24. Pennotti, R., E. Scallan, L. Backer, J. Thomas, and F.J. Angulo, 2013: Ciguatera and scombroid fish poisoning in the United States. *Foodborne Pathogens and Disease,* **10,** 1059-1066. http://dx.doi.org/10.1089/fpd.2013.1514

25. Tchounwou, P.B., W.K. Ayensu, N. Ninashvili, and D. Sutton, 2003: Review: Environmental exposure to mercury and its toxicopathologic implications for public health. *Environmental Toxicology,* **18,** 149-175. http://dx.doi.org/10.1002/tox.10116

26. Marques, A., M.L. Nunes, S.K. Moore, and M.S. Strom, 2010: Climate change and seafood safety: Human health implications. *Food Research International,* **43,** 1766-1779. http://dx.doi.org/10.1016/j.foodres.2010.02.010

27. Downs, S.G., C.L. MacLeod, and J.N. Lester, 1998: Mercury in precipitation and its relation to bioaccumulation in fish: A literature review. *Water, Air, and Soil Pollution,* **108,** 149-187. http://dx.doi.org/10.1023/a:1005023916816

28. Booth, S. and D. Zeller, 2005: Mercury, food webs, and marine mammals: Implications of diet and climate change for human health. *Environmental Health Perspectives,* **113,** 521-526. http://dx.doi.org/10.1289/ehp.7603

29. Boxall, A.B.A., A. Hardy, S. Beulke, T. Boucard, L. Burgin, P.D. Falloon, P.M. Haygarth, T. Hutchinson, R.S. Kovats, G. Leonardi, L.S. Levy, G. Nichols, S.A. Parsons, L. Potts, D. Stone, E. Topp, D.B. Turley, K. Walsh, E.M.H. Wellington, and R.J. Williams, 2009: Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environmental Health Perspectives,* **117,** 508-514. http://dx.doi.org/10.1289/ehp.0800084

30. Strawn, L.K., E.D. Fortes, E.A. Bihn, K.K. Nightingale, Y.T. Gröhn, R.W. Worobo, M. Wiedmann, and P.W. Bergholz, 2013: Landscape and meteorological factors affecting prevalence of three food-borne pathogens in fruit and vegetable farms. *Applied and Environmental Microbiology,* **79,** 588-600. http://dx.doi.org/10.1128/aem.02491-12

31. Liu, C., N. Hofstra, and E. Franz, 2013: Impacts of climate change on the microbial safety of pre-harvest leafy green vegetables as indicated by Escherichia coli O157 and Salmonella spp. *International Journal of Food Microbiology,* **163,** 119-128. http://dx.doi.org/10.1016/j.ijfoodmicro.2013.02.026

32. Wu, F., D. Bhatnagar, T. Bui-Klimke, I. Carbone, R. Hellmich, G. Munkvold, P. Paul, G. Payne, and E. Takle, 2011: Climate change impacts on mycotoxin risks in US maize. *World Mycotoxin Journal,* **4,** 79-93. http://dx.doi.org/10.3920/WMJ2010.1246

33. Castro-Ibáñez, I., M.I. Gil, J.A. Tudela, and A. Allende, 2015: Microbial safety considerations of flooding in primary production of leafy greens: A case study. *Food Research International,* **68,** 62-69. http://dx.doi.org/10.1016/j.foodres.2014.05.065

34. Lake, I.R., I.A. Gillespie, G. Bentham, G.L. Nichols, C. Lane, G.K. Adak, and E.J. Threlfall, 2009: A re-evaluation of the impact of temperature and climate change on foodborne illness. *Epidemiology and Infection,* **137,** 1538-1547. http://dx.doi.org/10.1017/s0950268809002477

35. Cook, D.W., 1994: Effect of time and temperature on multiplication of *Vibrio vulnificus* in postharvest Gulf Coast shellstock oysters. *Applied and Environmental Microbiology,* **60,** 3483-3484. PMC201838

36. Gooch, J., A. DePaola, J. Bowers, and D. Marshall, 2002: Growth and survival of *Vibrio parahaemolyticus* in postharvest American oysters. *Journal of Food Protection,* **65,** 911-1053.

37. Paterson, R.R.M. and N. Lima, 2010: How will climate change affect mycotoxins in food? *Food Research International,* **43,** 1902-1914. http://dx.doi.org/10.1016/j.foodres.2009.07.010

38. Lipp, E.K., R. Kurz, R. Vincent, C. Rodriguez-Palacios, S.R. Farrah, and J.B. Rose, 2001: The effects of seasonal variability and weather on microbial fecal pollution and enteric pathogens in a subtropical estuary. *Estuaries,* **24,** 266-276. http://dx.doi.org/10.2307/1352950

39. Kovats, R.S., M.J. Bouma, S. Hajat, E. Worrall, and A. Haines, 2003: El Niño and health. *The Lancet,* **362,** 1481-1489. http://dx.doi.org/10.1016/s0140-6736(03)14695-8

40. Paz, S., N. Bisharat, E. Paz, O. Kidar, and D. Cohen, 2007: Climate change and the emergence of *Vibrio vulnificus* disease in Israel. *Environmental Research,* **103,** 390-396. http://dx.doi.org/10.1016/j.envres.2006.07.002

41. Monge, R. and M. Chinchilla, 1996: Presence of *Cryptosporidium* oocysts in fresh vegetables. *Journal of Food Protection,* **59,** 202-203.

42. Solomon, E.B., S. Yaron, and K.R. Matthews, 2002: Transmission of *Escherichia coli* O157:H7 from contaminated manure and irrigation water to lettuce plant tissue and its subsequent internalization. *Applied and Environmental Microbiology,* **68,** 397-400. http://dx.doi.org/10.1128/aem.68.1.397-400.2002

43. Sales-Ortells, H., X. Fernandez-Cassi, N. Timoneda, W. Dürig, R. Girones, and G. Medema, 2015: Health risks derived from consumption of lettuces irrigated with tertiary effluent containing norovirus. *Food Research International,* **68,** 70-77. http://dx.doi.org/10.1016/j.foodres.2014.08.018

44. Miraglia, M., H.J.P. Marvin, G.A. Kleter, P. Battilani, C. Brera, E. Coni, F. Cubadda, L. Croci, B. De Santis, S. Dekkers, L. Filippi, R.W.A. Hutjes, M.Y. Noordam, M. Pisante, G. Piva, A. Prandini, L. Toti, G.J. van den Born, and A. Vespermann, 2009: Climate change and food safety: An emerging issue with special focus on Europe. *Food and Chemical Toxicology,* **47,** 1009-1021. http://dx.doi.org/10.1016/j.fct.2009.02.005

45. Foulds, S.A., P.A. Brewer, M.G. Macklin, W. Haresign, R.E. Betson, and S.M.E. Rassner, 2014: Flood-related contamination in catchments affected by historical metal mining: An unexpected and emerging hazard of climate change. *Science of the Total Environment,* **476-477,** 165-180. http://dx.doi.org/10.1016/j.scitotenv.2013.12.079

46. Umlauf, G., G. Bidoglio, E.H. Christoph, J. Kampheus, F. Kruger, D. Landmann, A.J. Schulz, R. Schwartz, K. Severin, B. Stachel, and D. Stehr, 2005: The situation of PCDD/Fs and dioxin-like PCBs after the flooding of River Elbe and Mulde in 2002. *Acta Hydrochimica et Hydrobiologica,* **33,** 543-554. http://dx.doi.org/10.1002/aheh.200400597

47. Rotkin-Ellman, M., G. Solomon, C.R. Gonzales, L. Agwaramgbo, and H.W. Mielke, 2010: Arsenic contamination in New Orleans soil: Temporal changes associated with flooding. *Environmental Research,* **110,** 19-25. http://dx.doi.org/10.1016/j.envres.2009.09.004

48. Kim, Y.S., K.H. Park, H.S. Chun, C. Choi, and G.J. Bahk, 2015: Correlations between climatic conditions and foodborne disease. *Food Research International,* **68,** 24-30. http://dx.doi.org/10.1016/j.foodres.2014.03.023

49. Lal, A., S. Hales, N. French, and M.G. Baker, 2012: Seasonality in human zoonotic enteric diseases: A systematic review. *PLoS ONE,* **7,** e31883. http://dx.doi.org/10.1371/journal.pone.0031883

50. Pérez de León, A.A., P.D. Teel, A.N. Auclair, M.T. Messenger, F.D. Guerrero, G. Schuster, and R.J. Miller, 2012: Integrated strategy for sustainable cattle fever tick eradication in USA is required to mitigate the impact of global change. *Frontiers in Physiology,* **3,** Article 195. http://dx.doi.org/10.3389/fphys.2012.00195

51. Baranyi, J. and M.L. Tamplin, 2004: ComBase: A common database on microbial responses to food environments. *Journal of Food Protection,* **67,** 1967-1971.

52. Oscar, T.P., 2009: Predictive model for survival and growth of Salmonella typhimurium DT104 on chicken skin during temperature abuse. *Journal of Food Protection,* **72,** 304-314.

53. CDC, 2014: *Salmonella*: Multistate Outbreak of Multidrug-Resistant Salmonella Heidelberg Infections Linked to Foster Farms Brand Chicken (Final Update), July 31, 2014. Centers for Disease Control and Prevention, Atlanta, GA. http://www.cdc.gov/salmonella/heidelberg-10-13/index.html

54. Ravel, A., E. Smolina, J.M. Sargeant, A. Cook, B. Marshall, M.D. Fleury, and F. Pollari, 2010: Seasonality in human salmonellosis: Assessment of human activities and chicken contamination as driving factors. *Foodborne Pathogens and Disease,* **7,** 785-794. http://dx.doi.org/10.1089/fpd.2009.0460

55. Rose, J.B., P.R. Epstein, E.K. Lipp, B.H. Sherman, S.M. Bernard, and J.A. Patz, 2001: Climate variability and change in the United States: Potential impacts on water- and foodborne diseases caused by microbiologic agents. *Environmental Health Perspectives,* **109 Suppl 2,** 211-221. PMC1240668

56. Semenza, J.C., S. Herbst, A. Rechenburg, J.E. Suk, C. Höser, C. Schreiber, and T. Kistemann, 2012: Climate change impact assessment of food- and waterborne diseases. *Critical Reviews in Environmental Science and Technology,* **42,** 857-890. http://dx.doi.org/10.1080/10643389.2010.534706

57. Rohayem, J., 2009: Norovirus seasonality and the potential impact of climate change. *Clinical Microbiology and Infection,* **15,** 524-527. http://dx.doi.org/10.1111/j.1469-0691.2009.02846.x

58. McLaughlin, J.B., A. DePaola, C.A. Bopp, K.A. Martinek, N.P. Napolilli, C.G. Allison, S.L. Murray, E.C. Thompson, M.M. Bird, and J.P. Middaugh, 2005: Outbreak of *Vibrio parahaemolyticus* gastroenteritis associated with Alaskan oysters. *The New England Journal of Medicine,* **353,** 1463-1470. http://dx.doi.org/10.1056/NEJMoa051594

59. Martinez-Urtaza, J., J.C. Bowers, J. Trinanes, and A. DePaola, 2010: Climate anomalies and the increasing risk of *Vibrio parahaemolyticus* and *Vibrio vulnificus* illnesses. *Food Research International,* **43,** 1780-1790. http://dx.doi.org/10.1016/j.foodres.2010.04.001

60. Cook, D.W., 1997: Refrigeration of oyster shellstock: Conditions which minimize the outgrowth of *Vibrio vulnificus*. *Journal of Food Protection,* **60,** 349-352.

61. Kunkel, K.E., L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Wuebbles, and J.G. Dobson, 2013: Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 9. Climate of the Contiguous United States. NOAA Technical Report NESDIS 142-9, 85 pp. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, D.C. http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-9-Climate_of_the_Contiguous_United_States.pdf

62. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds., 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program, Washington, D.C., 842 pp. http://dx.doi.org/10.7930/J0Z31WJ2

63. Polley, L. and R.C.A. Thompson, 2009: Parasite zoonoses and climate change: Molecular tools for tracking shifting boundaries. *Trends in Parasitology,* **25,** 285-291. http://dx.doi.org/10.1016/j.pt.2009.03.007

64. Mills, J.N., K.L. Gage, and A.S. Khan, 2010: Potential influence of climate change on vector-borne and zoonotic diseases: A review and proposed research plan. *Environmental Health Perspectives,* **118,** 1507-1514. http://dx.doi.org/10.1289/ehp.0901389

65. Esteve-Gassent, M.D., A.A. Pérez de León, D. Romero-Salas, T.P. Feria-Arroyo, R. Patino, I. Castro-Arellano, G. Gordillo-Pérez, A. Auclair, J. Goolsby, R.I. Rodriguez-Vivas, and J.G. Estrada-Franco, 2014: Pathogenic landscape of transboundary zoonotic diseases in the Mexico–US border along the Rio Grande. *Frontiers in Public Health,* **2,** 177. http://dx.doi.org/10.3389/fpubh.2014.00177

66. Schijven, J., M. Bouwknegt, A.M. de Roda Husman, S. Rutjes, B. Sudre, J.E. Suk, and J.C. Semenza, 2013: A decision support tool to compare waterborne and foodborne infection and/or illness risks associated with climate change. *Risk Analysis,* **33,** 2154-2167. http://dx.doi.org/10.1111/risa.12077

67. Patz, J.A., S.J. Vavrus, C.K. Uejio, and S.L. McLellan, 2008: Climate change and waterborne disease risk in the Great Lakes region of the US. *American Journal of Preventive Medicine,* **35,** 451-458. http://dx.doi.org/10.1016/j.amepre.2008.08.026

68. Tornevi, A., O. Bergstedt, and B. Forsberg, 2014: Precipitation effects on microbial pollution in a river: Lag structures and seasonal effect modification. *PloS ONE,* **9,** e98546. http://dx.doi.org/10.1371/journal.pone.0098546

69. Cho, K.H., Y.A. Pachepsky, J.H. Kim, A.K. Guber, D.R. Shelton, and R. Rowland, 2010: Release of *Escherichia coli* from the bottom sediment in a first-order creek: Experiment and reach-specific modeling. *Journal of Hydrology,* **391,** 322-332. http://dx.doi.org/10.1016/j.jhydrol.2010.07.033

70. Jamieson, R., D.M. Joy, H. Lee, R. Kostaschuk, and R. Gordon, 2005: Transport and deposition of sediment-associated *Escherichia coli* in natural streams. *Water Research,* **39,** 2665-2675. http://dx.doi.org/10.1016/j.watres.2005.04.040

71. Jamieson, R.C., D.M. Joy, H. Lee, R. Kostaschuk, and R.J. Gordon, 2005: Resuspension of sediment-associated *Escherichia coli* in a natural stream. *Journal of Environment Quality,* **34,** 581-589. http://dx.doi.org/10.2134/jeq2005.0581

72. Fleury, M., D.F. Charron, J.D. Holt, O.B. Allen, and A.R. Maarouf, 2006: A time series analysis of the relationship of ambient temperature and common bacterial enteric infections in two Canadian provinces. *International Journal of Biometeorology,* **50,** 385-391. http://dx.doi.org/10.1007/s00484-006-0028-9

73. Senhorst, H.A. and J.J. Zwolsman, 2005: Climate change and effects on water quality: A first impression. *Water Science & Technology,* **51,** 53-59.

74. Zhang, G., L. Ma, L.R. Beuchat, M.C. Erickson, V.H. Phelan, and M.P. Doyle, 2009: Heat and drought stress during growth of lettuce (*Lactuca sativa* L.) does not promote internalization of *Escherichia coli* O157: H7. *Journal of Food Protection,* **72,** 2471-2475.

75. Cotty, P.J. and R. Jaime-Garcia, 2007: Influences of climate on aflatoxin producing fungi and aflatoxin contamination. *International Journal of Food Microbiology,* **119,** 109-115. http://dx.doi.org/10.1016/j.ijfoodmicro.2007.07.060

76. Tirado, M.C., R. Clarke, L.A. Jaykus, A. McQuatters-Gollop, and J.M. Frank, 2010: Climate change and food safety: A review. *Food Research International,* **43,** 1745-1765. http://dx.doi.org/10.1016/j.foodres.2010.07.003

77. Medina, A., A. Rodriguez, and N. Magan, 2014: Effect of climate change on *Aspergillus flavus* and aflatoxin B1 production. *Frontiers in Microbiology,* **5**. http://dx.doi.org/10.3389/fmicb.2014.00348

78. Gould, L.H., K.A. Walsh, A.R. Vieira, K. Herman, I.T. Williams, A.J. Hall, and D. Cole, 2013: Surveillance for foodborne disease Outbreaks — United States, 1998–2008. *MMWR. Morbidity and Mortality Weekly Report,* **62,** 1-34. http://www.cdc.gov/mmwr/preview/mmwrhtml/ss6202a1.htm

79. Gingold, D.B., M.J. Strickland, and J.J. Hess, 2014: Ciguatera fish poisoning and climate change: Analysis of National Poison Center Data in the United States, 2001–2011. *Environmental Health Perspectives,* **122,** 580-586. http://dx.doi.org/10.1289/ehp.1307196

80. Akil, L., H.A. Ahmad, and R.S. Reddy, 2014: Effects of climate change on Salmonella infections. *Foodborne Pathogens and Disease,* **11,** 974-980. http://dx.doi.org/10.1089/fpd.2014.1802

81. Strosnider, H., E. Azziz-Baumgartner, M. Banziger, R. Bhat, R. Breiman, M. Brune, K. DeCock, A. Dilley, J. Groopman, K. Hell, S. Henry, D. Jeffers, C. Jolly, J. P, G. Kibata, L. Lewis, X. Liu, G. Luber, L. McCoy, P. Mensah, M. Miraglia, A. Misore, H. Njapau, C. Ong, M. Onsongo, S. Page, D. Park, M. Patel, T. Phillips, M. Pineiro, J. Pronczuk, H. Rogers, C. Rubin, M. Sabino, A. Schaafsma, G. Shephard, J. Stroka, C. Wild, J. Williams, and D. Wilson, 2006: Workgroup report: Public health strategies for reducing aflatoxin exposure in developing countries. *Environmental Health Perspectives,* **114,** 1898-1903. http://dx.doi.org/10.1289/ehp.9302 http://www.jstor.org/stable/4119604

82. Lewis, L., M. Onsongo, H. Njapau, H. Schurz-Rogers, G. Luber, S. Kieszak, J. Nyamongo, L. Backer, A.M. Dahiye, A. Misore, K. DeCock, and C. Rubin, 2005: Aflatoxin contamination of commercial maize products during an outbreak of acute aflatoxicosis in eastern and central Kenya. *Environmental Health Perspectives,* **113,** 1763-1767. http://dx.doi.org/10.1289/ehp.7998

83. Wild, C.P. and Y.Y. Gong, 2010: Mycotoxins and human disease: A largely ignored global health issue. *Carcinogenesis,* **31,** 71-82. http://dx.doi.org/10.1093/carcin/bgp264

84. Liu, Y. and F. Wu, 2010: Global burden of aflatoxin-induced hepatocellular carcinoma: A risk assessment. *Environmental Health Perspectives,* **118,** 818-824. http://dx.doi.org/10.1289/ehp.0901388

85. Battilani, P., V. Rossi, P. Giorni, A. Pietri, A. Gualla, H.J. Van der Fels-Klerx, C.J.H. Booij, A. Moretti, A. Logrieco, F. Miglietta, P. Toscano, M. Miraglia, B. De Santis, and C. Brera, 2012: Modelling, Predicting and Mapping the Emergence of Aflatoxins in Cereals in the EU due to Climate Change. Question No. EFSA-Q-2009-00812. European Food Safety Authority, Parma, Italy. http://www.efsa.europa.eu/sites/default/files/scientific_output/files/main_documents/223e.pdf

86. Alavanja, M.C.R., M.K. Ross, and M.R. Bonner, 2013: Increased cancer burden among pesticide applicators and others due to pesticide exposure. *CA: A Cancer Journal for Clinicians,* **63,** 120-142. http://dx.doi.org/10.3322/caac.21170

87. Presley, S.M., T.R. Rainwater, G.P. Austin, S.G. Platt, J.C. Zak, G.P. Cobb, E.J. Marsland, K. Tian, B. Zhang, T.A. Anderson, S.B. Cox, M.T. Abel, B.D. Leftwich, J.R. Huddleston, R.M. Jeter, and R.J. Kendall, 2006: Assessment of pathogens and toxicants in New Orleans, LA following Hurricane Katrina. *Environmental Science & Technology,* **40,** 468-474. http://dx.doi.org/10.1021/es052219p

88. Carrie, J., F. Wang, H. Sanei, R.W. Macdonald, P.M. Outridge, and G.A. Stern, 2010: Increasing contaminant burdens in an arctic fish, Burbot (*Lota lota*), in a warming climate. *Environmental Science & Technology,* **44,** 316-322. http://dx.doi.org/10.1021/es902582y

89. Bodaly, R.A., J.W.M. Rudd, R.J.P. Fudge, and C.A. Kelly, 1993: Mercury concentrations in fish related to size of remote Canadian shield lakes. *Canadian Journal of Fisheries and Aquatic Sciences,* **50,** 980-987. http://dx.doi.org/10.1139/f93-113

90. Dijkstra, J.A., K.L. Buckman, D. Ward, D.W. Evans, M. Dionne, and C.Y. Chen, 2013: Experimental and natural warming elevates mercury concentrations in estuarine fish. *PLoS ONE,* **8,** e58401. http://dx.doi.org/10.1371/journal.pone.0058401

91. Pack, E.C., C.H. Kim, S.H. Lee, C.H. Lim, D.G. Sung, M.H. Kim, K.H. Park, S.-S. Hong, K.M. Lim, D.W. Choi, and S.W. Kim, 2014: Effects of environmental temperature change on mercury absorption in aquatic organisms with respect to climate warming. *Journal of Toxicology and Environmental Health, Part A,* **77,** 1477-1490. http://dx.doi.org/10.1080/15287394.2014.955892

92. González-Estecha, M., A. Bodas-Pinedo, M.A. Rubio-Herrera, N. Martell-Claros, E.M. Trasobares-Iglesias, J.M. Ordóñez-Iriarte, J.J. Guillén-Pérez, M.A. Herráiz-Martínez, J.A. García-Donaire, R. Farré-Rovira, E. Calvo-Manuel, J.R. Martínez-Álvarez, M.T. Llorente-Ballesteros, M. Sáinz-Martín, T. Martínez-Astorquiza, M.J. Martínez-García, I. Bretón Lesmes, M.A. Cuadrado-Cenzual, S. Prieto-Menchero, C. Gallardo-Pino, R. Moreno-Rojas, P. Bermejo-Barrera, M. Torres-Moreno, M. Arroyo-Fernández, and A. Calle-Pascual, 2014: Effectos sobre la salud del metilmercurio in ninos y adultos: Estudios nacionales e internacionales [The effects of methylmercury on health in children and adults: National and international studies]. *Nutricion Hospitalaria,* **30,** 989-1007. http://dx.doi.org/10.3305/nh.2014.30.5.7728

93. Bebber, D.P., 2015: Range-expanding pests and pathogens in a warming world. *Annual Review of Phytopathology,* **53,** 335-356. http://dx.doi.org/10.1146/annurev-phyto-080614-120207

94. Sanchez-Guillen, R.A., A. Cordoba-Aguilar, B. Hansson, J. Ott, and M. Wellenreuther, 2015: Evolutionary consequences of climate-induced range shifts in insects. *Biological Reviews,* **July 6**. http://dx.doi.org/10.1111/brv.12204

95. Bale, J.S. and S.A.L. Hayward, 2010: Insect overwintering in a changing climate. *Journal of Experimental Biology,* **213,** 980-994. http://dx.doi.org/10.1242/jeb.037911

96. Rosenzweig, C., A. Iglesias, X.B. Yang, P.R. Epstein, and E. Chivian, 2001: Climate change and extreme weather events: Implications for food production, plant diseases, and pests. *Global Change and Human Health,* **2,** 90-104. http://dx.doi.org/10.1023/a:1015086831467

97. Ziska, L.H. and G.B. Runion, 2007: Future weed, pest, and disease problems for plants. *Agroecosystems in a Changing Climate*. Newton, P.C.D., R.A. Carran, G.R. Edwards, and P.A. Niklaus, Eds. CRC Press, Boca Raton, FL, 261-287. http://www.ars.usda.gov/SP2UserFiles/Place/60100500/csr/ResearchPubs/runion/runion_07a.pdf

98. Zavala, J.A., C.L. Casteel, E.H. DeLucia, and M.R. Berenbaum, 2008: Anthropogenic increase in carbon dioxide compromises plant defense against invasive insects. *PNAS,* **105,** 5129-5133. http://dx.doi.org/10.1073/pnas.0800568105

99. O'Neill, B.F., A.R. Zangerl, E.H. DeLucia, C. Casteel, J.A. Zavala, and M.R. Berenbaum, 2011: Leaf temperature of soybean grown under elevated CO2 increases *Aphis glycines* (Hemiptera: Aphididae) population growth. *Insect Science,* **18,** 419-425. http://dx.doi.org/10.1111/j.1744-7917.2011.01420.x

100. Chen, C.-C. and B.A. McCarl, 2001: An investigation of the relationship between pesticide usage and climate change. *Climatic Change,* **50,** 475-487. http://dx.doi.org/10.1023/a:1010655503471

101. Ziska, L.H., 2014: Increasing minimum daily temperatures are associated with enhanced pesticide use in cultivated soybean along a latitudinal gradient in the Mid-Western United States. *PLoS ONE,* **9,** e98516. http://dx.doi.org/10.1371/journal.pone.0098516

102. Ziska, L.H., J.R. Teasdale, and J.A. Bunce, 1999: Future atmospheric carbon dioxide may increase tolerance to glyphosate. *Weed Science,* **47,** 608-615.

103. Ziska, L.H., S. Faulkner, and J. Lydon, 2004: Changes in biomass and root:shoot ratio of field-grown Canada thistle (*Cirsium arvense*), a noxious, invasive weed, with elevated CO_2: Implications for control with glyphosate. *Weed Science,* **52,** 584-588. http://dx.doi.org/10.1614/WS-03-161R

104. McDonald, A., S. Riha, A. DiTommaso, and A. DeGaetano, 2009: Climate change and the geography of weed damage: Analysis of U.S. maize systems suggests the potential for significant range transformations. *Agriculture, Ecosystems & Environment,* **130,** 131-140. http://dx.doi.org/10.1016/j.agee.2008.12.007

105. Manea, A., M.R. Leishman, and P.O. Downey, 2011: Exotic C_4 grasses have increased tolerance to glyphosate under elevated carbon dioxide. *Weed Science,* **59,** 28-36. http://dx.doi.org/10.1614/ws-d-10-00080.1

106. Ziska, L.H., 2011: Climate change, carbon dioxide and global crop production: Food security and uncertainty. *Handbook on Climate Change and Agriculture*. Dinar, A. and R. Mendelsohn, Eds. Edward Elgar Publishing, Cheltenham, United Kingdom, 9-31.

107. DiTommaso, A., Q. Zhong, and D.R. Clements, 2014: Identifying climate change as a factor in the establishment and persistence of invasive weeds in agricultural crops. *Invasive Species and Global Climate Change*. Ziska, L.H. and J.S. Dukes, Eds. CABI Books, Wallingford, Oxfordshire, UK, 253-270.

108. Ziska, L.H. and L.L. McConnell, 2015: Climate change, carbon dioxide, and pest biology: Monitor, mitigate, manage. *Journal of Agricultural and Food Chemistry*. http://dx.doi.org/10.1021/jf506101h

109. Bailey, S.W., 2004: Climate change and decreasing herbicide persistence. *Pest Management Science,* **60,** 158-162. http://dx.doi.org/10.1002/ps.785

110. Delcour, I., P. Spanoghe, and M. Uyttendaele, 2015: Literature review: Impact of climate change on pesticide use. *Food Research International,* **68,** 7-15. http://dx.doi.org/10.1016/j.foodres.2014.09.030

111. WHO, 2014: Antimicrobial Resistance: Global Report on Surveillance. 257 pp. World Health Organization, Geneva. http://www.who.int/drugresistance/documents/surveillancereport/en/

112. Cooper, K.M., C. McMahon, I. Fairweather, and C.T. Elliott, 2015: Potential impacts of climate change on veterinary medicinal residues in livestock produce: An island of Ireland perspective. *Trends in Food Science & Technology,* **44,** 21-35. http://dx.doi.org/10.1016/j.tifs.2014.03.007

113. Gormaz, J.G., J.P. Fry, M. Erazo, and D.C. Love, 2014: Public health perspectives on aquaculture. *Current Environmental Health Reports,* **1,** 227-238. http://dx.doi.org/10.1007/s40572-014-0018-8

114. Lafferty, K.D., J.W. Porter, and S.E. Ford, 2004: Are diseases increasing in the ocean? *Annual Review of Ecology, Evolution, and Systematics,* **35,** 31-54. http://dx.doi.org/10.1146/annurev.ecolsys.35.021103.105704

115. Karvonen, A., P. Rintamäki, J. Jokela, and E.T. Valtonen, 2010: Increasing water temperature and disease risks in aquatic systems: Climate change increases the risk of some, but not all, diseases. *International Journal for Parasitology,* **40,** 1483-1488. http://dx.doi.org/10.1016/j.ijpara.2010.04.015

116. Bhaskaram, P., 2002: Micronutrient malnutrition, infection, and immunity: An overview. *Nutrition Reviews,* **60,** S40-S45. http://dx.doi.org/10.1301/00296640260130722

117. Ezzati, M., A.D. Lopez, A. Rodgers, S. Vander Hoorn, and C.J.L. Murray, 2002: Selected major risk factors and global and regional burden of disease. *The Lancet,* **360,** 1347-1360. http://dx.doi.org/10.1016/s0140-6736(02)11403-6

118. Kennedy, G., G. Nantel, and P. Shetty, 2003: The scourge of "hidden hunger": Global dimensions of micronutrient deficiencies. *Food Nutrition and Agriculture* **32,** 8-16. ftp://193.43.36.93/docrep/fao/005/y8346m/y8346m01.pdf

119. Kaidar-Person, O., B. Person, S. Szomstein, and R.J. Rosenthal, 2008: Nutritional deficiencies in morbidly obese patients: A new form of malnutrition? *Obesity Surgery,* **18,** 1028-1034. http://dx.doi.org/10.1007/s11695-007-9350-5

120. Stein, A.J., 2010: Global impacts of human mineral malnutrition. *Plant and Soil,* **335,** 133-154. http://dx.doi.org/10.1007/s11104-009-0228-2

121. Gibson, R.S., 2012: Zinc deficiency and human health: Etiology, health consequences, and future solutions. *Plant and Soil,* **361,** 291-299. http://dx.doi.org/10.1007/s11104-012-1209-4

122. Fulgoni, V.L., D.R. Keast, R.L. Bailey, and J. Dwyer, 2011: Foods, fortificants, and supplements: Where do Americans get their nutrients? *Journal of Nutrition,* **141,** 1847-1854. http://dx.doi.org/10.3945/jn.111.142257

123. Song, Y., S.W. Leonard, M.G. Traber, and E. Ho, 2009: Zinc deficiency affects DNA damage, oxidative stress, antioxidant defenses, and DNA repair in rats. *Journal of Nutrition,* **139,** 1626-1631. http://dx.doi.org/10.3945/jn.109.106369

124. Flancbaum, L., S. Belsley, V. Drake, T. Colarusso, and E. Tayler, 2006: Preoperative nutritional status of patients undergoing Roux-en-Y gastric bypass for morbid obesity. *Journal of Gastrointestinal Surgery,* **10,** 1033-1037. http://dx.doi.org/10.1016/j.gassur.2006.03.004

125. Kimmons, J.E., H.M. Blanck, B.C. Tohill, J. Zhang, and L.K. Khan, 2006: Associations between body mass index and the prevalence of low micronutrient levels among US adults. *Medscape General Medicine,* **8,** 59. PMC1868363

126. Lopez-Ridaura, R., W.C. Willett, E.B. Rimm, S. Liu, M.J. Stampfer, J.E. Manson, and F.B. Hu, 2004: Magnesium intake and risk of type 2 diabetes in men and women. *Diabetes Care,* **27,** 134-140. http://dx.doi.org/10.2337/diacare.27.1.134

127. Conroy, J.P., 1992: Influence of elevated atmospheric CO_2 concentrations on plant nutrition. *Australian Journal of Botany,* **40,** 445-456. http://dx.doi.org/10.1071/bt9920445

128. Manderscheid, R., J. Bender, H.J. Jäger, and H.J. Weigel, 1995: Effects of season long CO_2 enrichment on cereals. II. Nutrient concentrations and grain quality. *Agriculture, Ecosystems & Environment,* **54,** 175-185. http://dx.doi.org/10.1016/0167-8809(95)00602-o

129. Ziska, L.H., C.F. Morris, and E.W. Goins, 2004: Quantitative and qualitative evaluation of selected wheat varieties released since 1903 to increasing atmospheric carbon dioxide: Can yield sensitivity to carbon dioxide be a factor in wheat performance? *Global Change Biology,* **10,** 1810-1819. http://dx.doi.org/10.1111/j.1365-2486.2004.00840.x

130. Högy, P. and A. Fangmeier, 2008: Effects of elevated atmospheric CO_2 on grain quality of wheat. *Journal of Cereal Science,* **48,** 580-591. http://dx.doi.org/10.1016/j.jcs.2008.01.006

131. Högy, P. and A. Fangmeier, 2009: Atmospheric CO_2 enrichment affects potatoes: 2. Tuber quality traits. *European Journal of Agronomy,* **30,** 85-94. http://dx.doi.org/10.1016/j.eja.2008.07.006

132. Fernando, N., J. Panozzo, M. Tausz, R.M. Norton, N. Neumann, G.J. Fitzgerald, and S. Seneweera, 2014: Elevated CO_2 alters grain quality of two bread wheat cultivars grown under different environmental conditions. *Agriculture, Ecosystems & Environment,* **185,** 24-33. http://dx.doi.org/10.1016/j.agee.2013.11.023

133. Loladze, I., 2002: Rising atmospheric CO_2 and human nutrition: Toward globally imbalanced plant stoichiometry? *Trends in Ecology & Evolution,* **17,** 457-461. http://dx.doi.org/10.1016/s0169-5347(02)02587-9

134. Taub, D.R., B. Miller, and H. Allen, 2008: Effects of elevated CO_2 on the protein concentration of food crops: A meta-analysis. *Global Change Biology,* **14,** 565-575. http://dx.doi.org/10.1111/j.1365-2486.2007.01511.x

135. Myers, S.S., A. Zanobetti, I. Kloog, P. Huybers, A.D.B. Leakey, A.J. Bloom, E. Carlisle, L.H. Dietterich, G. Fitzgerald, T. Hasegawa, N.M. Holbrook, R.L. Nelson, M.J. Ottman, V. Raboy, H. Sakai, K.A. Sartor, J. Schwartz, S. Seneweera, M. Tausz, and Y. Usui, 2014: Increasing CO_2 threatens human nutrition. *Nature,* **510,** 139-142. http://dx.doi.org/10.1038/nature13179

136. Raubenheimer, D., G.E. Machovsky-Capuska, A.K. Gosby, and S. Simpson, 2014: Nutritional ecology of obesity: From humans to companion animals. *British Journal of Nutrition,* **113,** S26-S39. http://dx.doi.org/10.1017/s0007114514002323

137. Jablonski, L.M., X. Wang, and P.S. Curtis, 2002: Plant reproduction under elevated CO_2 conditions: A meta-analysis of reports on 79 crop and wild species. *New Phytologist,* **156,** 9-26. http://dx.doi.org/10.1046/j.1469-8137.2002.00494.x

138. Tans, P. and R. Keeling, 2012: Trends in Atmospheric Carbon Dioxide, Full Mauna Loa CO_2 Record. NOAA Earth System Research Laboratory. http://www.esrl.noaa.gov/gmd/ccgg/trends/

139. Cotrufo, M.F., P. Ineson, and A. Scott, 1998: Elevated CO2 reduces the nitrogen concentration of plant tissues. *Global Change Biology,* **4,** 43-54. http://dx.doi.org/10.1046/j.1365-2486.1998.00101.x

140. Taub, D.R. and X. Wang, 2008: Why are nitrogen concentrations in plant tissues lower under elevated CO_2? A critical examination of the hypotheses. *Journal of Integrative Plant Biology,* **50,** 1365-1374. http://dx.doi.org/10.1111/j.1744-7909.2008.00754.x

141. Layman, D.K., R.A. Boileau, D.J. Erickson, J.E. Painter, H. Shiue, C. Sather, and D.D. Christou, 2003: A reduced ratio of dietary carbohydrate to protein improves body composition and blood lipid profiles during weight loss in adult women. *Journal of Nutrition,* **133,** 411-417. http://jn.nutrition.org/content/133/2/411.full.pdf+html

142. Krieger, J.W., H.S. Sitren, M.J. Daniels, and B. Langkamp-Henken, 2006: Effects of variation in protein and carbohydrate intake on body mass and composition during energy restriction: A meta-regression. *The American Journal of Clinical Nutrition,* **83,** 260-274. http://ajcn.nutrition.org/content/83/2/260.long

143. Ebbeling, C.B., J.F. Swain, H.A. Feldman, W.W. Wong, D.L. Hachey, E. Garcia-Lago, and D.S. Ludwig, 2012: Effects of dietary composition on energy expenditure during weight-loss maintenance. *JAMA - Journal of the American Medical Association,* **307,** 2627-2634. http://dx.doi.org/10.1001/jama.2012.6607

144. Grifferty, A. and S. Barrington, 2000: Zinc uptake by young wheat plants under two transpiration regimes. *Journal of Environment Quality,* **29,** 443-446. http://dx.doi.org/10.2134/jeq2000.00472425002900020011x

145. McGrath, J.M. and D.B. Lobell, 2013: Reduction of transpiration and altered nutrient allocation contribute to nutrient decline of crops grown in elevated CO_2 concentrations. *Plant, Cell & Environment,* **36,** 697-705. http://dx.doi.org/10.1111/pce.12007

146. Ericksen, P.J., 2008: Conceptualizing food systems for global environmental change research. *Global Environmental Change,* **18,** 234-245. http://dx.doi.org/10.1016/j.gloenvcha.2007.09.002

147. Koetse, M.J. and P. Rietveld, 2009: The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D: Transport and Environment,* **14,** 205-221. http://dx.doi.org/10.1016/j.trd.2008.12.004

148. Koetse, M.J. and P. Rietveld, 2012: Adaptation to climate change in the transport sector. *Transport Reviews,* **32,** 267-286. http://dx.doi.org/10.1080/01441647.2012.657716

149. Zhang, Y. and A. Erera, 2012: Consequence assessment for complex food transportation systems facing catastrophic disruptions. *Homeland Security Affairs,* **4**. http://hdl.handle.net/10945/25011

150. McGuirk, M., S. Shuford, T.C. Peterson, and P. Pisano, 2009: Weather and climate change implications for surface transportation in the USA. *WMO Bulletin,* **58,** 84-93. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.459.696&rep=rep1&type=pdf

151. USDA, 2005: Grain Transportation Report, November 17, 2005. 20 pp. U.S. Department of Agriculture, Transportation Services Branch. http://apps.ams.usda.gov/SearchReports/Documents/steldev3100982.pdf

152. IPCC, 2007: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (Eds.), 976 pp. Cambridge University Press, Cambridge, UK. https://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4_wg2_full_report.pdf

153. Blake, E.S., T.B. Kimberlain, R.J. Berg, J.P. Cangialosi, and J.L. Beven, II, 2013: Tropical Cyclone Report: Hurricane Sandy (AL182012), 22-29 October 2012. 157 pp. National Hurricane Center. http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf

154. CCSP, 2008: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Study, Phase I. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Savonis, M.J., V.R. Burkett, and J.R. Potter (Eds.), 445 pp. U.S. Department of Transportation, Washington, D.C. http://downloads.globalchange.gov/sap/sap4-7/sap4-7-final-all.pdf

155. NOAA, 2014: Storm Surge Overview. National Oceanic and Atmospheric Administration, National Weather Service, National Hurricane Center, Miami, FL. http://www.nhc.noaa.gov/surge/

156. Lal, R., J.A. Delgado, J. Gulliford, D. Nielsen, C.W. Rice, and R.S. Van Pelt, 2012: Adapting agriculture to drought and extreme events. *Journal of Soil and Water Conservation,* **67,** 162A-166A. http://dx.doi.org/10.2489/jswc.67.6.162A

157. DOE, 2012: Electric Disturbance Events (OE-417). U.S. Department of Energy, Office of Electricity Delivery & Energy Reliability, Washington, D.C. http://www.oe.netl.doe.gov/oe417.aspx

158. Marx, M.A., C.V. Rodriguez, J. Greenko, D. Das, R. Heffernan, A.M. Karpati, F. Mostashari, S. Balter, M. Layton, and D. Weiss, 2006: Diarrheal illness detected through syndromic surveillance after a massive power outage: New York City, August 2003. *American Journal of Public Health,* **96,** 547-553. http://dx.doi.org/10.2105/ajph.2004.061358

159. NOAA, 2012: NCDC Announces Warmest Year on Record for Contiguous U.S. National Oceanic and Atmospheric Administration, National Centers for Environmental Information. http://www.ncdc.noaa.gov/news/ncdc-announces-warmest-year-record-contiguous-us

160. USDA, 2013: U.S. Drought 2012: Farm and Food Impacts. United States Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/topics/in-the-news/us-drought-2012-farm-and-food-impacts.aspx#.UgzjpG3W5AA

161. Olson, K.R. and L.W. Morton, 2014: Dredging of the fractured bedrock-lined Mississippi River Channel at Thebes, Illinois. *Journal of Soil and Water Conservation,* **69,** 31A-35A. http://dx.doi.org/10.2489/jswc.69.2.31A

162. AWO, 2015: Jobs and Economy: Industry Facts. American Waterways Operators, Arlington, VA. http://americanwaterways.com/initiatives/jobs-economy/industry-facts

163. Schmidhuber, J. and F.N. Tubiello, 2007: Global food security under climate change. *Proceedings of the National Academy of Sciences,* **104,** 19703-19708. http://dx.doi.org/10.1073/pnas.0701976104

164. CDC, 2014: *E. coli* Infection and Food Safety. Centers for Disease Control and Prevention, Atlanta, GA. http://www.cdc.gov/features/ecoliinfection/

165. Tarr, P.I., C.A. Gordon, and W.L. Chandler, 2005: Shiga-toxin-producing *Escherichia coli* and haemolytic uraemic syndrome. *The Lancet,* **365,** 19-25. http://dx.doi.org/10.1016/S0140-6736(05)71144-2

166. Wong, C.S., J.C. Mooney, J.R. Brandt, A.O. Staples, S. Jelacic, D.R. Boster, S.L. Watkins, and P.I. Tarr, 2012: Risk factors for the hemolytic uremic syndrome in children infected with *Escherichia coli* O157:H7: A multivariate analysis. *Clinical Infectious Diseases,* **55,** 33-41. http://dx.doi.org/10.1093/cid/cis299

167. Forman, J., J. Silverstein, Committee on Nutrition, and Council on Environmental Health, 2012: Organic foods: Health and environmental advantages and disadvantages. *Pediatrics,* **130,** e1406-e1415. http://dx.doi.org/10.1542/peds.2012-2579

168. Eskenazi, B., L.G. Rosas, A.R. Marks, A. Bradman, K. Harley, N. Holland, C. Johnson, L. Fenster, and D.B. Barr, 2008: Pesticide toxicity and the developing brain. *Basic & Clinical Pharmacology & Toxicology,* **102,** 228-236. http://dx.doi.org/10.1111/j.1742-7843.2007.00171.x

169. Hendrickson, D., C. Smith, and N. Eikenberry, 2006: Fruit and vegetable access in four low-income food deserts communities in Minnesota. *Agriculture and Human Values,* **23,** 371-383. http://dx.doi.org/10.1007/s10460-006-9002-8

170. Furey, S., C. Strugnell, and H. McIlveen, 2001: An investigation of the potential existence of "food deserts" in rural and urban areas of Northern Ireland. *Agriculture and Human Values,* **18,** 447-457. http://dx.doi.org/10.1023/a:1015218502547

171. Bennett, T.M.B., N.G. Maynard, P. Cochran, R. Gough, K. Lynn, J. Maldonado, G. Voggesser, S. Wotkyns, and K. Cozzetto, 2014: Ch. 12: Indigenous Peoples, Lands, and Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 297-317. http://dx.doi.org/10.7930/J09G5JR1

172. Schneider Chafen, J.J., S.J. Newberry, M.A. Riedl, D.M. Bravata, M. Maglione, M.J. Suttorp, V. Sundaram, N.M. Paige, A. Towfigh, B.J. Hulley, and P.G. Shekelle, 2010: Diagnosing and managing common food allergies: A systematic review. *JAMA - Journal of the American Medical Association,* **303,** 1848-1856. http://dx.doi.org/10.1001/jama.2010.582

173. Branum, A.M. and S.L. Lukacs, 2008: Food Allergy Among U.S. Children: Trends in Prevalence and Hospitalizations. NCHS Data Brief No. 10, October 2008, 8 pp. National Center for Health Statistics, Hyattsville, MD. http://www.cdc.gov/nchs/data/databriefs/db10.pdf

174. Singer, B.D., L.H. Ziska, D.A. Frenz, D.E. Gebhard, and J.G. Straka, 2005: Increasing Amb a 1 content in common ragweed *(Ambrosia artemisiifolia*) pollen as a function of rising atmospheric CO_2 concentration. *Functional Plant Biology,* **32,** 667-670. http://dx.doi.org/10.1071/fp05039

175. Beggs, P.J., 2004: Impacts of climate change on aeroallergens: Past and future. *Clinical & Experimental Allergy,* **34,** 1507-1513. http://dx.doi.org/10.1111/j.1365-2222.2004.02061.x

176. Welch, A.H., D.B. Westjohn, D.R. Helsel, and R.B. Wanty, 2000: Arsenic in ground water of the United States: Occurrence and geochemistry. *Ground Water,* **38,** 589-604. http://dx.doi.org/10.1111/j.1745-6584.2000.tb00251.x

177. Appleyard, S.J., J. Angeloni, and R. Watkins, 2006: Arsenic-rich groundwater in an urban area experiencing drought and increasing population density, Perth, Australia. *Applied Geochemistry,* **21,** 83-97. http://dx.doi.org/10.1016/j.apgeochem.2005.09.008

178. Levin, R.B., P.R. Epstein, T.E. Ford, W. Harrington, E. Olson, and E.G. Reichard, 2002: U.S. drinking water challenges in the twenty-first century. *Environmental Health Perspectives,* **110,** 43-52. PMC1241146

179. Soto-Arias, J.P., R. Groves, and J.D. Barak, 2013: Interaction of phytophagous insects with *Salmonella enterica* on plants and enhanced persistence of the pathogen with *Macrosteles quadrilineatus* infestation or *Frankliniella occidentalis* feeding. *PLoS ONE,* **8,** e79404. http://dx.doi.org/10.1371/journal.pone.0079404

180. Kopanic, R.J., B.W. Sheldon, and C. Wright, 1994: Cockroaches as vectors of Salmonella: Laboratory and field trials. *Journal of Food Protection,* **57,** 125-131.

181. Soto-Arias, J.P., R.L. Groves, and J.D. Barak, 2014: Transmission and retention of *Salmonella enterica* by phytophagous hemipteran insects. *Applied and Environmental Microbiology,* **80,** 5447-5456. http://dx.doi.org/10.1128/aem.01444-14

182. Rose, J.B. and F. Wu, 2015: Waterborne and foodborne diseases. *Climate Change and Public Health*. Levy, B. and J. Patz, Eds. Oxford University Press, Oxford, UK, 157-172. http://dx.doi.org/10.1093/med/9780190202453.003.0008

183. Ahmed, S.M., B.A. Lopman, and K. Levy, 2013: A systematic review and meta-analysis of the global seasonality of norovirus. *PLoS ONE,* **8,** e75922. http://dx.doi.org/10.1371/journal.pone.0075922

184. Meinshausen, M., S.J. Smith, K. Calvin, J.S. Daniel, M.L.T. Kainuma, J.-F. Lamarque, K. Matsumoto, S.A. Montzka, S.C.B. Raper, K. Riahi, A. Thomson, G.J.M. Velders, and D.P.P. van Vuuren, 2011: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change,* **109,** 213-241. http://dx.doi.org/10.1007/s10584-011-0156-z

185. USGS, 2015: USGS Water Resources: 07010000 Mississippi River at St. Louis, MO. National Water Information System, United States Geological Survey. http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=07010000