CLIMATE CHANGE GLOBAL FOOD SECURITY AND THE U.S. FOOD SYSTEM

U.S. GLOBAL CHANGE RESEARCH PROGRAM

Climate Change, Global Food Security, and the U.S. Food System

December 2015

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Additional Technical Contributors: Mamta Chaudhari (GWU), Shannon Mesenhowski (USAID), Micah Rosenblum (USDA FAS), Isabel Walls (USDA NIFA), and Keith Wiebe (IFPRI)

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Dear Colleagues:

On behalf of the National Science and Technology Council and the U.S. Global Change Research Program, we are pleased to transmit to you the *Climate Change, Global Food Security, and the U.S. Food System* assessment report. This state-of-the-science assessment establishes the technical foundation for managing food security outcomes around the world and for preparing consumers, agricultural producers, and others in the United States for changing conditions.

This report, in response to the President's Climate Action Plan, integrates research from the biophysical and the social sciences, across multiple sectors, to evaluate climate-driven changes in global food security and analyze the U.S. role in food security in a changing world.

The result of a three-year effort led by the U.S. Department of Agriculture, this study brought together over thirty experts at nineteen institutions in four countries. The authors drew on information gathered in stakeholder workshops and public commentary, as well as on analysis by technical experts within the Federal government.

We would like to thank the authors, reviewers, and staff who prepared this report, and the stakeholders and members of the public whose comments ensured its usefulness and applicability.

Food security represents one of humanity's most urgent and important challenges. The science in this report provides a particularly useful tool in meeting that challenge.

Sincerely,

John P. Holdren
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy
Executive Office of the President

Thomas J. Vilsack
Secretary
U.S. Department of Agriculture

Climate Change, Global Food Security, and the U.S. Food System

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Acknowledgments

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Report in Brief

Food security—the ability to obtain and use sufficient amounts of safe and nutritious food—is a fundamental human need. Climate change is very likely to affect global, regional, and local food security by disrupting food availability, decreasing access to food, and making food utilization more difficult.

Food security exists "when all people at all times have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life" and affects people through both under- and overconsumption. Food security requires that food be simultaneously (1) *available*—that it exist in a particular place at a particular time, (2) that people can *access* that food through economic or other means, (3) that people can *utilize* the food that is available and accessible to them, and (4) that each of these components be *stable* over time. Constrictions within any of these components can result in food insecurity.

Food is provisioned through a food system that manifests in diverse ways across the globe. The food system includes all activities related to producing, transporting, trading, storing, processing, packaging, wholesaling, retailing, consuming, and disposing of food. Whether an individual food system includes few, many, or all of these elements, each is susceptible to risks from a changing climate.

Human activities, such as burning fossil fuels and deforestation, have increased global greenhouse gas concentrations; atmospheric carbon dioxide levels have risen from 280 parts per million (ppm) in the late 1700s to today's level of about 400 ppm. Concentrations continue to rise, though future levels depend on choices and development pathways yet to be determined. Additionally, the future condition of the food system depends upon socioeconomic trajectories that are external to the food system itself. For these reasons, a range of possible emissions futures and socioeconomic pathways have been considered by this assessment.

The *Climate Change, Global Food Security, and U.S. Food System* assessment represents a consensus of authors and includes contributors from 19 Federal, academic, nongovernmental, and intergovernmental organizations in four countries, identifying climate-change effects on global food security through 2100, and analyzing the United States' likely connections with that world.

The assessment finds that climate change is likely to diminish continued progress on global food security through production disruptions leading to local availability limitations and price increases, interrupted transport conduits, and diminished food safety, among other causes. The risks are greatest for the global poor and in tropical regions. In the near term, some high-latitude production export regions may benefit from changes in climate.

As part of a highly integrated global food system, consumers and producers in the United States are likely to be affected by these changes. The type and price of food imports from other regions are likely to change, as are export demands placed upon U.S. producers and the transportation, processing, and storage systems that enable global trade. Demand for food and other types of assistance may increase, as may demand for advanced technologies to manage changing conditions.

Adaptation across the food system has great potential to manage climate-change effects on food security, and the complexity of the food system offers multiple potential points of intervention for decision makers at every level, from households to nations and international governance structures. However, effective adaptation is subject to highly localized conditions and socioeconomic factors, and the technical feasibility of an adaptive intervention is not necessarily a guarantee of its application if it is unaffordable or does not provide benefits within a relatively short time frame, particularly for smaller operations around the world with limited capacity for long-term investments. The accurate identification of needs and vulnerabilities, and the effective targeting of adaptive practices and technologies across the full scope of the food system, are central to improving global food security in a changing climate.

Climate Change, Global Food Security, and the U.S. Food System

Executive Summary

Food security—the ability to obtain and use sufficient amounts of safe and nutritious food—is a fundamental human need. Achieving food security for all people everywhere is a widely agreed upon international objective, most recently codified in the United Nations Sustainable Development Goals for 2030. This report describes the potential effects of climate change on global food security and examines the implications of these effects for the United States.

Food-security challenges are widely distributed, afflicting urban and rural populations in wealthy and poor nations alike. Food-security challenges are particularly acute for the very young, because early-life undernutrition results in measurably detrimental and lifelong health and economic consequences. Food insecurity affects people through both under- and overconsumption. Much of the scientific literature to date addresses the former issue, though the latter is now receiving more attention. For an individual, food insecurity may manifest as a reduced capacity to perform physically, diminished mental health and development, and an increased risk of chronic disease. Collectively, food insecurity diminishes global economic productivity by 2%–3% annually (USD 1.4–2.1 trillion), with individual country costs estimated at up to 10% of country GDP.

The last several decades have seen significant progress in overcoming the obstacles of population growth, food waste, inefficient distribution, and ineffective social-safety nets to improve global food security. There are currently about 805 million people, or 11% of the global population, who are undernourished according to the Food and Agriculture Organization of the United Nations, down from about 1.01 billion, or 19%, in 1990–1992. At least 2 billion people currently receive insufficient nutrition. The fundamental issue addressed by the *Climate Change, Global Food Security, and the U.S. Food System* assessment is whether progress can be maintained in the face of a changing climate.

Relationships between climate and agriculture are well documented. Agricultural production is governed in large part by climate conditions and is a central consideration for food availability. It is less widely appreciated that climate conditions also affect access to food, its utilization, and the overall stability of each. These effects occur through climate's influence on global food-system activities, including food processing, packaging, transportation, storage, waste, and consumption (Figure ES-1).

Climate change is a long-term trend in the state of the climate, usually described as changes in the average and/or variability of properties such as temperature and precipitation. Since 1750, rapidly growing human-induced emissions of greenhouse gases have caused increases in global average temperatures, changes in precipitation timing and intensity, rising sea levels, and many other changes, including direct physiological effects of changing greenhouse-gas concentrations on crop development. This report considers how all of these changes are affecting global food systems and food security.

Table ES-1: The Components of Food Security. *For food security to be achieved, all four components must be attained and maintained, simultaneously. Each is sensitive to climate change.*

Component	Definition
Availability	The existence of food in a particular place at a particular time.
Access	The ability of a person or group to obtain food.
Utilization	The ability to use and obtain nourishment from food. This includes a food's nutritional value and how the body assimilates its nutrients.
Stability	The absence of significant fluctuation in availability, access, and utilization.

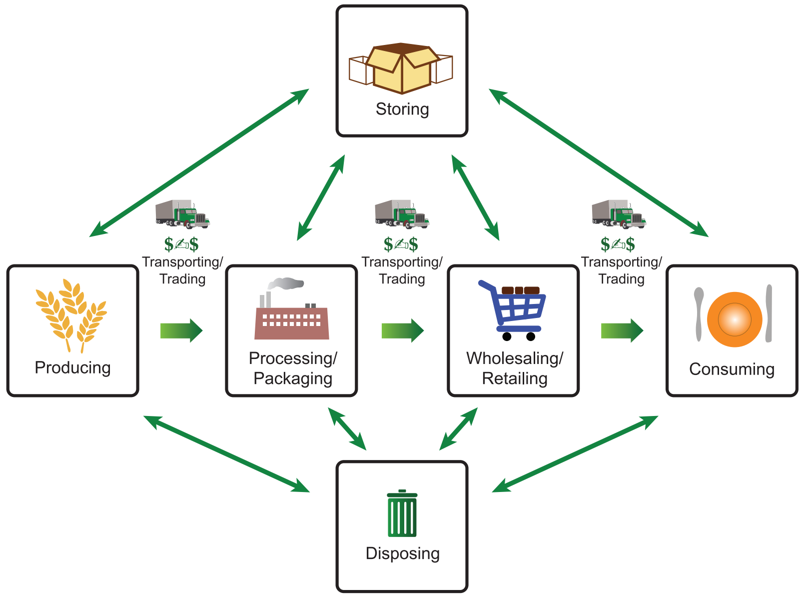

Figure ES- 1. Food-system activities and feedbacks. *Food-system activities include the production of raw food materials, transforming the raw material into retail products, marketing those products to buyers and product consumption. Food transportation, storage and waste disposal play a role in each of these activities.*

Many factors aside from climate change influence future food systems and food security. The most relevant include technological and structural changes in food production, processing, distribution, and markets; increasing population, demographic changes, and urbanization; changes in wealth; changes in eating habits and food preferences; disasters and disaster response; and changes in energy availability and use. Some of these amplify the effects of climate change and increase the risks to food security (e.g., population growth), while others appear likely to diminish risk and to help offset damaging climate-change impacts (e.g., increasing levels of wealth).

Food security, food systems, and climate change are each multifaceted topics. Their interactions are likewise complex and are affected by a wide range of environmental and socioeconomic factors. It is nevertheless clear that there are multiple connections between changing climate conditions and food systems and that climate change affects food systems in ways that alter food-security outcomes.

Report Findings

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. Climate change is projected to result in more frequent disruption of food production in many regions and in increased overall food prices. Climate risks to food security are greatest for poor populations and in tropical regions. Wealthy populations and temperate regions that are not close to limiting thresholds for food availability, access, utilization, or stability are less at risk. Some high-latitude regions may actually experience near-term productivity increases due to high adaptive capacity, CO_2 fertilization, higher temperatures, and precipitation increases. However, damaging outcomes become increasingly likely in all cases from 2050–2100 under higher emissions scenarios.

The potential of climate change to affect global food security is important for food producers and consumers in the United States. The United States is part of a highly integrated global food system: climate-driven changes in the United States influence other nations, and changes elsewhere influence the United States. The United States appears likely to experience changes in the types and cost of foods available for import. The United States is similarly likely to experience increased demand for agricultural exports from regions that experience production difficulties yet have sufficient wealth to purchase imports; the United States is likely to be able to meet increased export demand in the near term. Demand for food and other types of assistance from the United States could increase in nations that lack purchasing power. In the longer term and for higher-emissions scenarios, increased water stress associated with climate change could diminish the export of “virtual water” (the water that is embodied throughout the entire production process of a traded commodity) in agricultural commodities. Climate change is likely to increase demand from developing nations with relatively low per-hectare yields for

advanced technologies and practices, many of which were developed in the United States.

Climate change risks extend beyond agricultural production to other elements of global food systems that are critical for food security, including the processing, storage, transportation, and consumption of food. Production is affected by temperature increases; changes in the amount, timing, and intensity of precipitation; and reduced availability of water in dry areas. Processing, packaging, and storage are very likely to be affected by temperature increases that could increase costs and spoilage. Temperature increases could also make utilization more difficult by increasing food-safety risks. Sea-level rise and precipitation changes alter river and lake levels, and extreme heat can impede waterborne, railway, and road transportation. Constraints in one component of food security may sometimes be compensated through another—for example, food insecurity may be avoided when production decreases *(availability)* are substituted with food acquired through purchase *(access)*. Alternatively, constrictions at one point within the food system may be so severe, or have no feasible alternative possibilities within a local context, that food security may be compromised. As a consequence of these interactions and dependencies, a systems-based approach is needed to understand the implications of climate change on food security.

Climate risks to food security increase as the magnitude and rate of climate change increase. Higher emissions and concentrations of greenhouse gases are much more likely to have damaging effects than lower emissions and concentrations. Worst-case projections based on high greenhouse-gas (GHG) concentrations (~850 ppm), high population growth, and low economic growth imply that the number of people at risk of undernourishment would increase by as much as 175 million above today's level by 2080. The same socioeconomic conditions with GHG concentrations of about 550 ppm result in up to 60 million additional people at risk, while concentrations of about 350 ppm—less than today's level—do not increase risk. Scenarios with lower population growth and more robust economic growth result in large reductions in the number of food-insecure people compared to today, even when climate change is included, but higher emissions still result in more food insecurity than lower emissions.

Effective adaptation can reduce food-system vulnerability to climate change and reduce detrimental climate-change effects on food security, but socioeconomic conditions can impede the adoption of technically feasible adaptation options. The agricultural sector has a strong record of adapting to changing conditions. There are still many opportunities to bring more advanced methods to low-yield agricultural regions, but water and nutrient availability may be limiting in some areas, as is the ability to finance expensive technologies. Other promising adaptations include innovative packaging and expanded cold storage that lengthen shelf life, improvement and expansion of transportation infrastructure to move food more rapidly to markets, and changes in cooking methods, diets, and purchasing practices.

The complexity of the food system within the context of climate change allows for the identification of multiple food-security intervention points, which are relevant to decision makers at every level. The future need for, and cost of, adaptation is lower under lower-emissions scenarios. Trade decisions could help to avoid large-scale price shocks and maintain food availability in the face of regional production difficulties such as drought. Improved transportation systems help to reduce food waste and enable participation in agricultural markets. Public- and private-sector investments in agricultural research and development, coupled with rapid deployment of new techniques, can help to ensure continued innovation in the agricultural sector. Refined storage and packaging techniques and materials could keep foods safer for longer and allow for longer-term food storage where refrigeration is absent and food availability is transient.

Accurately projecting climate-change risks to food security requires consideration of other large-scale changes. Ecosystem and land degradation, technological development, population growth, and economic growth affect climate risks and food security outcomes. Population growth, which is projected to add another 2 billion people to Earth's population by 2050, increases the magnitude of the risk, particularly when coupled with economic growth that leads to changes in the types of foods demanded by consumers. Sustained economic growth can help to reduce vulnerability if it reduces the number of poor people and if income growth exceeds increases in food costs in vulnerable populations. Analyses based on scenarios of sustained economic growth and moderate population growth without climate change suggest that the number of food-insecure people could be reduced by 50% or more by 2040, with further reductions over the rest of the century. Such analyses should not be misinterpreted as projections, since climate change is already occurring, but they clearly indicate that socioeconomic factors have large effects on food insecurity.

Report Background and Scope

This report is a consensus-based assessment developed by a team of technical experts and based on the peer-reviewed scientific literature. The report supports the National Climate Assessment activities of the U.S. Global Change Research Program. This report represents a consensus of authors and contributors from 19 Federal, academic, nongovernmental, and intergovernmental organizations in four countries, identifying climate-change effects on global food security through 2100, and analyzing the United States' likely connections with that issue.

Climate Change, Global Food Security, and the U.S. Food System is a technical, scientific, and economic analysis of climate-change effects on global food security and food systems. The report's scope is global, due to the interdependencies within and among food systems and the shifting geography of food supplies and demands. Policy recommendations are outside the scope of this report. Discussion of the secondary effects of changes in food security upon other sectors (e.g., human health, national security) is outside the scope of this report. Domestic U.S. food security has been detailed elsewhere and is not the topic of this report. This assessment considers anticipated changes 25 and 100 years into the future to the degree supported by the available literature or through explicit inference based on information established by the scientific record.

Scenarios and Projections of Climate and Socioeconomic Changes

Vast observational evidence demonstrates that human activities, such as burning fossil fuels and deforestation, have increased global greenhouse-gas concentrations; atmospheric carbon dioxide levels increased from 280 ppm in the late 1700s to today's level of about 400 ppm. This has, in turn, increased global average temperature by about 0.8 °C since 1900.

Scenarios and Projections of Climate Change

In order to investigate how climate might change in the future, scientists use different levels of greenhouse-gas emissions as inputs to earth-system modeling experiments that project future climate conditions. The most recent set of inputs, called Representative Concentration Pathways (RCPs), was developed through the Coupled Model Intercomparison Project (CMIP) for use in climate modeling experiments and assessment efforts, such as those conducted by the Intergovernmental Panel on Climate Change (IPCC). The RCPs are the basis for the climate projections in the recent 5th Assessment Report of the IPCC and are used in this document, except for occasional instances where we consider results based on previous widely used scenarios such as those developed in the IPCC Special Report on Emissions Scenarios (SRES). This report focuses primarily on the climate implications of two possible emissions futures.

- RCP 2.6 is a low-emissions scenario with extensive mitigation and a CO_2 concentration of about 421 ppm by 2100. This results in a global average temperature increase of about 1 °C by 2050, with no further change by 2100, and global average sea-level rise of about 0.17–0.32 m by mid-century and 0.26–0.55 m by late century. Referred to as "low emissions" in this report.
- RCP 8.5 is a high-emissions scenario, where emissions continue to increase rapidly, producing a CO_2 concentration of 936 ppm by 2100. This results in a global average temperature increase of about 2 °C by 2050 and 4 °C by 2100, and global average sea-level rise of about 0.22–0.38 m by mid-century (2046–2064) and 0.45–0.82 m by late century. Referred to as "high emissions" in this report.

The range of 0.26–0.82 m for late-century sea-level rise projected by the IPCC and used in this document is slightly less than the estimated range of 0.3–1.2 m by 2100 used by the latest U.S. National Climate Assessment.

There is considerable regional variability within these broad global averages. Figure ES-2a shows the global distribution of projected temperature changes in mid- and late-century for low and high emissions. Warming is greater at high latitudes and in continental interiors. Figure ES-2b shows the precipitation based on the same emissions and in the same time frames. In general, wet areas become wetter over time and dry areas drier. For both temperature and precipitation, the differences between scenarios become larger as time progresses.

Scenarios of Socioeconomic Change

One of the challenges of projecting the societal effects of various emissions scenarios is the complexity and rapid rate of societal change. As an illustration, from 1950 to today, global population increased from about 2.5 billion to over 7 billion and global GDP from about USD 5.3 trillion to USD 77.6 trillion. We know that future society and adaptive capacity will differ in many respects from today, but it is not yet possible to determine the relative likelihood of many possible societal changes. It

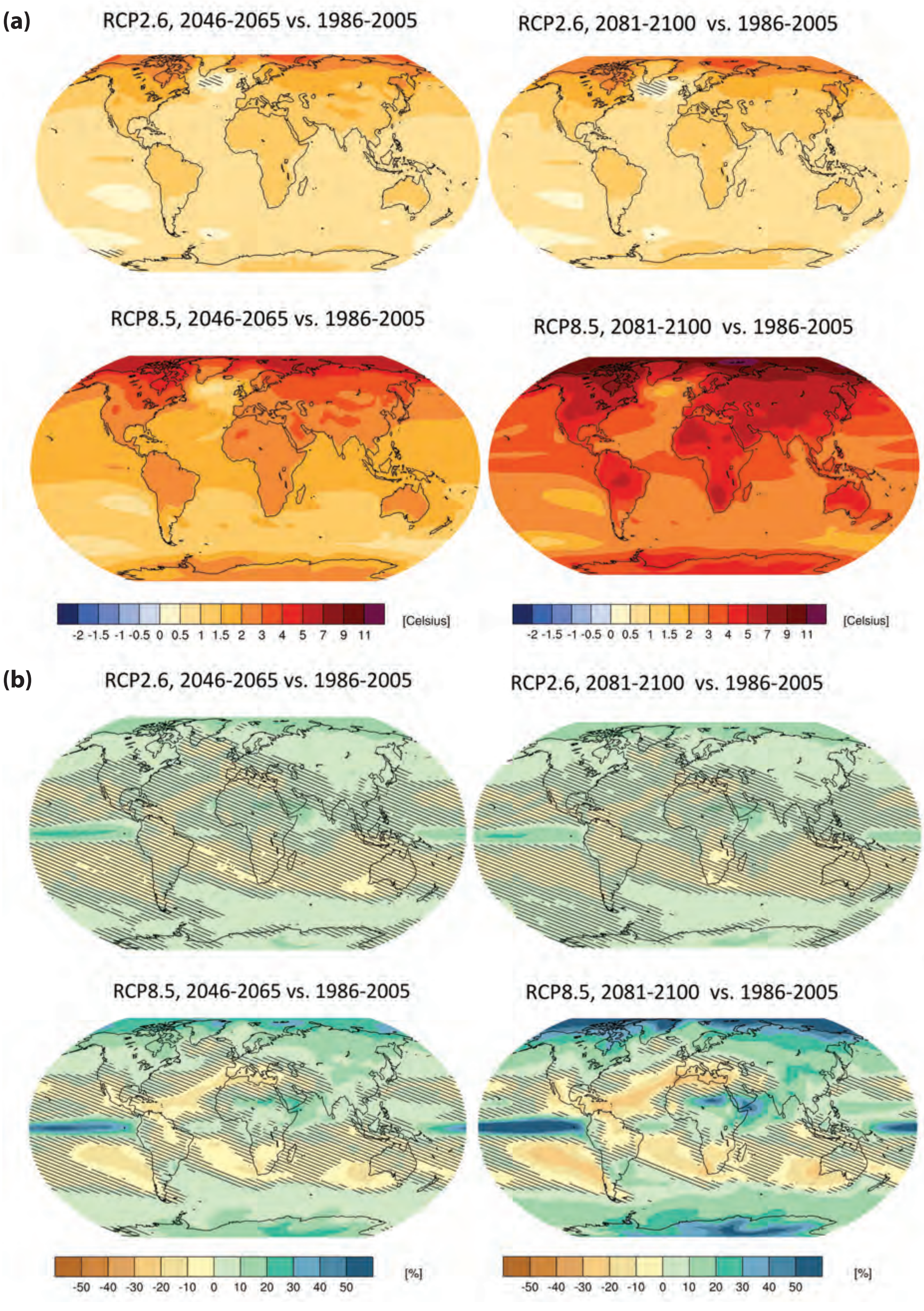

Figure ES- 2. Projected changes in global surface temperature (a) and precipitation (b). *Mid (left) and late (right) 21st century changes are compared with the period 1986 to 2005 for low emissions (RCP 2.6 – top) and high emissions (RCP 8.5 – bottom) scenarios. Multimodel ensemble-mean changes are shown, where gray dashes indicate areas for which changes have less than one standard deviation compared to natural variability. This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

is, however, possible to identify alternative sets of internally consistent future changes that could occur together. Scientists can then compare plausible future climates to plausible future societies and determine likely effects of different combinations.

The scientific community has developed new scenarios called Shared Socioeconomic Pathways (SSPs) to facilitate this work. The five SSPs are designed to span a range of societal conditions in two particular dimensions: (1) challenges to mitigation and (2) challenges to adaptation, defined by different combinations of socioeconomic elements. SSP1 assumes low challenges to mitigation and adaptation; SSP2 assumes medium challenges to both; SSP3 assumes high challenges to both; SSP4 assumes adaptation challenges dominate; and SSP5 assumes mitigation challenges dominate. Each SSP has a qualitative narrative that describes general trends in societal conditions and how and why these trends unfold together over time, along with quantitative projections of key elements; none is considered more or less likely than another.

Taken together, the set of RCPs and SSPs provides a basis for the scientific community to conduct systematic and comparable analyses of future vulnerability, risks, and effects of climate change in the context of other environmental and socioeconomic changes. Most of the integrated modeling results examined in this assessment used combinations of SSP1, SSP2, and SSP3 with RCP 2.6 and RCP 8.5. This report occasionally includes results based on the socioeconomic conditions in the SRES scenarios developed previously in the IPCC process. In some cases, SSPs are also used as a frame for qualitative assessment of likely future risks to food security.

Integrated Assessment Modeling of Agriculture and Food Systems

These studies use climate and socioeconomic scenarios like RCPs and SSPs to study how the food system responds to stresses and project climate-change effects. They do not usually produce direct calculations of food-security outcomes (i.e., numbers of undernourished people), but do provide insights about possible changes in food prices, consumption, and trade, in addition to changes in yield, cultivated area, and production.

Most assessments use a structure like that outlined in Figure ES-3, which links climate models, biophysical models of agricultural systems, and economic models. Such integrated assessments help explain food-system changes that affect food security. Outputs are too aggregated to assess all of the important food-security concerns related to food availability, access, utilization, and stability, but have been used for statistical calculation of childhood malnutrition and number of people at risk of hunger. More detailed data and models and additional model intercomparisons are needed to fully assess climate-change effects on all dimensions of food security at subnational, local, and household levels.

Results reviewed in this assessment show that climate-change effects on overall global food production are likely to be detrimental, particularly later in the century. Figure ES-4 shows recent global modeling results across three different scenarios for 2050. Yields are reduced, area in production has increased, prices are higher, and production and consumption are slightly reduced relative to a baseline projection for 2050 that does not include further climate change between now and then.

It is important to recognize that effects vary substantially by region due to differing biophysical and socioeconomic conditions that determine both the effects of climate change and the potential for adaptation. The most adverse effects are likely to be in the tropics and subtropics, and some near-term benefits are possible at higher latitudes, due to the combined effects of CO_2 fertilization, higher temperatures, precipitation increases, and stronger adaptive capacity.

Integrated assessment studies clearly show that technological, economic, and policy decisions each play a major role in the global food system and future

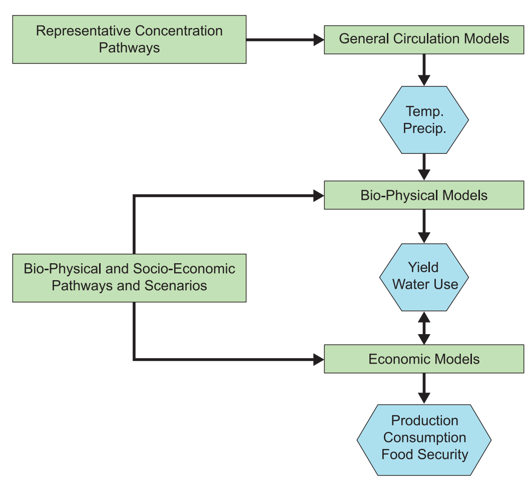

Figure ES-3. Framework for integrated agricultural and food system impact assessments. *Models of global economic and biophysical system, driven by climate-model outputs for different RCPs, are linked to assess outcomes under different future scenarios.*

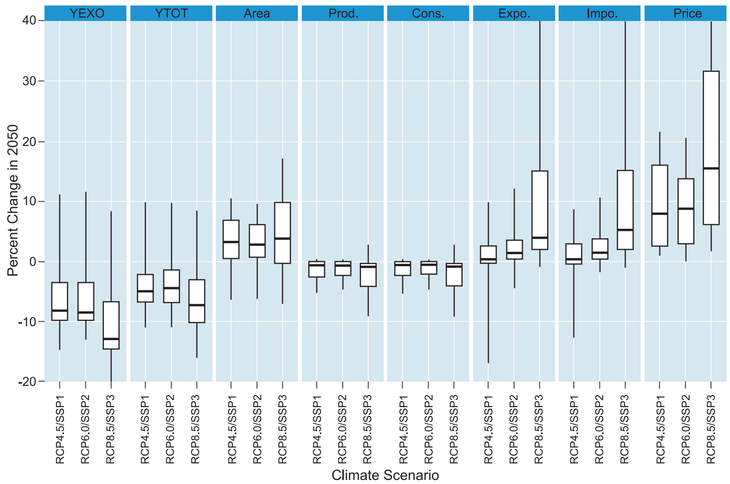

Figure ES-4. Climate-change effects on agricultural commodities in 2050 under different SSPs and RCPs. *The more pessimistic "high concentration/low international cooperation" scenario (RCP8.5/SSP3) shows much larger and more variable climate-change effects for the five commodities (coarse grains, rice, wheat, oilseeds and sugar), than the "medium concentration/middle of the road" (RCP6.0/SSP2) and "low concentration/sustainable development" (RCP4.5/SSP1) scenarios. All are compared to baseline of SSPs with no climate change. Results are from three GCMs and five economic models, aggregated across thirteen regions (n = 75). YEXO = yield effect of climate change without technical or economic adaptation, YTOT = realized yields after adaptation, AREA = agricultural area in production, PROD = total production, CONS = consumption, Expo = exports, IMPO = imports, PRICE = prices.*

global food security, demonstrating that climate assessments need to be made in the context of plausible future socioeconomic scenarios.

Many studies indicate that these technological and socioeconomic factors are likely to be more important to food security than climate change under low-to-medium emissions and concentration scenarios in the near term to mid-century. Under less-optimistic socioeconomic scenarios, higher-emissions scenarios, and longer time frames, climate effects are projected to be equal to or greater than the effects of socioeconomic change.

Food Availability and Stability

The first component of food security, *availability*, addresses the question of whether food exists locally. Where food is, or is not, is in part a function of production types, rates, and locations. Food production occurs through the cultivation of crops and livestock, fishing, and hunting outside of cultivated systems. Production forms the foundation of food availability, providing calories and nutrients for human consumption. The processing, packaging, and storage of food also contribute to food availability, as do trade and the transportation systems that enable it.

Climate change influences food availability and stability through each food-system activity. Climate can also interact with external stressors (e.g., conflict) and with the natural-resource base (e.g., soils) to alter the stability of food supplies. Increased risk can also result from agricultural expansion into less optimal lands in response to climate trends. The literature suggests that world food production needs to increase by 60%–100% to feed a larger, wealthier, and more urban global population.

Crop yields have increased globally by about 1.8% per year on average since 2000, while the area of per-capita–cultivated land has decreased by 9% over the same period, leading to an 8% increase in total per-capita global cereal production since 2000. Yield increases appear to be diminished by up to 2.5% per decade, globally, due to climate change. Local production is particularly important in the tropics, where crops' biophysical thresholds are already closer to their limitations and where higher temperatures are likely to result in diminished yields. In addition to the direct physical effects of temperature and precipitation changes, climate change influences the range and infestation intensity of crop pests and pathogens.

Livestock production provides a livelihood for over a billion people, including 600 million households in less-developed areas of the world, and contributes the equivalent of over USD 1 trillion to the global economy. Heat stress from higher temperatures diminishes food intake and physical activity for livestock, leading to lower growth, survival, and reproductive rates, as well as lower production of meat, milk, and eggs. Climate change also affects livestock indirectly through changes in the incidence of disease and pests, pasture and forage crop quality and quantity, and feed-grain production.

Fisheries, both cultivated and capture, as well as wild game, are important protein sources for large segments of the global population and are subject to multiple stressors that affect food availability, stability, and incomes (food access). Current methodological techniques cannot distinguish the importance of climate change relative to other influences upon food supplies from fisheries and wild game.

Processing, packaging, storing, trading, and transporting food are frequently prerequisites for food to reach its ultimate consumers. The influence of climate change on which crops are grown where in the world affects the location of storage, processing, and packaging facilities, as well as that of the underlying transportation infrastructure for moving food from producer to consumers or to trade hubs. Higher temperatures require more postharvest cooling for fresh fruits and vegetables, which is likely to result in additional energy expenditures and costs. Temperature and precipitation, along with extreme events, directly influence transportation systems (e.g., flooding of roads, storm surge in ports) and can impair just-in-time food distribution networks. One-sixth of global agricultural production (by mass) is traded internationally, which can act to stabilize food supplies when local or regional production fails due to climate or other factors.

Food production, processing, packaging, storage, transport, and trade all have dependencies upon climate variables. The agricultural sector is highly adaptive but limited in many regions by financial or other restrictions of local producers to realistically adopt relevant technologies and practices for responding to changing conditions. In addition, some adaptations can have undesirable side effects, requiring a systemic approach when implementing adaptive strategies. Adaptation via effective food packaging, higher levels of food processing, increased and improved cold storage and cold-chain continuity, and greater redundancies in transportation options each represent adaptive food-system approaches to help ensure food availability and its stability.

Future climate-change effects on food availability and its stability are considered using the SSP and emissions futures frameworks, and reflect the informed judgment of the authors. The risks posed by climate change to food production are greatest under SSPs 2, 3, and 4, where yield increases weaken due to reduced agricultural investment and increasing land degradation. This trend exposes more production to variable climate influences and therefore can lead to local availability challenges under these SSPs. Under SSPs 3 and 4 this challenge could be particularly pronounced, given that, under these scenarios, those living in the poorest countries lack access to agricultural technologies that could offset some climate-variability effects on production in arid and marginal lands. The risks posed by climate change to food production are lowest under the economic conditions described in SSPs 1 and 5 for a given scenario of climate change. Under these SSPs, gradual intensification is likely to be the principal means of increasing crop yields.

Climate change influences food availability and stability throughout the food system. Understanding systemic connections allows decision makers to identify strengths, vulnerabilities, and compensatory mechanisms to help to ensure food availability and stability. The condition of the natural-resource base and adaptive capacity are important to agricultural production and strongly influence food-security outcomes. Now and in the future, climate influences on food availability and stability depend on the relative balance of changes being experienced within localized conditions; at the global scale, however, such changes are increasing challenges to food security.

Food Access and Stability

The second component of food security—*access*—addresses whether an individual or community has the resources necessary to acquire food. Access involves prices (trading); proximity to food *(availability)*; retail outlets (wholesaling/retailing) or farmable lands (producing); and the social and cultural norms that shape food distribution and preferences.

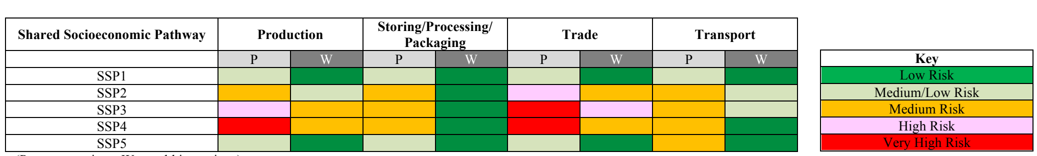

Figure ES- 5. Relative risks to food availability for different SSPs. *The risks to food availability would be lowest under the economic conditions described in in SSP 1 and SSP 5 for a given scenario of climate change, with poorer nations being at higher risk across all food production, distribution and trade categories for all SSPs. Shading represents higher or lower risks for each SSP from climate change. Risks reflect the informed judgment of the authors of this report based on the available literature.*

Global real food prices generally decreased over the second half of the 20th century and have been increasing since 2000. Price affects food affordability, which integrates food prices with income for purchasing food and can originate outside of the food system.

Trade in agricultural commodities and food can reduce price volatility and enhance stability for both producers and consumers by enabling areas of food production surpluses to supply areas of deficit. Food prices are affected by the balance between supply and demand, which is a function of food production, global population, and consumption rates. Price volatility has risen in recent years due to a combination of factors, including the widespread occurrence of extreme climate events, competition for land, and changes in commodity markets as global demand for commodities from nonfood sectors increases. Low-income households, whose food budgets represent a larger portion of their incomes, are generally more vulnerable to price spikes.

Extreme temperatures, heavy rainfall events, drought, sea-level rise, and storm surge can damage road, rail, and shipping infrastructure. Climate's effects upon transportation infrastructure can hinder the movement of food from its place of production to consumers, altering food prices in response to changes in the cost of transportation and disrupting the timing and operation of logistical supply systems between producers and distributors.

Rapid changes already underway in the food retail sector can improve or reduce resilience to climate change, depending on specific adaptive capacities. Adaptation to higher temperatures may be accomplished with increased refrigeration, for example, though that often comes with increased costs for wholesalers, retailers, and consumers. Repairs, modifications, changes to shipping logistics, and transportation substitutions may be used to adapt to changing conditions.

There is high uncertainty about future changes in real food prices, even in the absence of climate change. Socioeconomic models that include climate change generally show an increase in food prices, implying that climate change is likely to diminish other gains in food accessibility that might be achieved under any socioeconomic development scenario.

Using the SSP and emissions futures, we can examine how climate change is likely to affect food access in the future. This discussion reflects the informed judgment of the authors. Under SSPs 1 and 5, highly integrated and well-functioning world

Shared Socioeconomic Pathway	Price	
	P	W
SSP1	Medium Risk	Medium/Low Risk
SSP2	High Risk	Medium/Low Risk
SSP3	Very High Risk	Medium Risk
SSP4	Very High Risk	Medium/Low Risk
SSP5	Medium Risk	Medium/Low Risk

(P: poorer nations, W: wealthier nations)

Key
Low Risk
Medium/Low Risk
Medium Risk
High Risk
Very High Risk

Figure ES-6. Relative risks to food access for different SSPs. *The risks to food access would be lowest under the economic conditions described in SSP 1 and SSP 5 for a given scenario of climate change, with poorer nations being at higher risk across almost all food affordability and allocation categories for all SSPs. Shading represents higher or lower risks for each SSP from climate change. Risks reflect the informed judgment of the authors of this report based on the available literature.*

markets suggest that climate change alone would be unlikely to generate the exceptional price shocks that compromise widespread food availability. SSPs 2, 3, and 4 each present various futures under somewhat constrained global trade. SSP2 would likely experience many stresses and shocks in availability, and issues of price increases and affordability are prevalent in poorer countries. Under SSPs 3 and 4, this pattern and outcome are accentuated.

Climate and weather have demonstrable effects on food prices, transportation infrastructure, and the costs and operations of food distributors, affecting food access and stability. Food access is strongly influenced by additional factors outside of the food system, such as household income. The adaptive capacity of food access to changes in climate is potentially very high but varies enormously between high-income and low-income countries and individuals, between urban and rural populations, and the ways in which each of these develops in the future.

Food Utilization and Stability

Food *utilization* is the ability of individuals to make use of the food otherwise available and accessible to them. Nutritional outcomes are frequently measured in terms of malnutrition, which manifests as undernutrition or overnutrition. The prevalence of child stunting in the developing world decreased from approximately 47% in 1980 to 29.2% in 2000 and is expected to further decrease to 23.7% by 2020. The prevalence of obesity since 1970 has increased for all developed countries and for a number of developing countries, with the largest increases seen in urban populations and in the lowest income groups.

Climate has a number of potential and observed effects on food utilization, which include contamination of the food supply, the nutritional composition of food, and a body's ability to assimilate available nutrients. Climate change

affects food safety by influencing vectors of food contamination and levels of toxins in food. Elongated supply chains expose food products to greater risk of contamination and make it harder to verify the quality of food at various stages, but also allow more diversity in consumption and more stability over time. Temperature increases are associated with bacteria-caused illness related to poor food storage and handling practices in the supply chain. Fungal contamination resulting in the increase of mycotoxins in the food supply occurs due to high temperature and moisture levels during pre- and post-harvest and during storage, transportation, and processing, as well as pre-harvest practices and timing, the handling of agricultural products, and insect damage. Aquatic and fishery food sources can be affected by climate when more frequent or widespread harmful algal blooms lead to high toxin levels and uptake rates within the food supply.

Elevated atmospheric carbon dioxide leads to lower protein content in important global food staples.

Elevated atmospheric carbon dioxide leads to lower protein content in important global food staples. Disease burden, the status of women, and water, sanitation, and hygiene factors each influence nutritional outcomes as well and are affected by changing climate.

Food waste that occurs as a result of climate-sensitive activities during food storage, processing, packaging, and trade affects utilization rates. Estimates suggest that 30%–50% of total global food production by mass is lost globally as waste. Food waste in retail, in food service, and at home accounts for most food waste in developed regions; in developing nations, the absence of adequate food system infrastructure is a primary cause.

Diminished food utilization or utilization stability can result when the food system fails to adapt to changes in climate. Food safety and waste vulnerabilities are particularly apparent during extreme weather events when time is critical. Adaptive options can include increased and improved cold storage, varietal selection, biological control, storage structures, chemical treatments, botanical and inert dusts, and improved handling and processing to reduce vulnerabilities.

The influence of climate change on food utilization depends on how the food system responds under differing socioeconomic and climate futures; this section reflects the informed judgment of the authors. Rates of economic growth and environmental quality are expected to be high or improve in poor countries under SSPs 1 and 5, expanding their capacity to manage changes in climate and respond quickly to climate-related disasters. Under SSP2, technology transfer and economic growth would be somewhat lower than under SSP1, but globalized trade might compel investment in, or transfer of, food safety technologies to meet international certification requirements, limiting significant challenges to food safety. Environmental quality is expected to deteriorate under SSPs 2, 3, and 4, leading to more illness-based diseases that affect a body's capacity for absorbing nutrients from food. In SSPs 3 and 4, poor countries will experience low rates of economic growth and technology transfer, limiting adaptive capacity in these cases. Under SSP4, high levels of intracountry inequality could produce highly variable outcomes within a country, with the wealthy largely insulated and the poor experiencing increasing exposure to food utilization and stability challenges posed by climate change.

Biological contaminants in the food supply are highly sensitive to changing temperature and humidity, affecting food-spoilage rates and human health, the latter of which in turn affects a body's capacity to absorb nutrients. Adaptive capacity is potentially very high but is also highly variable, and depends on decisions made at multiple levels throughout a diverse food system. Climate variability has already affected the stability of food utilization through extreme-weather events; to the degree that more extreme events may be anticipated in the future, food utilization stability should be expected to be challenged.

The United States as a Global Food-System Actor

The United States makes significant contributions to global food security through trade, assistance

Shared Socioeconomic Pathway	Food Safety		Health Status	
	P	W	P	W
SSP1	Medium/Low Risk	Low Risk	Medium/Low Risk	Low Risk
SSP2	Medium Risk	Medium/Low Risk	Medium Risk	Low Risk
SSP3	High Risk	Low Risk	Medium Risk	Low Risk
SSP4	Medium Risk	Medium/Low Risk	Medium Risk	Low Risk
SSP5	Medium/Low Risk	Low Risk	Medium/Low Risk	Low Risk

(P: poorer nations, W: wealthier nations)

Key
Low Risk
Medium/Low Risk
Medium Risk
High Risk
Very High Risk

Figure ES- 7. Relative risks to food utilization for different SSPs. *The risks to food utilization would be lowest under the economic conditions described in SSP 1 and SSP 5, with poorer nations being at higher risk across all food utilization categories for all SSPs. Shading represents higher or lower risks for each SSP from climate change. Risks reflect the informed judgment of the authors of this report based on the available literature.*

programs, technology transfer, and export of environmental-management systems used in agriculture. The U.S. agriculture sector is responsive to the main drivers of global food demand, including population and income growth. The trend of rapidly rising global incomes is expected to be a significant source of increasing demand for food, though this may be tempered somewhat as the growth in global population is expected to slow in the coming decades, bringing with it a lowering of the growth rate of food consumption. Three major challenges to meeting this demand and achieving broader global food security that are likely to involve the U.S. food system include (1) closing yield gaps, (2) increasing food production, and (3) reducing food waste.

Increasing food production is a key to providing continued upward growth in food supplies and is particularly important for producers for whom agriculture represents both a food and an income source. Yield gaps are the difference between the actual crop productivity of a place and what might otherwise be attained using the best genetic material, technology, and management practices. Yield gaps are typically caused by lack of access to contemporary technology and management knowledge. Genetically modified crop varieties and the technological advances that produce them could play a significant role in increased food production in nations with large yield gaps, if they are suited to the local cultural, ecological, and economic situation. Other technologies, such as high-efficiency irrigation systems and advanced mechanization and fertilization methods, can also contribute to reducing the yield gap.

The United States is the largest global exporter of corn, is among the top wheat and rice suppliers, and is responsible for one-quarter of the world's meat exports. These exports represent "virtual water" that can compensate for the effects of climate change on water resources in arid and semiarid regions around the world. Underlying food transportation, storage, processing, and related facilities will need to change to accommodate the shifting production areas for major export crops. Vulnerabilities in transportation infrastructure in the United States and around the world are evident in the available scientific literature and may impede export capacity in a changing climate.

The United States imports food to meet consumer demand for variety, quality, and convenience. Globally, the United States is the third-largest importer of agricultural products such as coffee and fresh fruit, which influences the production choices and incomes of overseas producers and food systems. Climate change affects the production of key food imports due to their specific climatic and ecological requirements.

Trade benefits the United States by contributing to the economy, bringing investment, and providing incomes across multiple economic sectors. Modeling shows that the U.S. trade balance in agricultural goods in the coming decades might be expected to change in a changing climate, with imports expected to increase slightly more than exports by 2050.

These results, however, do not account for potential vulnerability in transportation infrastructure, which affects access to trade markets for many actors in the U.S. food system.

In addition to helping countries meet agricultural development and long-term food security objectives, U.S. international food assistance is an important instrument for meeting the needs of vulnerable populations. Food assistance will likely continue to be an important tool for ameliorating food insecurity in the early stages of climate change, particularly in response to extreme climate events, while many low-income nations are just beginning to experience rising incomes. The consequences of climate change on food security in different global regions will influence, and be influenced by, development efforts. Technological development in the United States has demonstrably benefited global food production over the last century, the result of concerted investment in agricultural research and investment. Continued advancement could provide critical climate-change adaptation possibilities for developing countries, and demand for advanced technologies could grow as economic development proceeds. Proactive and targeted management is necessary, however, for technology and information products to be effective in reducing future food insecurity.

Increasing food production is particularly important for producers for whom agriculture represents both a food and an income source.

The United States maintains many important connections with the rest of the world, including trade, food and developmental assistance, and technological development. Each is essential for global food security and will be challenged by climate change. Climate change has the ability to disrupt food security by making it more difficult to get food from one region that is able to produce a food to another region that wants to consume it, due to vulnerabilities in transportation infrastructure and related trade arrangements. The United States will likely be directly and indirectly affected by changing global conditions but is expected to maintain strong food imports, exports, and assistance programs and be the source of new technologies and information products for addressing global food insecurity.

Chapter 1

Introduction and Report Background

The connections among weather, climate, and food production have long been recognized and studied. Over the last several decades, it has become increasingly clear that human activities such as fossil-fuel combustion and deforestation are changing the Earth's climate (IPCC 2013). It is likewise clear that these changes have affected and will continue to affect human society, natural ecosystems, and managed ecosystems (IPCC 2013). An extensive body of evidence shows that climate change will continue to have direct and indirect effects on food production throughout the next century (Walthall et al. 2012).

This report builds on previous analyses and assessments of climate change and agriculture to look more broadly at the potential effects of climate change on global food security and examine the implications of these effects for the United States. Food security is defined as "when all people at all times have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO 1996, 2012a). There are currently about 805 million people, or about 11% of the global population, facing chronic undernourishment (FAO et al. 2014). In 1990–1992, the undernourished population was estimated to be 1.01 billion, or about 19% of the global population (FAO et al. 2014). There has been real improvement over the last several decades, but a significant fraction of the global population still does not get enough food.

The fundamental question addressed by this report is whether this progress can be maintained in the face of changing global climate. Are further improvements in food security achievable? Is climate change likely to threaten and/or reduce food security in the future?

The components of food security are food availability, access, and utilization (including food safety and nutritional value), and the stability of each over time. Addressing the intersection of climate change and each of these components requires consideration of much more than food production; other important food-system activities include food processing, packaging, transporting, storing, trading, wholesaling, retailing, consuming, and waste disposing. It is not possible to understand and characterize the potential effects of climate change on food security without this broad food systems perspective. A systems perspective is needed to address the effects of climate change on global food security and feedbacks to the United States. The United States is tightly connected to the global food system through its role as a major exporter and importer of food, a provider of assistance for many food-insecure nations, and a developer of relevant food technologies and research outputs.

Food security is defined as "when all people at all times have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life."

Questions this report will address include the following:

- How are climate and society projected to change in the next 20–30 years and the next 70–100 years? (Chapter 3)
- How might plausible changes in climate and socioeconomic conditions influence the production, consumption, trade, and prices of food? (Chapter 4)
- What are the components of food security and how might climate change affect them? (Chapters 5, 6, and 7)
- How might climate change affect global food security and influence the U.S. food system? (Chapter 8)

1.1 Report Background

This publication is a comprehensive technical evaluation of the relationship between climate change, global food security, and the U.S. food system. It is a consensus-based assessment conducted by a team of technical experts led by the U.S. Department of Agriculture (USDA). It is based on the peer-reviewed scientific literature and was developed to support U.S. National Climate Assessment (NCA) process, as described in the Global Change Research Act (GCRA) of 1990. In response to stakeholders,

the scope was expanded to include how changes in global climate and food security in other parts of the world could affect the U.S. food system.

Through the USDA's participation in the U.S. Global Change Research Program (USGCRP), this report will help to meet the requirements of the GCRA, which directs agencies to "produce information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change" and to undertake periodic scientific assessments (United States Code, Title 15, Chapter 56A, 1990). The GCRA requires that the NCA project its findings 25 and 100 years into the future and meet the standards set forth by the Data Quality Act (Public Law 554, 2000). Section 1.4 below describes the types of literature and information used to inform this assessment.

1.2 Report Scope

Food security and the food systems that underpin it have been, are, and will continue to be subject to change as a result of many factors, including changes in food production, trade arrangements, transportation systems, civil unrest, health, energy costs, economic status, and others, each operating on a variety of spatial and temporal levels. This report documents how food systems and food security have already responded and may continue to respond to a world affected by climate change. A discussion of the secondary effects of these changes upon other sectors (e.g., human health, national security) is outside the scope of this report, as is consideration of the effects of food systems on climate and the associated mitigation options. Policy recommendations are outside the scope of this report. Finally, the more specific issue of domestic U.S. food security has been detailed extensively elsewhere (Gundersen et al. 2011, Takle et al. 2013, USDA ERS 2013a) and is not the topic of this report.

This report addresses the spectrum of food security components: availability, access, utilization, and stability. While food production (including livestock, fisheries, and wild harvesting, in addition to crops) is clearly related to food availability, post-farm gate activities (food processing, packaging, transporting, storing, trading, wholesaling, retailing, consuming, and waste disposing) matter a great deal to comprehensive food-security outcomes. Each is considered within economic, social, and biophysical contexts.

The geographic scope of this report is global. Food-system activities and the food-security outcomes of these activities in relation to food availability, access, utilization, and their stability are highly interactive, both geographically and temporally. Because of these interdependencies and the shifting geography of food supplies and demands, any given nation's food security must be considered within the global context. Hence, the global scale was necessarily selected for this report.

1.3 Report Organization

This report examines what is currently known about climate's historical relationship to food security and the food system. This stock of knowledge is then applied to a scenario-based future of plausible outcomes, reflecting a range of plausible future assumptions regarding climate, the economy, and agricultural development over the next 20–100 years. The report is organized as follows:

- The **Executive Summary** affords an overview of the report's full content.
- The **Introduction** (this chapter) provides background and an orientation to the report's layout.
- **Key Concepts and Definitions** (Chapter 2) includes a general description of key concepts that are prevalent throughout the report and definitions of important terms.
- **Models, Scenarios, and Projections of Climate Change and Socioeconomic Change (**Chapter 3), summarizes recent projections and scenarios that describe how overall global climate and climate variables relevant to food security are likely to change under different levels of greenhouse-gas emissions and concentrations. It also describes alternative pathways of future socioeconomic change that could affect food vulnerability and response capabilities. These scenarios reflect a range of plausible future conditions against which risks, vulnerabilities, and opportunities may be assessed in an integrated fashion.
- **Integrated Assessment Modeling of Agricultural and Food Systems** (Chapter 4), describes global and regional modeling of climate-change effects on food production, agricultural land use, prices, and numbers of food-insecure people.
- **Food Availability and Stability** (Chapter 5), documents the relationships between climate

change and the parts of the food system relevant to availability of food supplies.

- **Food Access and Stability** (Chapter 6), documents the relationships between climate change and the parts of the food system relevant to people's access to food.

- **Food Utilization and Stability** (Chapter 7), documents the relationships between climate change and the parts of the food system relevant to people's utilization of food.

- **Global Food Security, Climate Change, and the United States** (Chapter 8), describes how climate change affects global food systems and how global food security could affect the food system of the United States.

- **Report Conclusions** (Chapter 9), describes the high-level findings that the authors have drawn from this assessment.

- Finally, a series of **appendices** lists author and technical contributors and their affiliations (Appendix A), commonly used abbreviations (Appendix B), a glossary (Appendix C), and the report's references (Appendix D).

1.4 Report-Development Process

USDA engaged USGCRP agencies with an initial "scoping session," identifying specific interests in the report. Additional stakeholders were engaged at an initiation workshop with the report authors in June 2013 to help scope the report and provide the most useful possible information to those communities most likely to make use of it.[1] A second stakeholder meeting was held during a session of the National Council for Science and the Environment in January 2014.[2] Overall, more than 50 stakeholder groups representing food-production groups, food-assistance organizations, financiers, private industry, nongovernmental representatives, the Federal service, and others were engaged in the initial scoping and development stages of the report. Participation by an additional 26 organizations was solicited.

This report had two types of technical content contributors. Report authors contributed text to one or more chapters, participated in building consensus to develop a coherent interpretation of the available technical materials across the range of the report's subject matter content, and arrived at the conclusions presented in Chapter 9. Technical contributors wrote text for individual chapters and participated in developing conclusions related to the subject matter of that chapter alone; technical contributors were not involved in developing the overall report conclusions. Report authors and technical contributors were chosen for their expertise and represent academic institutions, Federal service, and nongovernmental and intergovernmental organizations. Contributors of nontechnical information listed glossary terms and abbreviations for the appendices but did not participate in content development or the consensus process. A list of report authors, chapter technical contributors, and nontechnical contributors is provided in Appendix A.

Peer-reviewed documents and specific types of government or intergovernmental data sources (e.g., FAOSTAT) have been included in this evaluation. Trade journals, online documents or webpages that document the existence of a particular program, and other types of publications may contain information both useful and important to the subject matter of this report that is not generally available in the peer-reviewed technical literature. However, because those sources are not subject to peer-review standards, their quality and veracity can vary greatly. As a consequence, those sources are included here only in cases where a specific opinion or perspective is being represented as such and is consequently not in need of review verification.

The report was primarily drafted between October 2013 and October 2014. Expert peer reviewers were solicited via Federal Register in July and August 2014. 652 comments were responded to through peer review and interagency comment, followed by a public comment period in September 2015. A revised draft was submitted for Federal clearance in October 2015.

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[1] http://www.globalchange.gov/sites/globalchange/files/Climate%20Change%20and%20Food%20Security%20Expert%20Stakeholder%20Mtg%20Summary%20%28Final%29.pdf

[2] http://www.buildingclimatesolutions.org/topics/view/523385840cf264abcce225e8/

Chapter 2

Key Concepts and Definitions

Climate change, food security, and food systems are each highly technical and interdisciplinary fields of study in their own right, with specialized concepts and lexicons. The purpose of this chapter is to briefly list and summarize a set of key terms and conceptualizations that appear throughout the report.

2.1 Food Security

Food security is defined as the state or condition "when all people at all times have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO 1996, 2012a). Globally, about 805 million people are food insecure (FAO et al. 2014) and at least 2 billion live with insufficient nutrients (Pinstrup-Andersen 2009, Barrett and Bevis 2015). Paradoxically, about 2.5 billion people are overweight or obese (Ng et al. 2014), though not necessarily obtaining the necessary nutrients for development and health. The FAO (Food and Agriculture Organization of the United Nations) definition above holds "sufficient, safe and nutritious" as the goal; overweight or obesity can themselves lead to damaging health effects (Ng et al. 2014).

Food production is an important prerequisite for food security to be achieved but is alone insufficient to do so. Many other factors determine food security, including economic conditions from the global to the micro levels and the conditions of trade, food safety, land use, demographics, and disease (Ericksen et al. 2009, Misselhorn et al. 2012). Food security is not only a reflection of the aggregate balance between supply and demand but integrally includes individual and community access to food as well as economic, social, political, and environmental factors (Devereux 2012, Headey 2013, Maxwell and Fitzpatrick 2012,

Regmi and Meade 2013, Simelton et al. 2012, World Bank 2012b).

Understanding food security requires recognizing its interdisciplinary, interactive, intersectoral, and multiscale nature; misconceptions are not uncommon. One common source of confusion occurs in the application of the term "food security" to the separate, though related, topic of national-scale or regional-scale agricultural production. While the terms were used interchangeably in the past (UN Human Rights 1974), this is no longer the case; food security is distinct from food production. Food production (not necessarily domestic) is an important element of the food-availability component of food security but alone is insufficient to guarantee food security. For example, the United States produces an annual average of over 3,600 kcal per-capita per day (FAOSTAT 2014b), yet 14.3% of the U.S. population is currently food insecure (Coleman-Jensen et al. 2014). In contrast, Singapore's population remains food secure and is ranked fifth out of 109 nations globally from the Economist's Global Food Security Index (Economist Intelligence Unit 2015), though the country has effectively no cropland under cultivation within its borders (FAOSTAT 2014a). This compares with 0.54 hectare (ha) under cultivation per-capita in the United States (FAOSTAT 2014b), demonstrating that food security may be achieved even in the absence of domestic crop production; trade can effectively substitute for domestic production where there is economic access to international markets.

The four components of food security (Table 2.1) are not mutually exclusive but serve to organize the topic into an analytically meaningful framework and allow for systematic analysis of food and nutritional outcomes (Ericksen 2008, Ingram 2011, Maxwell 1996, Maxwell and Smith 1992).

Food security is determined by each of these components acting and interacting across multiple spatial and temporal scales (Carr 2006, Davis et al. 2001, Kotzé 2003, Maxwell 1996, Maxwell and Smith 1992). Changes in one region may affect food security in other countries at great distances (Dronin and Kirilenko 2008). While some changes may directly diminish food security, they may be compensated for through alternative pathways (e.g., as when supply disruptions are addressed through trade (Parry et al. 2004). A globalized food system can in this way buffer the local effects of weather events but may also increase vulnerability by transmitting price shocks globally (Godfray and Beddington et al. 2010). As a major food importer and exporter (USDA ERS 2013a), the United States can be significantly influenced by climate events and changes in other parts of the world.

Climate change can affect food security in multiple ways (National Research Council 2007, Wheeler and von Braun 2013). Rising temperatures, altered precipitation patterns, and extreme weather events have already affected agricultural yields, the geographical distribution of food- and water-borne diseases, and trade patterns (Schmidhuber and Tubiello 2007). Meeting each component of food security described in Table 2.1 depends upon the functioning of each of the food system elements shown in Figure 2.1, whose climate sensitivities are described throughout this report.

Table 2.1: The Components of Food Security. *For food security to be achieved, all four components must be attained simultaneously. Adapted from FAO 2008d.*

Component	Definition
Availability	The existence of food in a particular place at a particular time. Addresses the "supply side" of food security, which is determined by food production, transportation, food stocks, storage, and trade.
Access	The ability of a person or group to obtain food. Economic access to food (including affordability) and allocation within society (including intranation and intrahousehold distribution) are integral to this component.
Utilization	The ability to use and obtain nourishment from food. This includes a food's nutritional value and how the body assimilates its nutrients. Sufficient energy and nutrient intake is also the result of biophysical and sociocultural factors related to food safety and food preparation, dietary diversity, cultural norms and religious practices, and the functional role of food in such practices.
Stability	The absence of significant fluctuation in availability, access, and utilization. When stable, food availability, access, and utilization do not fluctuate to the point of adversely affecting food security status, either on a seasonal or annual basis or as a result of unpredictable events. Weather, political unrest, or a change in economic circumstances may affect food security by introducing instabilities.

2.2 Food Insecurity

Food insecurity is the absence of food security. It exists over different time horizons and affects people through both under- and overconsumption. Much of the scientific literature to date addresses the former issue, though the latter is now receiving more attention (Hawkes et al. 2012, Ng et al. 2014).

When households face long-term deficits in acquiring sufficient food, often a result of long-term poverty and lack of resources, they experience "chronic food insecurity" (Maxwell and Smith 1992). Alternatively, households that face unexpected or short-term food deficits experience "transient food insecurity," often the result of reductions in food production, lack of imports, higher prices, or climatic events (Devereux 2006). Climate change can influence both types of food insecurity. Long-term changes in temperature and precipitation may reduce income and result in higher levels of chronic food insecurity, whereas extreme events such as droughts and floods might increase the frequency of transient food insecurity.

Just as food security is determined through interactions occurring across multiple spatial and temporal scales, the consequences of food insecurity are also observable across those ranges. For an individual, chronic food insecurity may manifest as a reduced capacity to perform physically, diminished mental health and development, and an increased risk of chronic disease (Jyoti et al. 2005, Seligman et al. 2007, Seligman et al. 2009, Slack and Yoo 2005, Whitaker et al. 2006). Undernourishment, including inadequate caloric and/or nutrient intake (WFP 2012), is a consequence of food insecurity and leads to outcomes such as stunting (short for one's age), wasting (thin for one's age), and micronutrient malnutrition.

Collectively, these changes diminish global economic productivity by 2%–3% annually (USD 1.4–2.1 trillion; FAO 2013b), with individual country costs estimated at up to 10% of national GDP (WFP 2013a, Martínez and Fernández 2008).

2.3 Food Systems

Food security depends not only on yields and trade but also on changes that affect food processing, storage, transportation, and retailing; the ability of consumers to purchase food; and food-consumption patterns. Food security is therefore an important outcome of a functioning food system (Figure 2.2; Ingram 2011, FAO 2008c), in concert with emergent properties of the food system, such as food prices, and (frequently) external factors, such as income.

- **Producing** food relies on agricultural production, including crops, livestock, and fisheries and their relationships with climate and environmental change (Crane et al. 2011, Ericksen et al. 2011, IPCC 2007c, Schlenker and Lobell 2010, Vermeulen and Aggarwal et al. 2012).

- **Processing** of primary agricultural commodities transforms these commodities into more-easily edible and digestible food (Boughton and Reardon 1997).

- **Packaging** food protects it during transportation, extends its shelf life, and reduces the chance of contamination.

- **Storing** food items keeps them in one location for a period of time and may occur at each step of the food system.

- **Wholesaling** refers to the purchase and resale of agricultural commodities and food in bulk, to be retailed by others.

- **Retailing** describes economic agents, from roadside vendors and open markets to supermarkets and restaurants, selling a range of unprocessed to processed and prepared foods to consumers.

- **Trading** refers to economic exchanges of food or other materials for payments or export revenue; it can occur across all of the food system activities.

- **Transporting** describes the movement of food to and between markets, and from markets to communities and homes.

- **Consuming** is individuals and families eating food to sustain themselves in their day-to-day lives.

- **Disposing** refers to feeding spoiled, inedible, or surplus food to animals, composting food to harvest it for nutrients, or discarding food into a landfill or centralized waste facility.

Food systems vary. Some are characterized by long distances separating production and consumption, greater reliance on technology, and industrial components; these are termed *capital-intensive* food systems in this report. Other food systems are simpler, with farmers eating the food they grow with minimal processing (Brown et al. 2009, Niles and Roff 2008); these are termed *labor-intensive* food systems in this report.

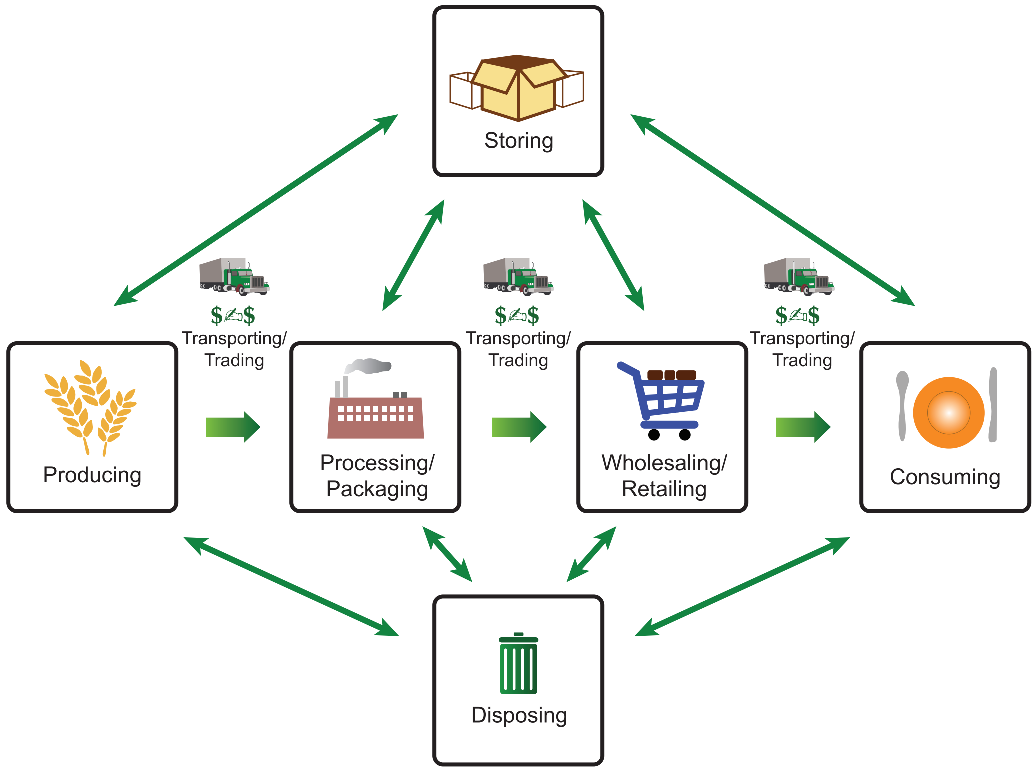


Figure 2.1. Food-system activities and feedbacks. *Food-system activities include the production of raw food materials, transforming the raw material into retail products, marketing those products to buyers and product consumption. Food transportation, storage and waste disposal play a role in each of these activities.*

Changes within any food-system activity have the potential to affect food-security outcomes (Ericksen et al. 2011, Ingram 2011). Effects are often most easily documented following extreme-weather events. Such extreme events are sometimes attributable to changes in climate, and in fact recent studies have been able to apportion the enhanced risk of some specific events to anthropogenic drivers; other times they are not, but either type of event can be used to understand underlying vulnerabilities in the food system. For example, a drought may expose regional susceptibility to supply shortages, whether or not the drought was attributable to climate change. This information can then be used together with projections of changing drought incidence in the future to help to determine future risk.

Climate change is identified by changes over an extended period in the average and/or variability of properties such as temperature and precipitation.

2.4 Climate Change

Climate change is identified by changes over an extended period in the average and/or variability of properties such as temperature and precipitation. This report also considers elevated atmospheric carbon dioxide (CO_2) concentrations, which are a driver of climate change. Human activities have resulted in large changes in Earth's climate over the last few centuries (Stocker et al. 2013). Much larger changes are projected for the next century if greenhouse-gas emissions (GHG) and concentrations continue to increase (Stocker et al. 2013).

Human activities have changed and will continue to change the Earth's climate (Stocker et al. 2013). Since 1750, atmospheric concentrations of CO_2 have increased by about 40%, nitrous oxide by 20%, and methane by about 150%, leading to increasing temperatures and changes in the timing and amount of precipitation in many areas. CO_2 concentrations have reached 400 ppm, and global average temperatures increased by 0.85 °C (about 1.6 °F) between 1880 and 2012 (Stocker et al. 2013). Precipitation has observably increased over the mid-latitude terrestrial areas of the Northern Hemisphere (estimates range from 1.44 to 3.82 mm per year per decade), while precipitation trends over other areas have been less significant. Increased ocean temperatures along with the melting of glaciers and ice caps have contributed to an observed rise in global sea level of approximately 0.2 m between 1901 and 2010 (Stocker et al. 2013).

This report investigates how past climate has influenced food-system activities and food security, using those historical relationships as a basis for understanding possible future near-term (~2040–

2060) and longer term (~2080–2100) food security outcomes. This report focuses on two different scenarios of climate change: (1) relatively low emissions and atmospheric concentrations of GHG, and (2) high emissions and concentrations of GHG, both derived from the recent climate assessments of the IPCC (IPCC 2013). The low scenario discussed in this report is Representative Concentration Pathway (RCP) 2.6, in which CO_2 concentrations increase to about 421 ppm and then stay at about that level (current concentrations are about 400 ppm). The high scenario is RCP 8.5, in which concentrations increase steadily throughout the 21st century, reaching a level of about 936 ppm by 2100. This report also outlines five broad scenarios, or pathways, of socioeconomic change that could affect the structure of society over time and future capabilities and willingness of society to adapt to and mitigate climate change and its effects.

Effects of changes in climate on agriculture tend to be gradual until a threshold is reached (IPCC 2013). For example, at increasingly high temperatures, plants may continue to grow at a reduced pace until a particular temperature is reached (with the precise temperature specific to the crop type and variety). At the point that the plant ceases to grow, it has reached a threshold temperature (Walthall et al. 2012). Thresholds may influence food security in a number of ways, with consequences for market access or for a community awaiting a shipment. Instances of thresholds are discussed in this report.

2.5 Non-climate Drivers of Food Systems and Food Security

Food security and food systems are driven by many factors. Although this report focuses on changes caused by climate change, climate change is only one set of interconnected trends and drivers facing agriculture, food systems, and hence, food security (FAO 2008d). Some of the most relevant technological and socioeconomic factors driving changes in food systems include technological and structural changes in the food system, including food production, processing, distribution, and markets; increasing population; changes in wealth; demographic changes; urbanization; disaster response; and changes in energy availability and use (Figure 2.2).

Technological and Structural Changes in the Food System: Technology has been historically important to allowing the food supply to keep pace with increased demands caused by population and income

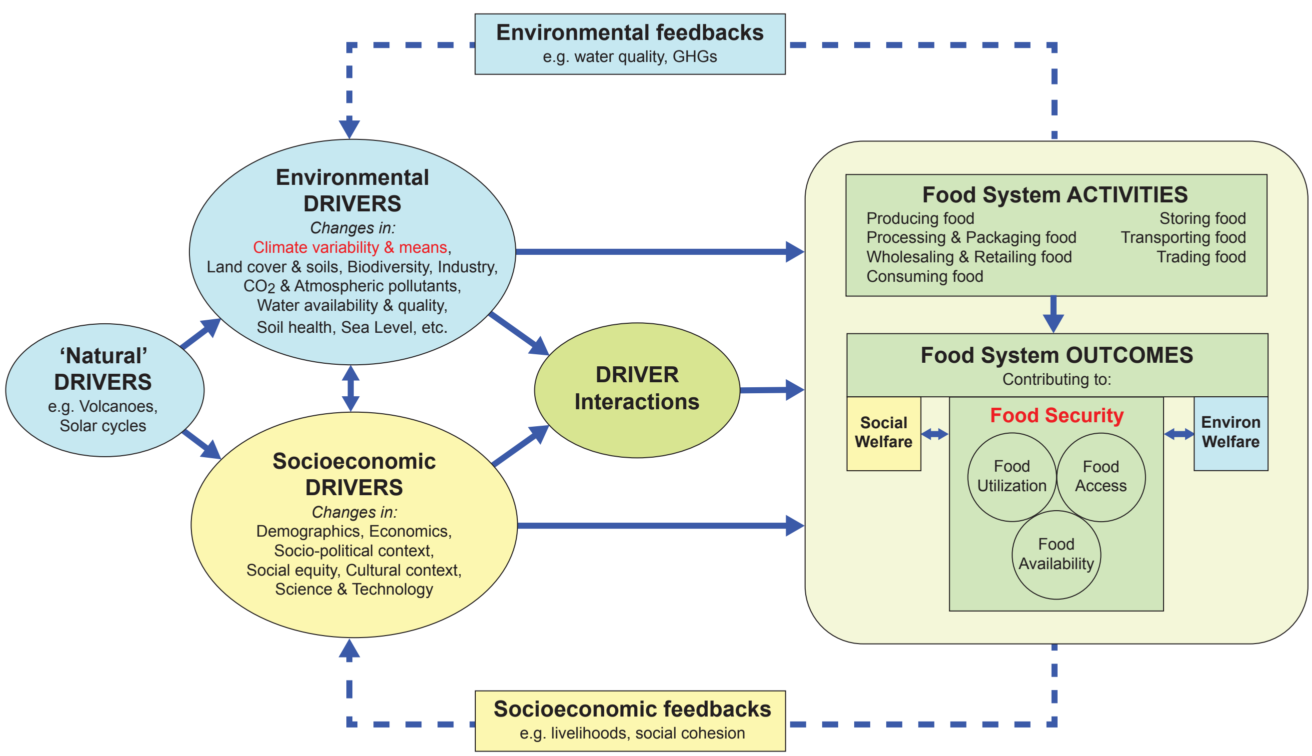


Figure 2.2 Food system drivers, interactions, and feedbacks. *Changes and interactions in environmental and socioeconomic conditions can affect food security outcomes in distant locations. The primary foci of this report are highlighted in red but occur within a broader context, with many feedbacks. Source: Adapted from Ingram 2011.*

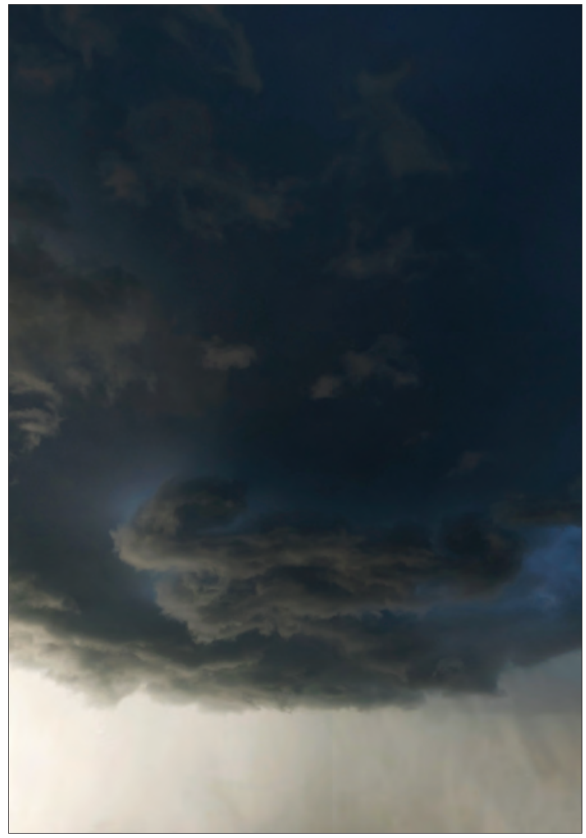
growth in the 20th century (Pingali 2012). Those technological advances included, for example, better fertilization, crop improvements through breeding and hybridization, and improved mechanization, all of which increased individual farm outputs. These technological changes went hand-in-hand with major structural changes in agricultural production, for example, with a continuing concentration of commercial production at larger farms in the United States and some other industrialized countries (MacDonald et al. 2013). Also, the food processing, distribution, and market systems have moved increasingly to larger scale, integrated firms (Ericksen 2008, Ingram 2011, Reardon et al. 2012).

Economic Growth: Between 2010 and 2013, GDP growth in developing countries was higher than in developed countries, at between 4% and 7% (International Monetary Fund 2013). As developing economies grow and incomes rise, marginal increases in disposable income have diminishing effects on food purchases, meaning that low-income households devote a larger proportion of their increasing incomes to food than higher-income households (FAO 2012a, Regmi and Meade 2013). Since the mid-20th century, real food prices have fallen as real per-capita incomes have risen, making food more accessible (Fuglie and Wang 2014, Schmidhuber and Tubiello 2007). At the same time, there have been important shifts in demand from cereal sources of calories and protein consumed by low-income people toward animal and fish sources of protein and the more diverse diets preferred by people with higher incomes. This is also important to achieving food security from the perspective of the nutrition aspect of food utilization.

Population and Demographic Change: Population is a strong driver of the demand for food. Population expansion over the next century is expected to occur primarily in less-developed, food-insecure nations, placing more pressure on stressed systems with limited adaptive capacity for climate change. By 2050, the world population is projected to be 9.6 billion, rising to 10.9 billion by 2100 (UN 2012). Globally, family size is expected to decline in the latter half of the 21st century due to changing age and educational structures (Lutz and Samir 2010, UN 2012). These changes in overall population size may be expected to lead to overall changes in food demand.

Population expansion over the next century is expected to occur primarily in less-developed, food-insecure nations, placing more pressure on stressed systems with limited adaptive capacity for climate change.

Urbanization: As of 2011, half of the global population is classified as urban (UN 2012). This is projected to increase to about 67% by 2100 (UN 2012). The growth in urban populations and reduction in rural populations leads to fewer



agricultural producers overall, shifting dietary demands, larger and more centralized food-distribution structures, and a greater role for transportation and trade (Lee et al. 2012, Neven et al. 2009, Reardon et al. 2012, Satterthwaite et al. 2010).

In coastal cities, in particular, imported food that is affordable and accommodates changing dietary preferences will increasingly compete with food produced by domestic inland producers (Pingali 2007). As urban centers expand to accommodate growing urban populations, neighboring arable land will be removed from production and remaining cultivated lands will be subject to greater pollution (Chen 2007). It is important to note that the overall loss of arable land attributable to urbanization is not large in a global context. Recent estimates of current urban land extent vary depending on methodological and classification decisions, but most range from about 0.2% to 2.4% of global land area circa 2000, excluding Greenland and Antarctica (Seto et al. 2011). This is projected to triple by 2030 (Seto et al. 2012) but would still amount to less than 2% of global arable land.

Urbanization therefore has a direct influence on food systems and food-security outcomes. Urban areas also face threats to food security induced by climate change, primarily through disruption of the transportation and distribution of food (Satterthwaite et al. 2010).

Disasters and Disaster Response: Food systems and their adaptive capacity are affected by changes in socioeconomic, cultural, and environmental conditions that play out over years and decades (Frankenberger et al. 2012). They can also be affected by more-rapid changes, such as conflicts or natural disasters, which disrupt production, transport, and trade.

Communication and food security analyses have improved knowledge of and past response to food-security shocks (Hillbruner and Moloney 2012). Management of environmental disruption often improves in a given location over the long term, though climate-related shocks—that is, abrupt changes that cause a sudden change in food security—tend to have a detrimental effect on the adaptive capacities of affected households, particularly when such shocks are repetitive (USAID 2011).

The actual effects of natural disasters and food-security shocks are mediated by socioeconomic conditions and the effectiveness of disaster response (Coughlan de Perez et al. 2014). A more-sensitive individual, household, or community has lower resilience to a given shock from any source. Chronic vulnerability anywhere in the world may be due to poverty, degraded ecosystems, inadequate physical infrastructure, conflict, and ineffective governance (FAO 2008a, Schreiner 2012), meaning that vulnerable people are at greater risk to weather extremes (Coughlan de Perez et al. 2014) and other stresses. In such settings, a relatively mild stress on chronically vulnerable households can lead to serious consequences due to the households' inability to respond effectively (Frankenberger et al. 2012).

Energy: Energy is a major driver of economies, societies, and food production. Agricultural production, food storage, and other elements of the food system are energy intensive. Therefore, energy costs are reflected at multiple stages of the food system (Vermeulen and Campbell et al. 2012), affecting access for income-limited consumers. Higher energy prices can also affect commodity markets, incentivizing biofuel production and land-use conversions away from food production (Diffenbaugh et al. 2012, Hazell 2013).

2.6 Conclusions

Food security, food systems, and climate change are multifaceted topics. Their interactions are likewise complex and affected by a wide range of environmental and socioeconomic factors. It is nevertheless clear that there are multiple connections between climate conditions and many different elements of food systems and that climate change can affect food systems in ways that alter food-security outcomes.

Chapter 3

Models, Scenarios, and Projections of Climate Change and Socioeconomic Change

Key Chapter Findings

- The Earth's climate is projected to change over the next century in ways that could affect food security during the next several decades. These changes, include increases in temperature, number of very hot days, precipitation intensity, length of very dry periods, and sea levels.
- The greater the increase in greenhouse-gas (GHG) emissions and concentrations, the greater the change in climate and the greater the climate-associated risks for food security.
- Societal conditions and changes are very important determinants of the ultimate impacts of climate change, because they affect overall wealth, vulnerability, willingness to allocate resources, and adaptive capacity.

The purpose of this chapter is to provide an overview of how climate and society are projected to change over the next century, to show the range of possible future conditions as currently described in the scientific literature and thus provide context for the discussion of potential effects of climate change on food security in subsequent chapters. Sections 3.1–3.3 focus on describing climate models and how they are used to project future climate change. These sections include an overview of the most recent projections of near-term (the next 20–30 years) and longer-term (the next 80–90 years) climate change, emphasizing possible changes in variables relevant to agriculture and food security. Section 3.4 describes scenarios of possible future changes in socioeconomic conditions, which are important for understanding future vulnerability and risk, as well as future adaptation and mitigation capacity.

3.1 Climate Modeling

Computer models are needed to study the highly nonlinear interactions of the Earth's climate system in a quantitative way because controlled large-scale experiments are not possible in the atmosphere itself. Climate studies rely largely on general circulation and Earth-system models, which use mathematical formulas to represent the linked, or "coupled," physical, chemical, and biological processes that drive the Earth's climate. Climate models, like weather models, generally represent the system in a three-dimensional mesh that reaches high into the atmosphere and deep into the oceans. At regularly spaced intervals, or grid points, the models use the laws of physics to calculate atmospheric and environmental variables, simulating the exchanges of mass (such as gases and aerosols/particles), momentum, and energy across the main components of the Earth system: atmosphere, oceans, land surface, and sea ice. In some models, changes in vegetation or chemical reactions between constituents are included, and a few include representation of the continental ice sheets. Because climate models cover far longer periods than weather models, their primary focus is to represent the coupled Earth system in a comprehensive way, with all the key feedback elements represented. But because of this system-level complexity, they cannot include as much detail at regional and local scales. Thus, climate projections usually focus on large regional-to-global scales rather than local scales. This approach enables researchers to simulate global climate over years, decades, centuries, or millennia. Most current-generation global models use grid points that are about 100–200 km apart, 15–30 vertical layers in the atmosphere, and up to 40 or more levels in the oceans. Scientists also use global-model results to drive finer-scale (regional) models, with grid spacing ranging from 2 to 50 km for more detailed studies of particular areas.

Climate studies rely largely on general circulation and Earth system models, which use mathematical formulas to represent the linked, or "coupled," physical, chemical, and biological processes that drive the Earth's climate.

Coupled climate models have been developed by many large institutions around the world. More than 40 such models contributed their output to the latest (fifth) phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012), which provides a coordinated suite of experiments that form the basis for the results described in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC; Stocker et al. 2013) and are also the basis of the climate projections included in this report. The output of Coupled Model Intercomparison Project (CMIP) experiments includes simulations of past and current conditions so that model fidelity can be evaluated through comparison to actual observations. Additionally, modeling groups perform common "control" experiments and compare results across models to help further diagnose and evaluate model performance. The full collection of models and experiments in CMIP, often including multiple experiments with the same model but different initial conditions, creates a very large database to support statistical analysis and enables better characterization of uncertainty in projections. The CMIP effort has been underway since 1995 and helps to assure that high-quality, well-documented, and comparable estimates of future climate change are available for use in research and scientific assessments, including those of the IPCC.

3.1.1 Uncertainty in Climate Models

Climate models work by representing the fundamental physical laws that govern our climate system. But they also need to approximate small-scale processes and their interaction with the larger scales that are directly simulated. There are no unique solutions to these approximations, and different models choose different approaches, all scientifically defensible, that result in different outcomes. This is the main source of model-to-model uncertainty in climate projections. For example, when the different models in CMIP5 used the same scenario of high GHG concentrations to project increases in global average temperature by 2100, the results ranged from about 3 °C to almost 6 °C (Figure 3.1), with a mean value of about 4 °C relative to average temperatures between 1986 and 2005 (Stocker et al. 2013).

It is also important to recognize that the scenario-based inputs, or "forcings" used to drive climate-model projections, such as levels of GHG emissions and concentrations, are themselves uncertain. The emissions in these scenarios depend on various assumptions about changes in global population, economic and technological development, and choices in transportation and energy use (Melillo et al. 2014). High concentrations lead to larger climate changes and lower concentrations to lower changes, but it is not possible to determine which concentration future is most likely.

Climate models differ in the way that they represent various processes (for example, cloud properties, ocean circulation, and turbulent mixing of air). As a result, different models produce slightly different projections of change, even when the models use the same scenarios. Scientists therefore often use multiple models. Section 3.3 provides mean results from all models contributing simulations to the CMIP process under a given scenario (Melillo et al. 2014).

The use of ensembles, or groups, of different climate models to perform the same simulations helps to characterize model-based uncertainty and identify the most robust patterns and, conversely, those aspects of future changes that are not yet pinned down. There is substantial agreement across models on large-scale patterns of temperature and precipitation change associated with different levels of GHG concentrations, and the driving physical processes are well understood. The choice of a high- or low-concentration scenario mainly modulates the intensity of the changes, but it does not substantially alter their geographic patterns. Intermodel variability (lack of agreement) mainly dominates in the areas around the sea-ice edge of the Arctic region for temperature-change projections and in the tropics for precipitation projections. Overall, the disagreement is significant in the magnitude of change, but not as much in the pattern or sign of the signal once it has emerged from natural variability. In general, model projections of changes in atmospheric temperatures are seen as more robust and easier to distinguish from natural variability than projections of changes in precipitation.

3.1.2 Downscaling Climate Model Results

Planning and decision processes in the agricultural sector happen at all spatial scales and generally involve a wide range of time horizons. However, global-scale modeling results at spatial resolutions of roughly 100 x 100 km, such as those discussed in this chapter, are generally seen as too coarse to be usable in regional- or local-scale analyses and management decisions. Thus, one of the most common complications when trying to integrate climate projections into these workflows is to bridge the gaps and mismatches in scales. This step of bringing the information from general circulation models to the decision level is called *downscaling*.

There is a long and deep history in downscaling climate-model output to various user needs (Benestad et al. 2008, Wilby et al. 1998). Approaches fall into two basic categories. The empirical-statistical methods exploit relationships between observed data (e.g., a weather station or grid points in a gridded observational product) and model output over a period when both are available—called the calibration period—and then estimate the higher-resolution field from the model projection, assuming a constant relationship (Benestad et al. 2008, Maurer and Hidalgo 2008, Stoner et al. 2013, Wood et al. 2002). In this category are also methods that determine the closest analog situations from the observed record, which are used to construct spatially more-coherent conditions.

The other broad downscaling approach uses dynamical models—commonly, regional climate models or regional hydrologic models—that are capable of representing important physical processes in a much more appropriate way than global models (Giorgi 1990, Hostetler et al. 2011, Mearns et al. 2013). One downside of this approach is that it often requires large (and thus expensive) computational resources. As a consequence, many downscaling analyses that use dynamical approaches cover only limited periods of time or are applied to only a limited set of general circulation models (GCMs). Additionally, "operational" regional downscaling is often still too coarse in resolution, though enhanced computational capabilities have somewhat ameliorated this problem.

Downscaling is an imperfect but often still-useful tool for bringing GCM-based climate-change predictions and projections to the appropriate scales for many uses. A number of portals are making such data available, including the Climate Change, Agriculture, and Food Security (CCAFS) project and the Nature Conservancy's Climate Wizard.

Each downscaling method has strengths and weaknesses. Users should be aware that downscaled climate information that is optimized for a particular purpose may not be ideal for different uses. For example, hydrologic and ecologic applications often require unbiased cumulative sums of precipitation over a basin or accumulated heat during the growing season while disaggregating and even reshuffling daily sequences (Maurer et al. 2002, Wood et al. 2002). Others focus specifically on the preservation of sequences, and particularly the occurrence of extremes (Yates et al. 2003, Clark et al. 2004, Bürger et al. 2012), with their specific multivariate and spatially coherent context to better represent feedback processes (Benestad et al. 2012). Similarly, direct analog-based methods (Abatzoglou and Brown 2012) also preserve the full context and are very useful to provide multivariate inputs into process models. Finally, the exploitation of dynamical methods, as is done through the use of high-resolution regional models driven by lower resolution global results, often provides the most flexible, and ultimately the only, geophysically consistent framework to study Earth system change (Kharin and Zwiers 2000, Giorgi and Mearns 2003, Racherla et al. 2012). However, such methods involve substantial computational costs and may introduce additional uncertainties through hand off of results across multiple modeling systems.

In the end, users need to be aware of the strength and weaknesses of different products, which are often designed for one particular application. Just because data are offered at spatial and temporal resolutions resembling observations does not necessarily mean that they also contain all the characteristics of real-world data. It is important to carefully evaluate data with regard to the key characteristics of the end application before application of the data.

3.2 Greenhouse-Gas (GHG) Emissions and Concentration Scenarios

To investigate human-induced climate change, researchers use projections of future GHG concentrations and other anthropogenic drivers of change, such as the emission of aerosol precursors and land-use change, as input to climate-model calculations. The most recent set of inputs developed by the scientific community, used in the CMIP5 process and many other experiments, are called representative concentration pathways (RCPs). The RCPs replace the scenarios described in the IPCC Special Report on Emissions Scenarios (SRES; Nakicenovic et al. 2000) that were used in the CMIP3 simulations (Meehl et al. 2007) that informed the IPCC 4th Assessment Report.

There are several differences between RCPs and previous sets of climate-change scenarios. RCPs are not tightly linked to a particular socioeconomic scenario; rather, each RCP is consistent with a variety of possible socioeconomic futures, including different combinations of mitigation and adaptation options. The RCPs also span a somewhat wider range of concentration pathways and outcomes than the SRES scenarios, particularly on the low end, because the RCPs include emissions-mitigation scenarios, while the SRES scenarios do not. Care must be taken when comparing RCP-driven results with those driven by previous scenarios, as there are significant differences in the underlying emissions and concentrations in some instances.

There are four different RCPs used in the CMIP5, each of which represents a different pathway of potential changes in GHG concentration levels over the 21st century and each of which is named for the approximate radiative forcing (a measure of the additional greenhouse effect imposed by the changes in gases, aerosols, and land use) it will produce in 2100 in terms of watts-per-square-meter change relative to preindustrial conditions. The output of climate-model simulations driven by each RCP is a projection of the rate and magnitude of climate change over the 21st century. This information can be combined with socioeconomic and biological information and models to investigate the potential effects of climate change.

For the purposes of this report, we concentrate our description on the differences between a low-emissions case and a high-emissions case. This approach spans a broad range of possible future climate conditions and enables us to address the potential effects of actions to reduce GHG emissions versus allowing continued rapid emissions growth. RCP 2.6 is a low-emissions scenario that assumes extensive mitigation efforts to reduce emissions, resulting in a CO_2 concentration of about 421 ppm by 2100 (van Vuuren et al. 2011). RCP 8.5 is a high-emissions scenario that produces a CO_2 concentration of 936 ppm by the end of the century (Riahi et al. 2011). In some instances, we also discuss results from studies that used other low- and high-emissions scenarios, such as SRES, or studies that used more intermediate scenarios, such as RCP 4.5 and RCP 6.0. For reference, current CO_2 concentrations in the atmosphere are around 400 ppm, whereas preindustrial levels were approximately 280 ppm.

3.3 Climate Projections

The CMIP5 process used the four RCPs described previously as drivers for simulations of the future evolution of Earth's climate (Moss et al. 2010, van Vuuren et al. 2011). This large ensemble of simulations delivers a wealth of information in terms of primary variables (temperature, precipitation, etc.) and derived indices (e.g., frost days, growing-season length, and precipitation intensity). Extensive documentation of many aspects of historical, short-term (next few decades), and long-term (throughout the century and beyond) climate trajectories is available in Chapters 10, 11, and 12 of the IPCC 5th Assessment Report. Chapter 9 of the same report includes a discussion of model evaluations (Stocker et al. 2013).

The new set of climate projections confirm and extend the findings of previous studies described in the scientific literature and earlier IPCC reports such as the 4th Assessment Report (Solomon et al. 2007). As expected, the range of results is somewhat wider because of the wider range of forcing levels spanned by the RCPs compared to previous emissions scenarios. The geographical patterns and magnitude of change (conditional on the scenario used) are consistent with previous work.

If GHG emissions and concentrations continue to increase rapidly throughout the 21st century (as represented in RCP 8.5), global average temperature is projected to increase by about 2 °C by 2050 and by about 4 °C by 2100 (Stocker et al. 2013), relative to global average temperature during the period from 1986–2005. Global average sea level is projected to rise by about 0.22–0.38 m by mid-century (2046–2064) and 0.45–0.82 m by late century (2081–2100) relative to 1986–2005 (Stocker et al. 2013).

If aggressive mitigation actions are taken to slow the increase of GHG emissions and concentrations, global average temperature is projected to increase by about 1 °C by 2050 and remain at about that level through 2100 (Stocker et al. 2013), relative to the 1986–2005 average. The likely range described here is slightly less than the 0.3–1.2 m projected by the Third U.S. National Climate Assessment for late century (Melillo et al. 2014).

Figure 3.1 shows global average temperature changes resulting from all four RCPs out to 2100, with respect to a baseline taken as 1986–2005. RCP 2.6 assumes strong mitigation actions, with GHG concentrations peaking at about 450 ppm in 2040 followed by a slight decline. It is the only scenario under which trajectories of global average temperature are not increasing steadily over the course of this century. The other three RCPs produce steadily increasing trajectories of GHG concentrations.

Projected changes from today's global average temperature by 2100 range from an ensemble mean value of about 1 °C for RCP 2.6 to an ensemble mean value of about 4 °C for the highest scenario, RCP 8.5. A 2 °C warming threshold with respect to preindustrial levels would not likely be exceeded under an RCP 2.6 scenario (Stocker et al. 2013). Under RCP 4.5, it is more likely than not to be exceeded, and under RCPs 6.0 and 8.5, it is likely to be exceeded (Stocker et al. 2013).

Geographical patterns of change have proven stable across at least the last three generations of assessments and models (Tebaldi and Arblaster 2014). Maps of annual average temperature change derived from the CMIP5 multimodel ensemble for RCP 2.6 and RCP 8.5 are shown in Figure 3.2.

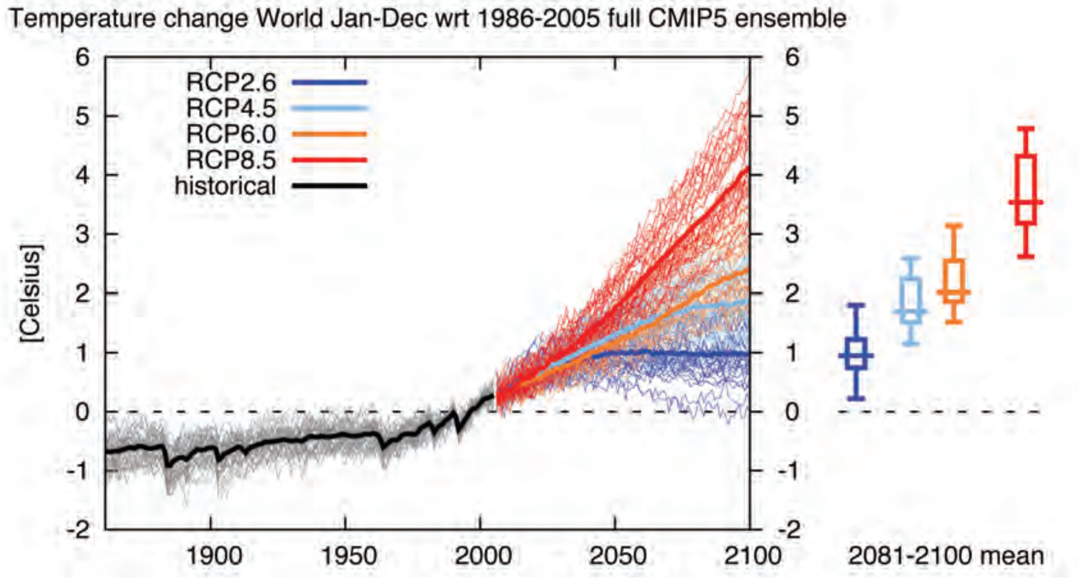


***Figure 3.1 Global average temperature change relative to 1986–2005 baseline.** Time series of surface temperature under historical forcings (gray) and future RCPs 2.6 (low-emissions scenario, in blue), 4.5 (aqua), 6.0 (orange), and 8.5 (high-emissions scenario, in red) are shown out to 2100. Thin lines show individual model trajectories; thick lines show the multimodel ensemble mean. Boxplots in margin show the distribution (mean, interquartile range, and 90% range) derived from the model ensemble for the average changes over the 20-year period at the end of the century. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

Well-known features of temperature change can be seen in Figure 3.2: high latitudes warm more than low latitudes, continents more than oceans, and the Northern Hemisphere more than the Southern. The RCP 2.6 low-emissions scenario results in warming of about 1–2 °C by mid-century for much of North and South America, Europe, Africa, Australia, and Asia, and this level of warming persists through the end of the century. Warming in some northern areas exceeds 2 °C. The RCP 8.5 high-emissions scenario results in warming of 2–3 °C by mid-century for North and South America, Europe, Africa, Australia, and Asia. By late century, this scenario results in 4–5 °C warming in these same areas, with some high-latitude northern regions experiencing warming of 7 °C or more. The North Atlantic experiences less warming than surrounding areas due to the Atlantic Meridional Overturning Circulation in the ocean slowing down because of warmer temperatures and increased freshwater inputs. Similarly, changes in the southern oceans also result in somewhat reduced warming in some locations due to better and deeper mixing of the ocean layers there.

Global precipitation is projected to increase, due to the ability of warmer air to hold more moisture (made available by enhanced evaporation from the oceans), but change may not be distributed uniformly in time or space (Figure 3.3). Increased precipitation is projected for many areas, but longer periods with little or no precipitation are projected for several regions that are already dry.

Precipitation is also projected to become more intense, but the distribution of precipitation intensity over the surface of the Earth is again not projected to be uniform (Figure 3.4). Mid-latitude land regions and wet tropical regions are very likely to see more-intense and more-frequent precipitation events by the end of the century (Stocker et al. 2013). In general, the pattern of wet areas becoming wetter and semiarid regions becoming drier seen in most earlier generations of climate simulations is confirmed by CMIP5 simulations for both low- and high-emissions scenarios. Some of the most prominent and robust features of future changes in precipitation are increases at high latitudes and the equatorial region of the Pacific Ocean and decreases in the subtropics, with a particularly strong negative signal over the Mediterranean basin and Western Australia.

Larger temperature increases over land than over ocean surfaces mean that most regions are projected to experience decreases in relative humidity as temperatures increase. The primary exceptions to this pattern are in regions of tropical Africa, India, and South America, where increases in relative humidity are anticipated (O'Gorman and Muller 2010).

These broad regional patterns of change in temperature and precipitation are common across all scenarios and are driven for the most part by increasing long-lived, well-mixed GHG. They are also common across time (for example, they can be seen in average changes around the middle of the

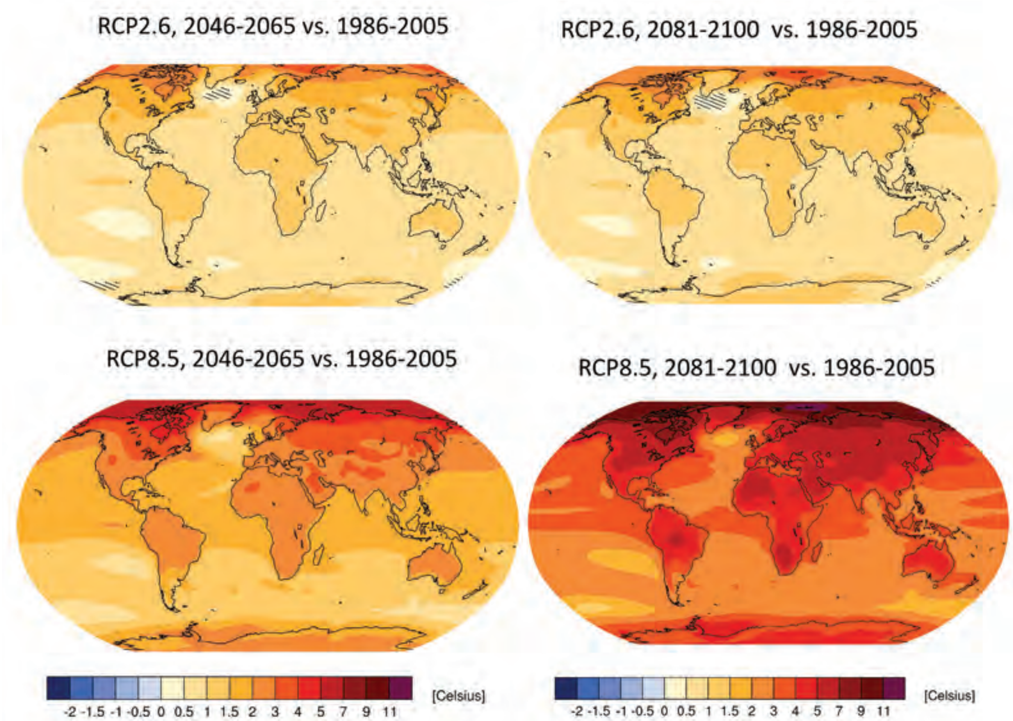


Figure 3.2 Projected changes in global surface temperature. *Mid (left) and late (right) 21st-century changes are compared with the period 1986–2005 for low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. The differences between scenarios get larger as time progresses. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

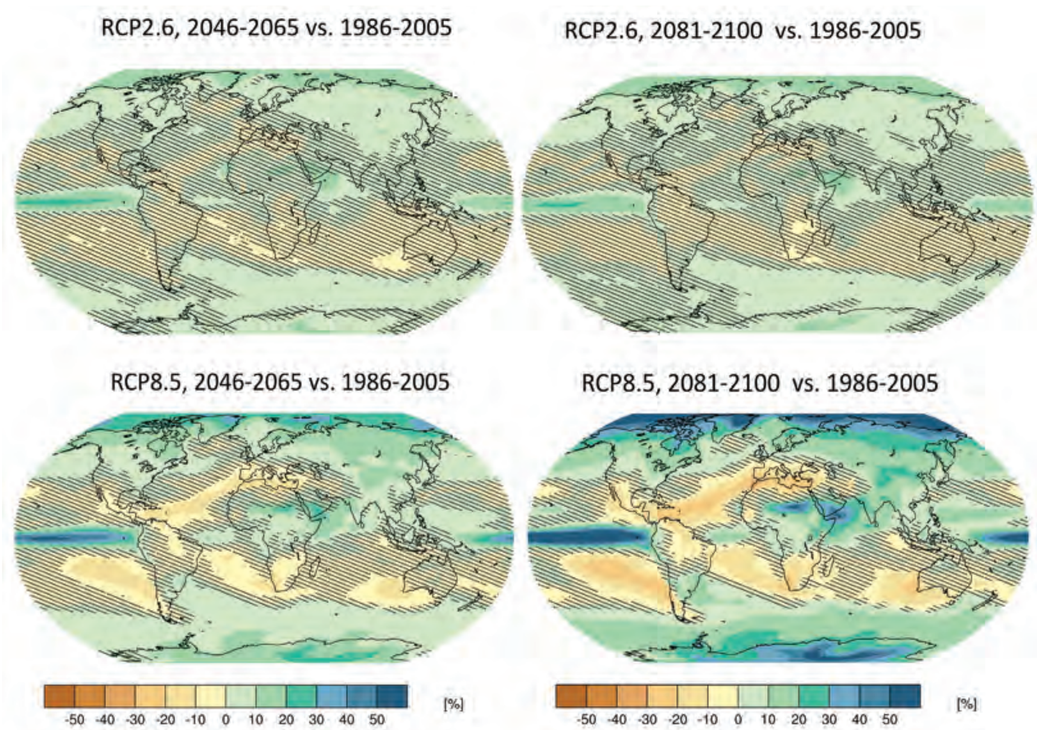


Figure 3.3 Projected changes in global precipitation. *Mid (left) and late (right) 21st-century changes are compared with the period 1986–2005 for low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. The general pattern is of wet regions becoming wetter and dry regions drier. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

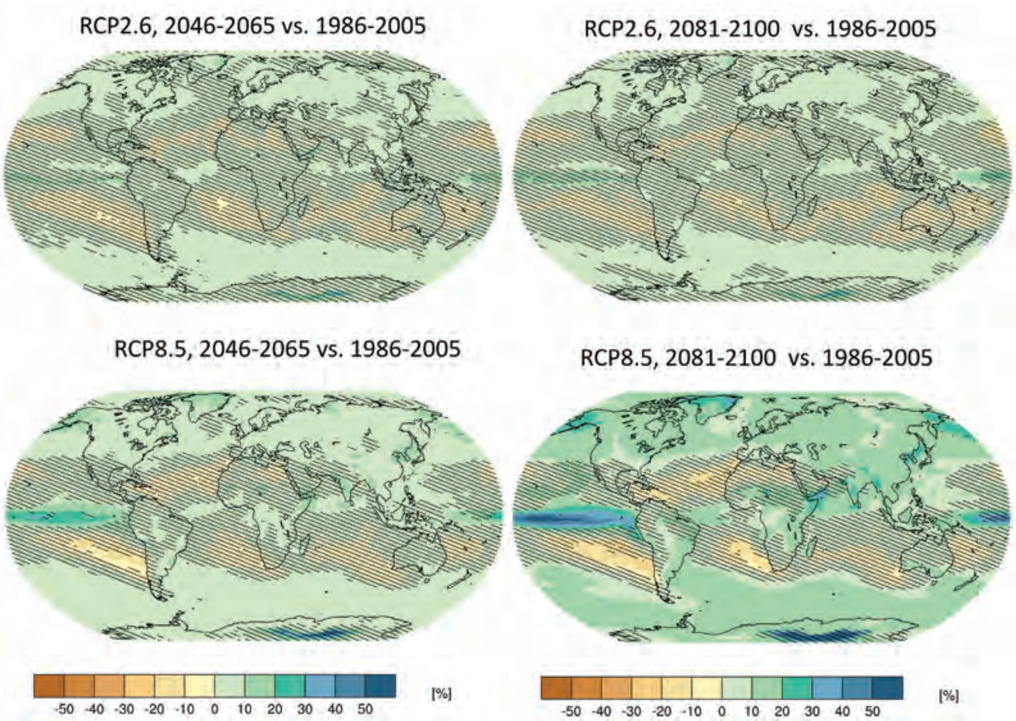


Figure 3.4 Projected changes in precipitation intensity. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Precipitation intensity is defined as the total amount of annual precipitation divided by the number of wet days. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

century as well as those at the end of the century) and, in first approximation, across models. The regions of largest discrepancies among models are the very high latitudes for temperature and, conversely, the low latitudes for precipitation.

Soil moisture is another important variable for agriculture that integrates the history of temperature and precipitation to some extent. Projected changes in soil moisture are shown in Figure 3.5. There are notable differences between changes under high versus low scenarios of GHG emissions and concentrations. Results for RCP 2.6 show some drying in high-latitude regions and central South America, with increased moisture in many other areas, while RCP 8.5 results in much more extensive drying in mid-latitude regions as well as high latitudes. This is seen in both the near-term and long-term projections, with the most extensive reductions found in the high-emissions results for the end of the century. This is a reflection of the fact that temperature plays an important role in depleting the soil of moisture through evaporation, and warming is significantly higher under the high-emissions scenario by the end of the century.

Another important agricultural quantity that can be derived from climate-model simulations is length of the growing season. Figure 3.6 shows projected changes in an index that adopts a simplified and uniform definition, where growing season length is represented by the number of consecutive days during the year with an average temperature above 5 °C. This index does not capture changes in tropical and subtropical areas that do not experience temperatures below 5 °C, where exceedance of physiological thresholds with higher temperatures can reduce growing season length. The RCP 2.6 low-emissions scenario results in growing seasons that are up to about 10% longer than currently throughout much of the mid-latitudes in the Northern Hemisphere by mid-century, without much further change by the end of the century. Some higher latitude areas of the Northern Hemisphere could see increases of 20%–30% and very high latitudes increases of 80%–100% by mid-century. For the RCP 8.5 high-emissions scenario, many of the northern mid-latitude areas see increases of 20%–30% by mid-century, with a more extensive area at very high latitudes increasing by 70%–100%.

The index displayed in Figure 3.6 does not capture change in tropical and subtropical areas, which are expected to experience shorter growing seasons due to lack of sufficient moisture and temperature increases that exceed physiological tolerances for

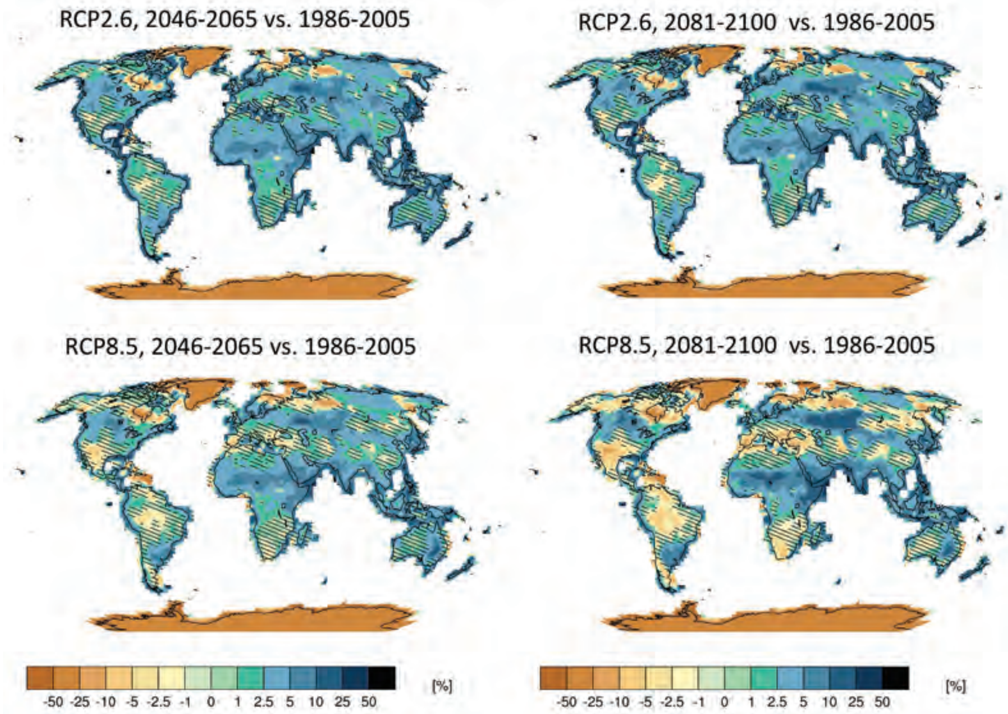


Figure 3.5 Projected changes in soil moisture. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Drying is much more pronounced in the higher emissions scenarios, particularly toward the end of the century. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

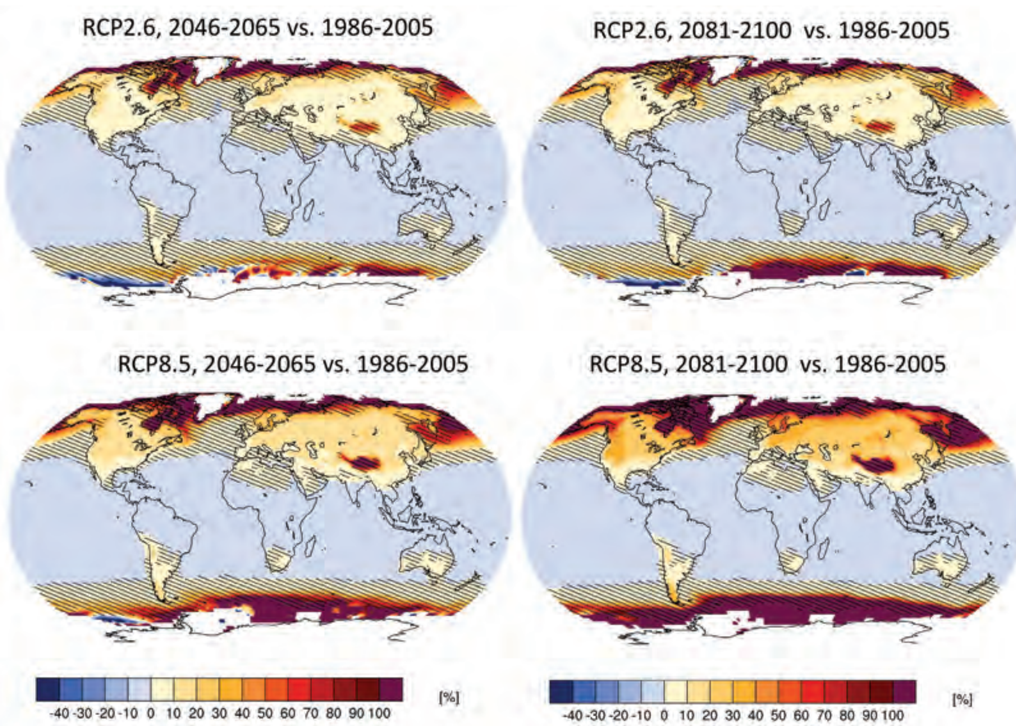


Figure 3.6 Projected changes in growing season length. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

many crops. In semiarid regions of the tropics, the length of the growing season is not determined by the number of days with temperatures greater than 5 °C, but by the balance between water supply (precipitation) and atmospheric water demand (potential evapotranspiration). In many areas, the latter will increase with increasing air temperatures. In some regions, these effects are expected to lead to substantial reductions in the length of the viable growing seasons by mid-century (Thornton et al. 2011, Cook and Vizy 2012).

Changes in average climate conditions are important, but agricultural production and other food-system elements are also affected by changes in extreme conditions. Figures 3.7 through 3.9 show changes in the tails (i.e., extremes) of the distribution of values derived from daily output of temperature or precipitation (Sillmann et al. 2013). The Frost Days index (Figure 3.7) counts the number of days in the year with minimum temperatures below freezing. The Consecutive Dry Days index (Figure 3.8) measures the longest stretch of days without agriculturally meaningful (>0.1 mm/day) precipitation every year. Finally, Figure 3.9 shows projected changes in the number of very hot days, defined as days with maximum temperatures in the upper 10% of observed daily highs in 1986–2005.

The maps of changes in frost days show a uniform decrease of such cold days all over the Earth's surface, with the regions experiencing the greatest warming (some areas of the high latitudes of the Northern Hemisphere) also showing the largest changes in this measure. The lowest decreases are seen in the near-term, low-emissions scenario and the greatest decreases in the long-term, high-emissions scenario.

The story told by changes in consecutive dry days (Figure 3.8) is consistent with precipitation changes, with large areas of the subtropics seeing significant lengthening of dry spells, while many of the high-latitude regions, where precipitation is expected to increase, see significant shortening of dry spells. The largest drying is seen in the long-term, high-emissions scenario, with many mid-latitude and tropical areas experiencing 30%–50% increases.

Looking at very hot days (Figure 3.9) in the low-emissions scenario (RCP 2.6), shows increases of 10%–20% in such days across large areas of

Changes in average climate conditions are important, but agricultural production and other food system elements are also affected by changes in extreme conditions.

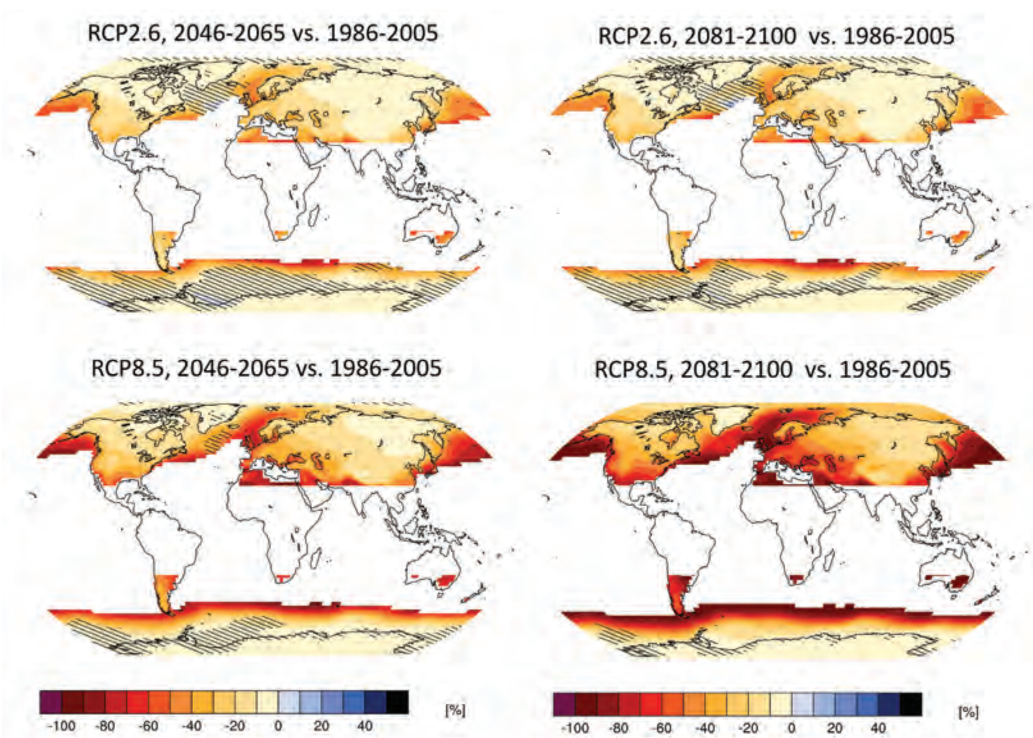


Figure 3.7 Projected changes in frost days. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Frost days are defined as the number of days during a calendar year with the minimum temperature falling below 0 °C. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/*

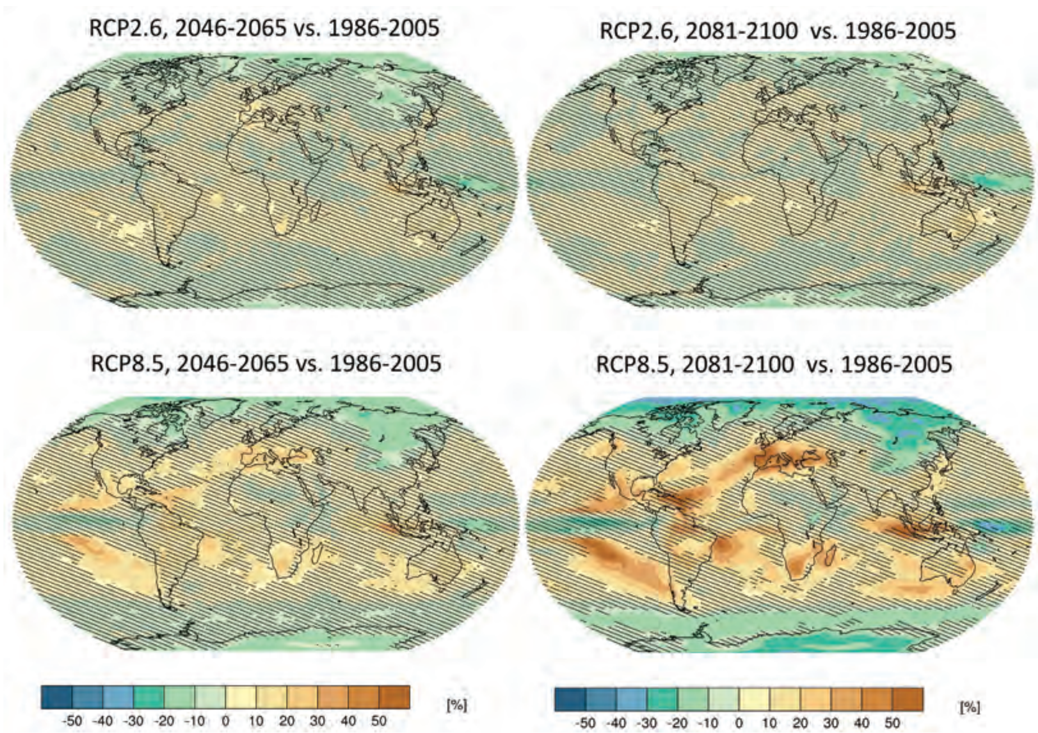


Figure 3.8 Projected changes in annual maximum number of consecutive dry days. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/*

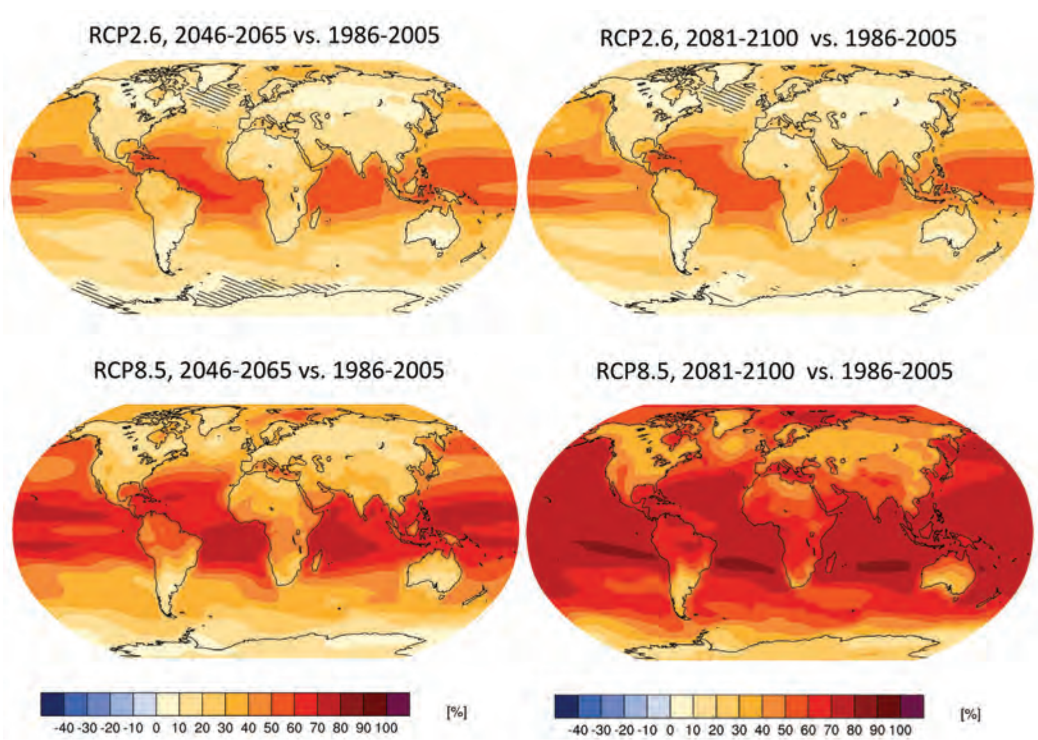


Figure 3.9 Projected changes in annual number of very hot days. *Mid (left) and late (right) 21st-century changes are compared to the 1986–2005 baseline under the low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where changes are small (less than one standard deviation) compared to natural variability. Very hot days are when maximum daily temperatures are above the 90th percentile of current climatology. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

continental interiors in the mid-latitudes and tropics, with smaller areas seeing increases of 30%–40%. This change persists in the long term, with late-century conditions quite similar to those seen in mid-century. The high-emissions scenario results in a greater number of very hot days. In the near term, large areas of the mid-latitude continental interiors are projected to see increases of 30%–40%, and some parts of South America and Africa may see increases of over 50%. In contrast to the low-emissions scenario, changes continue to occur and grow in magnitude. These increases may reduce the length of the effective growing season in some places in Africa, for example, by the middle of the 21st century (Cook and Vizy 2012). By the end of the 21st century, large parts of South America and Africa are projected to see increases of 60%–70% in the number of very hot days compared with today.

By mid-century, many regions are likely to experience temperatures that are outside historically observed natural variability, but changes in precipitation are not as clearly distinct. By late century, both temperature and precipitation are more unambiguously affected by increased atmospheric GHG concentrations. For the low-emissions scenario, the changes from mid-century to late century are not very large, reflecting the fact that this scenario stabilizes concentrations and thus the associated climate response. The continued increase in GHG concentrations under the high-emissions scenario results in greater change in the near term, with continued change from mid- to late century.

3.4 Socioeconomic Change

One of the challenges in assessing the potential future effects of climate change is that human systems and ecosystems are changing at the same time as climate changes are occurring. Some of these changes are themselves affected or driven by climate change while others are largely independent but still relevant to the overall capacity of society to adapt to or mitigate climate change. In addition, because many socioeconomic changes will not be tightly coupled with climate change, there is a range of possible climate futures associated with any given socioeconomic future and vice versa.

The rate and magnitude of recent technological and socioeconomic changes are very large. Global population increased from about 2.5 billion in 1950 to over 7 billion today. Global GDP changed from about USD 5.3 trillion to about USD 77.6 trillion over this same period. This rapid evolution must be considered in assessment of potential future effects

of climate change. Examining the way that different climate conditions would affect today's world can offer insights into some aspects of vulnerability but is unlikely to provide an accurate picture of future risks. In order to construct meaningful assessments of the potential future impacts of climate change, as well as possibilities for mitigation and adaptation, projections of future climate change need to be combined with projections of future biophysical and socioeconomic conditions, including demographic, economic, technological, social, and governance outcomes and the couplings and feedbacks between human and ecological systems (Ostrom 2009).

A wide variety of projections and scenarios of socioeconomic change have been created over the last several decades to support the assessment and analysis of environmental change, including those developed by the Millennium Ecosystem Assessment (2005), the IPCC Special Report on Emissions Scenarios (SRES; Nakicenovic et al. 2000), and the United Nations Environment Programme (UNEP 2007). All have been and continue to be widely used in climate impact studies–some results based on SRES scenarios are also considered in this document.

3.4.1 Shared Socioeconomic Pathways

More recently, the scientific community has developed new descriptions of socioeconomic futures called Shared Socioeconomic Pathways (SSPs) to facilitate climate-change research and assessment (O'Neill et al. 2014 and 2015, Ebi et al. 2014, Dellink et al. 2015). The SSPs are intended to describe future socioeconomic changes that could occur at the same time that climate is changing and that could affect the ability of societies to respond. Capturing the range of uncertainty in future societal conditions is an enormous task, given the myriad ways and rates at which societies may develop. In response to this difficulty, the SSPs are designed to span a wide but plausible range of societal conditions in two particular dimensions: (1) challenges to mitigation and (2) challenges to adaptation (O'Neill et al. 2014). These challenges are defined by a combination of elements, such as population growth, urbanization, education levels, income growth, technological progress, effectiveness of institutions, and so on (Rothman et al. 2013, Schweizer and O'Neill 2014).

Five SSPs have been developed. SSP1 assumes low challenges to mitigation and adaptation; SSP2 assumes medium challenges to both; SSP3 assumes high challenges to both; SSP4 assumes that adaptation challenges dominate; and SSP5 assumes that mitigation challenges dominate. Each SSP consists of a qualitative narrative, summarized below, describing general trends in the various elements of societal conditions and the logic for how and why these trends unfold together over time. In addition, each SSP will include quantitative projections—global and country-by-country—of key elements: population projections by age, sex, and education level; urbanization; and changes in GDP. Some of these have been published or submitted for publication; others are still under development. None is considered more or less likely than another.

SSP1: Low challenges to mitigation and adaptation. The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more-inclusive development that respects perceived environmental boundaries. Management of global environmental issues slowly improves, facilitated by increasingly effective and persistent cooperation and collaboration at local, national, and international levels across governments, the private sector, and civil society. Educational and health investments accelerate the demographic transition, leading to a relatively low population growth. Beginning with current high-income countries, the emphasis on economic growth shifts toward a broader emphasis on human well-being. Somewhat slower long-term economic growth is accepted and inequality is reduced across and within countries. Investment in environmental technology and changes in tax structures lead to improved resource efficiency, reducing overall energy and resource use and improving environmental conditions over the longer term. Increased investment, financial incentives, and changing perceptions make renewable energy more attractive.

SSP2: Moderate challenges to mitigation and adaptation. The world follows historical social, economic, and technological trends. Development and income growth proceed unevenly, but most economies are politically stable. Globally connected markets function imperfectly. Global and national institutions make slow progress improving living conditions and access to education, safe water, and health care. Technological development proceeds but without fundamental breakthroughs. Environmental systems mainly degrade, although there are some improvements. Overall intensity of resource and energy use declines. Fossil fuel dependency decreases slowly, but there is no reluctance to use unconventional fossil resources. Global population growth is moderate and levels off in the second half of the century, but the transition to low fertility rates in low-income countries is not accelerated. Persistent income inequality, continued societal stratification, and limited social cohesion result in continued vulnerability to societal and environmental changes and constrain sustainable development.

SSP3: High challenges to mitigation and adaptation. Concerns about regional identity, regional conflicts, competitiveness, and security, coupled with relatively weak global institutions, push countries to increase their focus on domestic and/or regional rather than global issues. Barriers to trade grow, particularly in the energy and agricultural markets. Countries focus on energy and food-security goals within their own regions and in some regions move toward more authoritarian government with highly regulated economies. Investment in education and technological development declines, economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time, especially in developing countries. Many countries struggle to provide access to safe water, improved sanitation, and health care for disadvantaged populations. The combination of impeded development and limited environmental concern results in environmental degradation and poor progress toward sustainability. Population growth is low in developed countries and high in developing countries.

SSP4: Low challenges to mitigation, high challenges to adaptation. Highly unequal investment in human capital, and increasing disparities in economic opportunities and political power, lead to increasing inequalities and stratification across and within countries. Over time, a gap widens between an internationally connected, well-educated society that contributes to and benefits from the global economy and a fragmented collection of lower-income, poorly educated societies that work in a labor-intensive, low-tech economy. Vulnerable groups have little representation in national and global institutions. Economic growth is moderate in developed and middle-income countries, while low-income countries struggle to provide adequate access to water, sanitation, and health care for the poor. Social cohesion degrades, and conflict and unrest are increasingly common. Technology development is high in the high-tech economy and sectors. Uncertainty in fossil fuel markets leads to underinvestment in new resources in many regions. Oil and gas prices rise, volatility increases, and energy companies invest in both low-carbon energy sources and carbon-intensive fuels such as coal and unconventional oil. Environmental policies focus on local issues around middle- and high-income areas.

SSP5: High challenges to mitigation, low challenges to adaptation. The world relies on competitive markets, innovation, and participatory societies (i.e., societies with extensive citizen involvement in decision making), to produce strong global economic growth, rapid technological progress, and development of human capital. Global markets are increasingly integrated and focused on maintaining competition and removing institutional barriers to the participation of disadvantaged population groups. Large investments in health, education, and institutions enhance human and social capital. Increased exploitation of abundant fossil-fuel resources results in adoption of resource- and energy-intensive lifestyles around the world. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary. Local environmental impacts are addressed effectively by technological solutions, but there is relatively little effort to avoid potential global environmental impacts due to a perceived trade-off with economic development. Global population peaks and declines in the 21st century. Though fertility declines rapidly in developing countries, fertility levels in high-income countries are relatively high (at or above replacement level) due to optimistic economic outlooks.

Taken together, the set of RCPs and SSPs provides a basis for the scientific community to conduct systematic and comparable analyses of future vulnerability, risks, and effects of climate change in the context of other environmental and socioeconomic changes. Most of the integrated modeling results examined in this assessment used combinations of SSP1, SSP2, and SSP3 with RCP 2.6 and RCP 8.5, although some results based on the SRES scenarios are also included. In some cases, SSPs are also used as a frame for qualitative assessment of likely future risks to food security, as they occur alongside other environmental and socioeconomic changes.

3.5 Conclusions

The projection of future climate and socioeconomic change is complicated by multiple interacting sources of uncertainty that vary over time. Climate projections are based on different estimates of future GHG emissions and concentrations. These emission- and concentration-scenario inputs, and the projections based on them, are more certain in the near term than the long because of the considerable inertia in energy infrastructure. However, near-term climate projections also include natural variability that is not always possible to distinguish from human-induced change in near-term results.

The Earth's climate is projected to continue changing over the coming decades and this century.

Over the longer term, socioeconomic futures and thus emission- and concentration-scenario inputs to projections are much more uncertain. The literature does not provide definitive answers about the relative likelihood of high versus low emissions and concentrations over the course of the next century, but there are increasingly clear differences between the climate outcomes from high-concentration and low-concentration scenarios. In low-concentration scenarios, natural variability still plays a significant role next to projected changes. In high-concentration scenarios, it is much easier to distinguish human-induced change from natural variability.

The current best practices for projecting climate change and its effects thus tend more toward identifying and investigating a range of plausible trajectories for future emissions and concentrations (e.g., representative concentration pathways) and a plausible range of possible societal conditions that affect vulnerability and adaptive capacity (e.g., shared socioeconomic pathways) rather than trying to determine a single, most-likely outcome. Using plausible future emissions to drive climate projections and plausible socioeconomic futures to assess vulnerability and response capabilities has enabled scientists to make contingent projections of future physical conditions and to identify some of the potential impacts of and adaptations to changing climate.

In summary, the Earth's climate is projected to continue changing over the coming decades and this century. Some degree of change will occur in response to past emissions even if aggressive action is taken to limit GHG increases in the future. Many projected changes are directly relevant to agriculture and food security, including increased temperatures, increased incidence of very hot days, decreased incidence of very cold days, increased precipitation, increased precipitation intensity, longer dry periods, decreased soil moisture in many regions, and rising sea levels.

The greater the increase in GHG concentrations, the greater the climate change and the greater the climate risks that will be experienced over the next 100 years and beyond; the lesser the increase, the lesser the change and the lesser the risks. It remains difficult to separate human-induced change from natural variability in near-term projections, particularly for regional and smaller-scale trends, but human-induced change becomes more obvious more quickly in projections driven by scenarios with larger and more rapid increases in GHG concentrations.

Global socioeconomic conditions are also projected to continue changing over the next century, but the rate and direction of some change is uncertain. For example, global population is projected to increase to 8.5–10 billion by 2050. Some estimates then show decreases back to about 7 billion during 2050–2100, while others show continued increase to more than 12 billion (UN 2012).

Societal factors are very important determinants of the magnitude of future climate change (because they affect GHG emissions and concentrations). They also help to determine the response to change, and ultimately, the level of effect and vulnerability, because they affect overall wealth, willingness, and ability to allocate resources to address societal issues, including practices and adaptation research. Thorough assessment of the risks and potential effects of climate change on food security thus requires consideration of a range of emissions/concentrations and socioeconomic pathways.

Chapter 4

Integrated Assessment Modeling of Agricultural and Food Systems

Key Chapter Findings

- Climate-change effects on overall global food production are likely to be detrimental, particularly later in the century, but these effects vary substantially by region.
- The most adverse effects are likely to occur in the tropics and subtropics, with some benefits possible at higher latitudes, due to differing biophysical and socioeconomic conditions.
- Technological, economic, and policy developments play important roles in the global food system. In the near term to mid-century, these factors are likely to be at least as important to food security as climate change for most emissions scenarios; under high emissions and later in the century, climate effects become much larger.

Previous chapters have described projections of climate and societal change and interactions of climate change and various elements of food security. Those chapters show that the global food system links farm-production systems to consumers globally through a web of interconnected food systems. In this chapter, we first discuss the quantitative models that are being used to project how climate change may affect regional and global food systems and thus food security. We then discuss agriculture-specific scenarios that are used to implement impact assessments and review some of the pathways and scenarios that have been developed.

4.1 Impact-Assessment Framework for Agricultural and Food Systems

Climate and adaptation analyses found in the literature can be described as answering three sets of questions about climate change: (1) What effects would a change in climate today have on the current food system? (2) What effects would a change in climate have on the food system in the future, *without* adaptation to any changes in climate? Who would be most vulnerable to climate change without adaptation, and who might benefit from climate change? (3) How could the food system perform in the future with climate change *and* adaptation? How would adaptation reduce vulnerabilities and help exploit any benefits of climate change? As previously discussed, studies addressing the first question can help to characterize current sensitivity and vulnerability but are of limited use in assessing future climate-change effects. We therefore focus most of the following discussion on studies addressing the latter questions.

Various models have been used to address these questions about possible climate impacts and adaptation. Most studies have utilized the modeling structure shown in Figure 4.1, in which climate projections from general circulation models (GCMs) are used by biophysical models to simulate productivity effects of climate change. These productivity impacts are then used as inputs to economic models that simulate economic outcomes. Some economic models directly incorporate climate variables, thus bypassing the biophysical-simulation models. Each of the model components in Figure 4.1 is implemented using corresponding pathways and scenarios that define inputs into the models. These pathways and scenarios represent the key nonclimate future conditions projected to exist in the future period represented for the impact assessment, such as those described in Chapters 2 and 3 (e.g., technological change, population growth, and income growth). These factors define the socioeconomic setting in which the analysis is couched and thus can strongly influence the outcomes of the analysis.

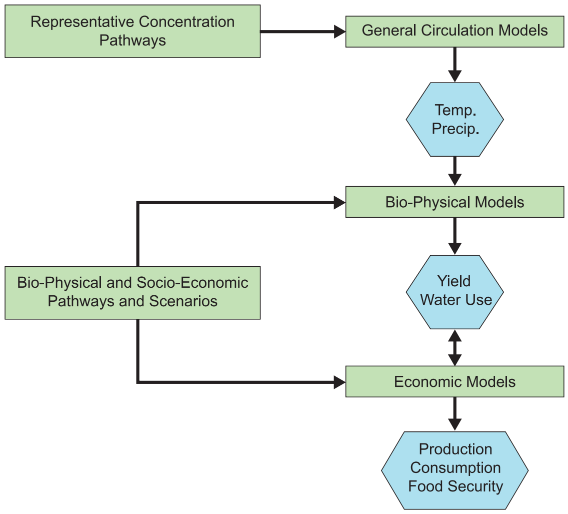


Figure 4.1 Framework for integrated agricultural and food system impact assessments. *Models of global economic and biophysical systems, driven by climate model outputs for different RCPs, are linked to assess outcomes under different future scenarios. Adapted from Wallach et al. 2015.*

The general modeling structure illustrated in Figure 4.1 can be elaborated in various ways, and the analysis can be carried out at various spatial and temporal scales. While in principle one large, fully integrated model could be constructed that would incorporate a dynamic system of nested biophysical and socioeconomic processes at different spatial and temporal scales, no such "supermodel" is currently feasible given data and computational limitations. Instead, a number of different models representing biophysical processes (e.g., crop growth) and economic processes (e.g., market determination of prices, production, consumption, and trade) are linked and simulated sequentially by passing outputs from one model to be used as inputs into another model in a logical sequence.

Global modeling systems generate outcomes such as food production and consumption at the national level or in multi-country regions and are thus relevant to food availability at those scales. To achieve higher analytical resolution for outcomes such as poverty and food security, several approaches have been developed. One approach is to link a global model to nationally disaggregated data (Hertel et al. 2010). Alternatively, the Agricultural Model Intercomparison and Improvement Project (AgMIP) has developed a coordinated global and regional approach to integrated assessment of agricultural effects and adaptation to address the three sets of questions identified earlier (Antle et al. 2015, Rosenzweig et al. 2013). In this approach (Figure 4.2), climate projections of temperature and precipitation from GCMs are downscaled and linked to globally gridded biophysical models that simulate productivity effects on crops and livestock. In addition, global socioeconomic pathways and scenarios are used to construct projections of other inputs needed for global agricultural economic models, such as productivity growth and trade policy. These global models simulate production, consumption, trade, and land use for multinational or national regions as well as market equilibrium prices. To obtain estimates of effects that are less highly aggregated (for example, specific to geographic regions or socioeconomic groups), the prices and yields from the global economic models are used as inputs into regional economic models. These regional models can simulate outcomes such as the regional distribution of production, income, and poverty rates and can be used to construct food-security indicators (see section 4.6.2).

4.2 Biophysical Models

The biophysical component of the assessment framework shown in Figure 4.1 can involve several parts. First, regional climate models or downscaling of gridded GCM outputs to higher spatial and temporal resolutions are needed to serve as inputs to global gridded production-system models and regional gridded or point-based models. These biophysical models should, in principle, represent major agricultural products, including crops and livestock, although thus far, most models have represented only major grain commodities (such as maize, soybeans, wheat, and rice), and some kinds of livestock. In addition, other components may represent water quantity, for example, by linking an economic model such as IMPACT to a watershed model (Rosegrant et al. 2012). Similar model linkages may be done with national or subnational models.

Biophysical crop and livestock models are important tools to use in translating the biophysical consequences of climate change (i.e., changes in temperature and precipitation) into yield changes that give rise to economic impacts. The findings of a large number of such crop model simulation studies is summarized in a recent meta-analysis that utilized over 1,700 studies of climate impacts on crop yields (Challinor et al. 2014) and in the latest assessment report of the IPCC (Porter et al. 2014). Challinor et al. (2014) found that without adaptation, losses in aggregate production of about 2%–10% are expected for wheat, rice, and maize in both temperate and tropical regions for a temperature increase of 2 °C over late 20th century temperatures. Crop-level

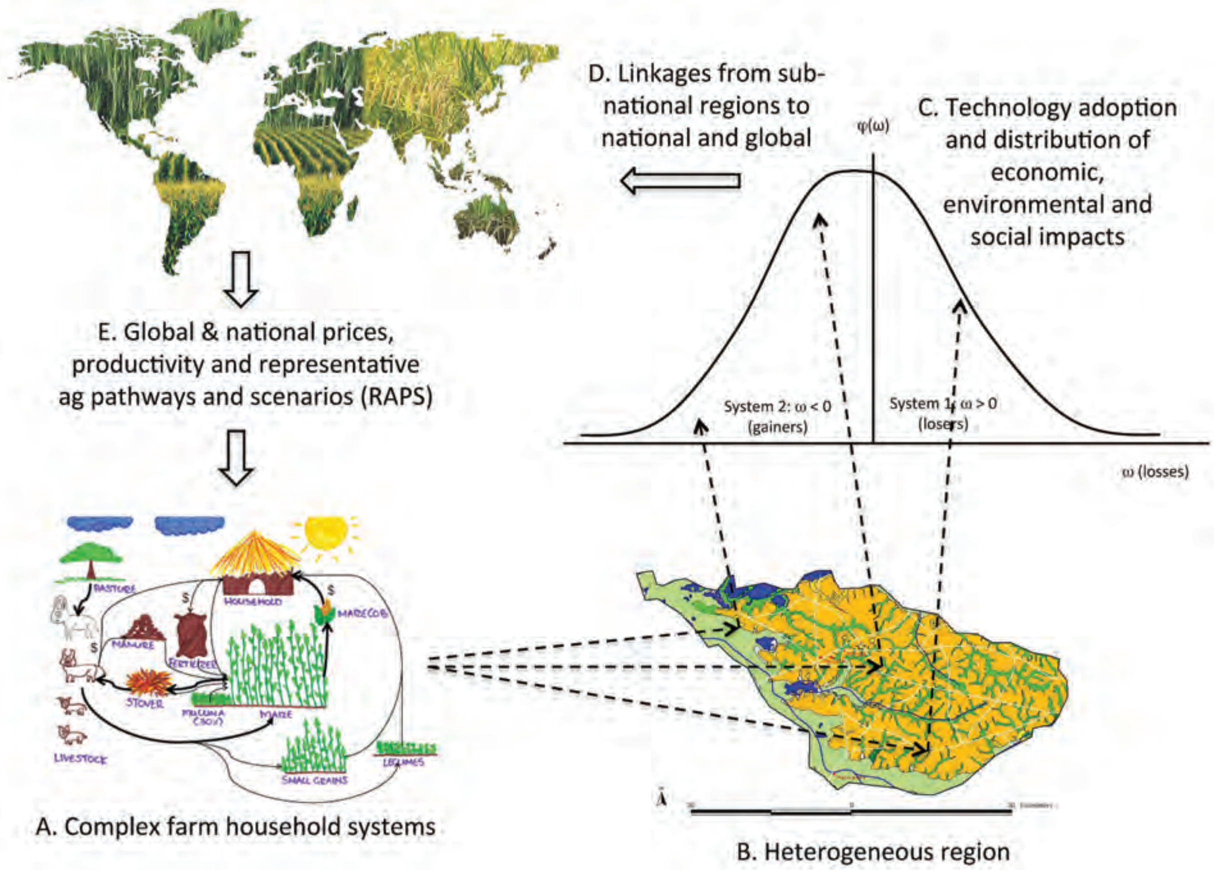


Figure 4.2 The AgMIP Regional Integrated Assessment Framework. *Climate-change impacts, adaptation, and vulnerability assessments are linked across scales, from the field and farm scale (A) to the landscape/subcountry scale (B), leading to analysis of technology adoption and impact assessment in heterogeneous farm household populations (C). This regional analysis may feed back to the country and global scales (D). The entire analysis uses consistent inputs and assumptions from global and national price and productivity projections and representative agricultural pathways (E). Source: Antle et al. 2015.*

adaptations increase simulated yields by an average of 7%–15% compared to yields modeled without adaptation, with adaptations more effective for wheat and rice than maize, again for a temperature increase of 2 °C over late 20th century temperatures. Yield losses were found to be greater in magnitude for the second half of the century than for the first. Consensus on yield decreases in the second half of the century is stronger for tropical than temperate regions, yet even moderate warming may reduce temperate crop yields in many locations.

When set up to operate on a spatial grid corresponding to climate data, crop and livestock models provide the expected changes in yield associated with downscaled future climate data generated from the GCMs (Jones and Thornton 2013). In recent model comparisons (Rosenzweig et al. 2014, Warszawski et al. 2014), three broad types of crop models were identified: (1) site-based crop models, (2) agro-ecological models, and (3) agro-ecological zone models. While differences in model types stem from the original purpose, scale, and parameterization of the models, the suite of models analyzed showed similarities in how they respond to changes in climate. These recent studies also indicate detrimental effects of climate change, especially at higher levels of warming and at low latitudes. Models that include explicit nitrogen stress project more severe impacts (see Figure 4.3 for the case of maize). Across seven global gridded crop models (GGCMs), five GCMs, and four representative concentration pathways, model agreement on the direction of yield changes is found in many major agricultural regions at both low and high latitudes. However, better understanding of yield response to factors such as atmospheric carbon dioxide (CO_2 fertilization), nitrogen applications, and high temperatures is needed to improve confidence in impact assessments and to evaluate adaptation strategies.

There are also important limitations to these models that are the subject of ongoing research and model improvements (Bryan et al. 2009, Mertz et al. 2010). For example, crop-simulation models can represent only some aspects of adaptation, such as changes in

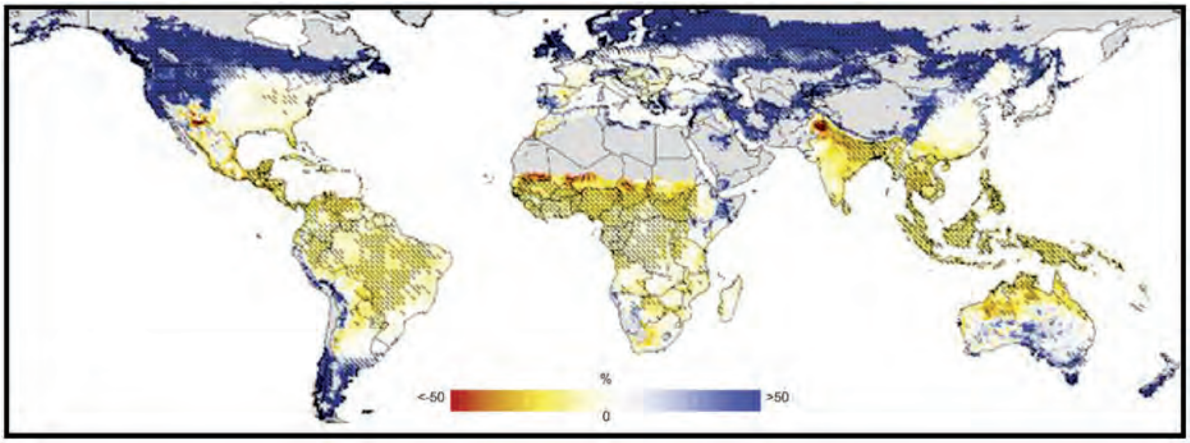


Figure 4.3 Median yield changes for RCP 8.5 (2070–2099) relative to 1980–2010. *Analysis includes CO_2 effects over five GCMs X seven GGCMs for rain-fed maize. Hatching indicates areas where more than 70% of the ensemble members agree on the directionality of the yield change. Gray areas indicate historical areas with little to no yield capacity. Source: Rosenzweig et al. 2014.*

cultivars, planting dates, and the use of irrigation. Another important limitation is that most models do not explicitly account for pests and diseases. Crop models also have difficulty predicting response of yields to the timing of rainfall and dry spells within a growing season (Baigorria et al. 2007, Lobell 2013, Ramirez-Villegas and Challinor 2012). Despite these issues, biophysical models are providing useful insights into potential effects of climate change on crop growth and yield.

4.3 Global Economic Models

Two types of economic models have been used for global assessments of climate impacts: (1) Partial Equilibrium (PE) models and (2) Computable General Equilibrium (CGE) models (Burfisher 2011). PE models represent one or a few sectors of the economy, whereas CGE models represent the entire economy, including linkages between sectors (manufacturing, agricultural, service, etc.) used to produce economy-wide final outputs (van der Mensbrugghe 2013). Both types of models use a set of mathematical equations to represent the economy, utilize databases of information that quantify economic activity of firms and consumers, and use assumptions that are often based on empirical literature to create initial input values (van Tongeren et al. 2001). PE models typically provide a more-detailed representation of the agricultural sector, but a less-complete representation of the entire economy, than CGE models.

These models are useful because they can simulate policy "experiments" before policies are implemented, making it possible to investigate possible future impacts of technological and climate changes and adaptations (Hertel et al. 2010, Lofgren et al. 2002). However, as discussed in the next section, the various models in the literature can produce substantially different projections of economic outcomes, suggesting substantial model uncertainty.

4.4 Regional Economic Impact-Assessment Models

There are various types of economic models that can be used for regional impact assessment, including regional optimization models (e.g., Mérel and Howitt 2014), regional technology-adoption and impact-assessment models (e.g., Antle 2011, Claessens et al. 2012), regional land-use models (Wu et al. 2004), and national partial-equilibrium economic models (Beach et al. 2010). Also, various statistical and econometric models have been used to assess climate-change impacts on economic outcomes, such as land values or value of production (e.g., Mendelsohn and Dinar 2009).

Some regional models are focused on commodities, while other models represent the linkages among crop- and livestock-production systems. Some models also include representation of household activities such as food preparation and nonagricultural income-generating activities such as off-farm work. These models utilize variables from global models as inputs—notably prices, productivity, and land use. However, the global models do not project the level of detail needed for a number of important input variables (for example, farm size, household size, the use of family and hired labor, and cost of production), so these input variables must be set by the researcher to be consistent with the future socioeconomic scenarios used in the analysis. Like global models, these regional models can be linked to biophysical crop and livestock production models to incorporate the effects of climate change on productivity. Van Wijk et al. (2014) reviewed 126 farm-level and regional models and found that none of them had been formulated to directly model food-security outcomes, but they did simulate food-production and income outcomes that are related to food availability and access.

4.5 Global Climate-Impact Assessments for Agricultural Systems

Most global agricultural assessments carried out over the past decade have utilized scenarios from the IPCC Special Report on Emissions Scenarios together with corresponding data from the CMIP. Some studies utilized "business as usual" trends, whereas others used scenarios with a range of alternate plausible futures. The latter studies include the recently updated FAO World Agriculture Towards 2030/2050 projections (Alexandratos and Bruinsma 2012), the reference-world scenario of the International Assessment of Agricultural Science and Technology for Development (IAASTD 2009), and the baseline scenarios of the IFPRI Food Security, Farming, and Climate Change to 2050 report (Nelson et al. 2010).

4.5.1 Global Assessment Pathways and Scenarios for Agriculture

In collaboration with AgMIP and the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Warszawski et al. 2014), a group of nine major modeling teams completed the first global agricultural economic model intercomparison of climate change impacts, in which all of the models used a standard set of scenarios that combined RCP 8.5 with the population- and economic-growth assumptions from two SSPs, two crop-simulation models to project the impacts of climate change on crop productivity, two biofuel-policy assumptions, and one scenario with a lower price of oil (Nelson and van der Mensbrugghe et al. 2014, von Lampe et al. 2014). The goal of the model-comparison exercise was to understand the differences in model projections and behavior and to identify the sources of these differences. The group did use a consistent set of assumptions for key driver variables, including assumptions for crop yields, energy-price (based on crude-oil price), and the production of biomass-based energy. Importantly, these scenarios did not embody the effects of increasing CO_2 concentrations, such as increased CO_2 fertilization, on crop yields and used climate projections based on RCP 8.5, so in these dimensions the scenarios can be viewed as relatively pessimistic. However, the group did incorporate a relatively optimistic set of projected growth rates for crop yields to represent the impacts of ongoing productivity improvements. These rates ranged from 1% to 2.5% for major crops (wheat, coarse grains, rice, sugar, and oilseed) across the major regions of the world (von Lampe et al. 2014), so in this regard the scenarios can be viewed as somewhat optimistic.

To increase the relevance of socioeconomic pathways to agriculture, AgMIP has developed the concept of *representative agricultural pathways* (RAPs) for both global and regional impact assessment. RAPs are designed to be an internally consistent set of narratives and drivers for integrated assessment of climate impact, adaptation, and vulnerability that can be linked to SSPs (Valdivia et al. 2015). As an extension of the previously described AgMIP/ISI-MIP global model intercomparison that was carried out with nine models, five of those global modeling teams developed a set of RAPs corresponding to SSPs 1, 2, and 3 (refer to Chapter 3 for SSP definitions). In addition to the economic-growth, population-growth, urbanization, and land-use assumptions associated with the three SSPs, these RAPs involved a set of distinct agricultural assumptions for yield growth and agricultural trade policy. The first RAP was associated with SSP1 and RCP 4.5, and included both standard SSP1 trade-policy assumptions and a variation with liberalized agricultural trade; the second RAP was associated with SSP2 and RCP 6.0, with SSP2's neutral (business as usual) agricultural trade; and the third RAP was associated with SSP3 and RCP 8.5, including both the standard SSP3 trade policy and a variation with more-restrictive trade (Wiebe et al. 2015). Results from these RAPs are reported in section 4.5.3.

4.5.2 Global Economic Model Projections and Implications

Literature on assessing the impacts of climate change on projected global agricultural productivity and food security is vast. A recent summary is provided by the Commission on Sustainable Agriculture and Climate Change (Beddington et al. 2012, Porter et al. 2014, Hertel and Lobell 2014). Here we highlight some key findings of this summary and their implications for food security.

Early interdisciplinary studies combined partial- and general-equilibrium economic models, crop models, and climate models to make projections about future food supplies (Rosenzweig and Parry 1994, Rosenzweig and Iglesias 1994, Sonka and Lamb 1987). These studies projected that climate change would cause an increase in the total number of people at risk of hunger relative to a world without climate change, though that number would represent a lower proportion of the total population due to population growth over that time period (Chen and Kates 1994, Fischer et al. 1994, Fischer et al. 1996, Rosenzweig and Parry 1994). Subsequent studies refined projections but did not substantially alter the implications of the earlier studies; however, they did emphasize more-adverse effects on developing countries in the tropics (Fischer et al. 2005, Parry et al. 2005). These and more-recent studies also demonstrated the differences that technological improvements and overall income growth could make in reducing food insecurity and showed that those effects could be much more important than the effects of climate change up to mid-century (Nelson et al. 2009 and 2010, Porter et al. 2014). Thus, recent studies have shown that socioeconomic conditions play a major role in determining vulnerability to climate change.

Global modeling studies simulate global and regional food production, prices, consumption, and trade. To translate these effects into changes in food security, additional assumptions and analyses are required. One approach used by global modeling studies is to develop statistical links between projected changes in production or consumption to food-security indicators. For example, Fischer et al. (2005) utilized the correlation between the share of individuals undernourished (as defined by the Food and Agriculture Organization) in the population and the ratio of average national food supply (including imports), relative to aggregate national food requirements, to assess the impacts of climate change on food security. Based on this relationship (Figure 4.4), and using a set of socioeconomic and GHG-concentration scenarios based on the SRES, Fischer et al. found that the percentage of undernourished population approached zero in countries where food production exceeds 160% of national requirements.

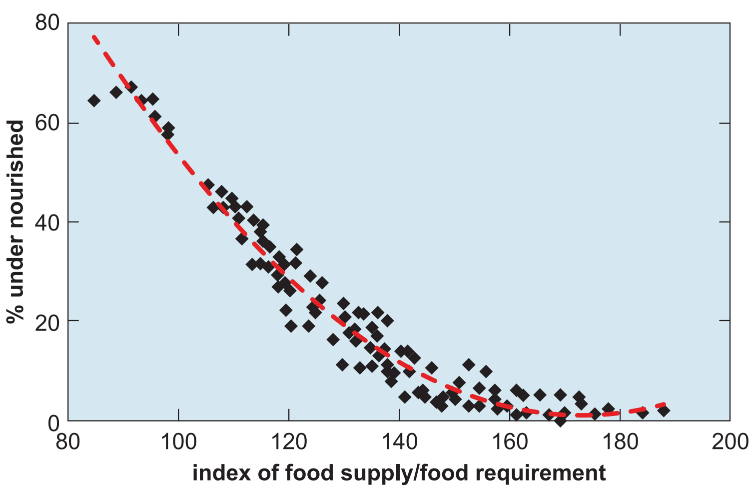


Figure 4.4 Estimates of undernourished population relative to food supply. *This relationship based on data from the Food and Agriculture Organization shows a correlation between the shares of undernourished individuals in the total population and the ratio of average national food supply, including imports, relative to aggregate national food requirements. Source: Fischer et al. 2005.*

Fischer et al. also projected that a scenario characterized by high GHG concentrations, high population growth rates, and constrained economic development (the SRES A2 scenario, roughly similar to SSP3) would increase the number of people at risk of hunger, finding that an additional 175 million people could be undernourished in 2080 because of climate change (representing 2.6% of the projected overall population of food-insecure countries in 2080). The same socioeconomic conditions in conjunction with CO_2 concentrations of about 550 ppm resulted in an estimate of up to 60 million additional people at risk; concentrations of about 350 ppm did not result in an increased number of people at risk. In the less-pessimistic SRES scenarios, declines in the risk of hunger over time due to socioeconomic change outweigh increase in hunger risk due to climate change. Analyses based on hypothetical scenarios of sustained economic growth and moderate population growth without climate change suggest that the number of food-insecure people could be reduced by 50% or more by 2040, with further reductions over the rest of the century. Such analyses should not be interpreted as projections, since climate change is already occurring, but they clearly indicate that socioeconomic factors have large effects on food insecurity.

Another example of an indicator used to examine economic outcomes on health and nutrition is found in a study by Nelson et al. (2010), which compared per-capita calorie availability from cereals and meat against an index of child malnutrition. For the former, the study used the IMPACT model, which estimates per-capita calorie availability by country. For the latter, the study estimated the percentage of malnourished children under the age of 5 using average per-capita calorie consumption, assuming that other important factors (life expectancy, maternal education, and clean-water access) are constant in all future scenarios. Estimates of calorie availability and child malnutrition were updated based on hypothetical investments in agricultural research, roads and irrigation. The goal of the study was to estimate the agricultural-productivity growth needed to meet a nutrition or calorie-availability target and then estimate the investment expenditures needed in research, irrigation, and roads to generate that productivity growth. As with the Fischer et al. (2005) study, a major limitation of this methodology is that it relies on data aggregated to the national level (in this case, data for calorie availability) and thus cannot represent changes in food access, utilization, or stability among country populations.

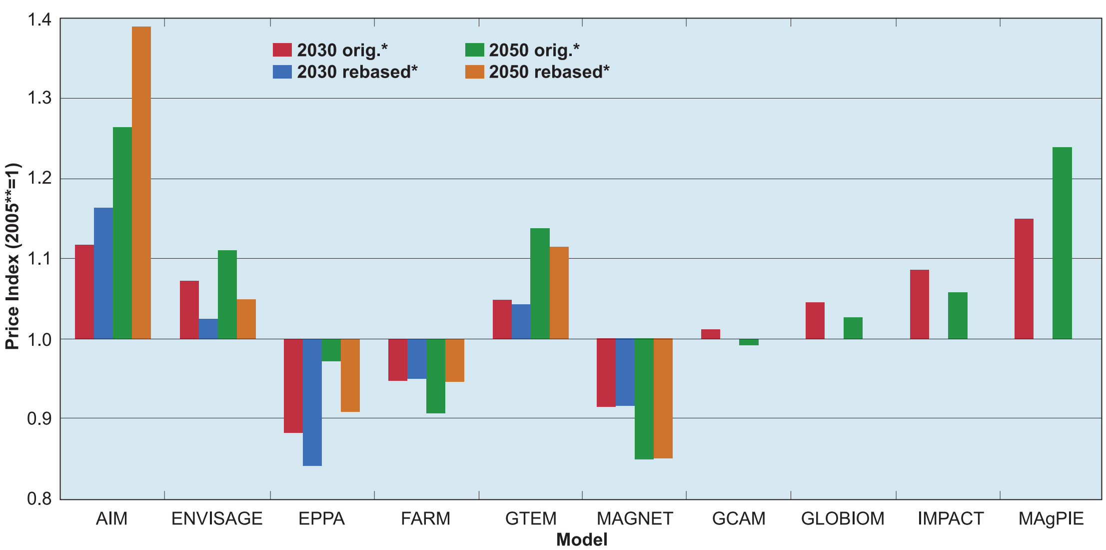
Based on this methodology, Nelson et al. (2010) found that climate change and ongoing global development could contribute to price increases for the most important agricultural crops—rice, wheat, maize, and soybeans—and that higher feed prices result in higher meat prices. These researchers projected that these price increases would slightly reduce growth in meat consumption and cause a more substantial fall in cereal consumption. Projections that combined climate change and pessimistic socioeconomic conditions resulted in a decline in calorie availability in 2050 relative to 2000 levels throughout the developing world. By 2050, this decline in calorie availability could increase child undernutrition in low-income developing countries by 20% relative to a world with no climate change. More positive socioeconomic conditions resulted in less-negative effects but still produced less improvement than cases with no climate change. In conclusion, this study shows that climate change could reduce much of the improvement in child malnourishment levels that could occur without climate change.

4.5.3 AgMIP Global Integrated Modeling Results

Some key findings of the AgMIP global agricultural model intercomparisons and related climate-impact assessments, based on nine global economic models, are discussed below and summarized in Figures 4.5, 4.6, and 4.7 (Nelson and Valin et al. 2014, Nelson and van der Mensbrugghe et al. 2014, von Lampe et al. 2014, Wiebe et al. 2015). Figure 4.5 presents price projections for five agricultural-commodity groups (wheat, coarse grains, rice, oilseeds, and ruminant meat) for 2050. These projections exclude climate change but include other factors such as income growth, population growth, and trends in agricultural productivity. This figure is useful because it shows how differently the nine models perform in terms of projecting future economic outcomes such as prices. The figure shows that some models project substantially higher agricultural-commodity prices in the future relative to those observed today, whereas other models show prices falling. Therefore, even without imposing climate change on the agricultural economic models, a wide range of plausible future price trends are possible, suggesting that there is a high degree of uncertainty in these model projections that is distinct from uncertainty associated with the introduction of climate-change effects.

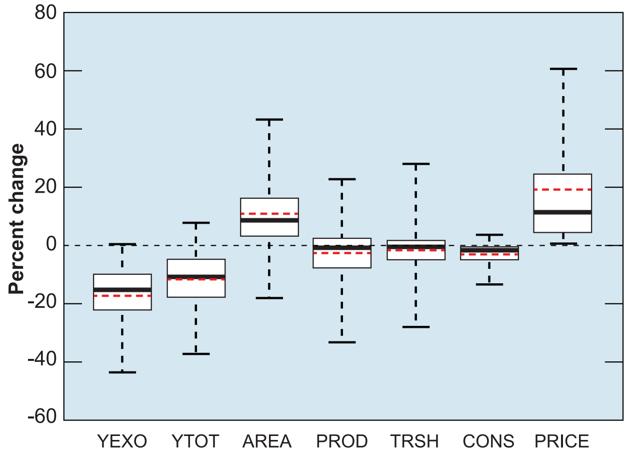
...climate change could reduce much of the improvement in child malnourishment levels that could occur without climate change.

Figure 4.6 summarizes the projected results for the impacts of climate change, using the nine global



* original: relative to model-standard numeraire; rebased; relative to the price index for the global GDP
** trended 2005, i.e. hypothetical in the absence of short-term shocks

Figure 4.5 Projected changes in commodity prices in 2050, absent climate change. *This aggregate index for wheat, coarse grains, rice, oilseeds, and sugar shows the differences in price projections across global agricultural economic models when socioeconomic changes such as population growth and economic growth are included and climate change is not. Source: von Lampe et al. 2014.*



	YEXO	YTOT	AREA	PROD	TRSH	CONS	PRICE
n	2891	2891	2891	2891	2891	2891	2891
Mean	-0.17	-0.11	0.11	-0.02	-0.01	-0.03	0.2
SD	(0.13)	(0.17)	(0.25)	(0.25)	(0.26)	(0.06)	(0.24)

Figure 4.6 Change and variability of crop and economic model projections for 2050. *In 2050, lower average yields under climate change, either with (YTOT) or without (YEXO) climate adaptation management measures, result in higher prices (PRICE) for most agricultural commodities, in spite of increased land area under production (AREA). Adaptation measures reduce climate impacts on yields (YEXO vs. YTOT), while global production (PROD), consumption (CONS), and trade (TRSH) are not projected to dramatically change. Significant variability results from the study spanning nine models, four crop aggregates, seven crop models and socioeconomic scenarios, and 13 regions. Source: Nelson and Valin et al. 2014.*

economic models in the AgMIP study. This figure shows results from seven different socioeconomic scenarios that included two SSPs, two different crop models to project effects of climate change on productivity, and alternative assumptions about the prices of biofuels and fossil fuels. Several important points can be observed from the different columns presented within the figure. The lower average yields associated with climate change in most parts of the world are reflected in higher prices for most agricultural commodities compared to a world with a 2005 climate, but the size of this effect varies widely across the models, ranging from 0% to 20% for most models. Global consumption in 2050, however, is not expected to decline significantly relative to the baseline scenario without climate change. Most models project some increases in land area under production but with little impact on trade relative to a world without climate change in 2050.

An important question for the U.S. food system is how these global projections for production, consumption, trade, and prices compare to impacts on the United States. When the results of the global models are disaggregated by major regions of the world, the results show substantially the same patterns as Figure 4.6, even though the impacts of climate change on crop and livestock productivity is projected

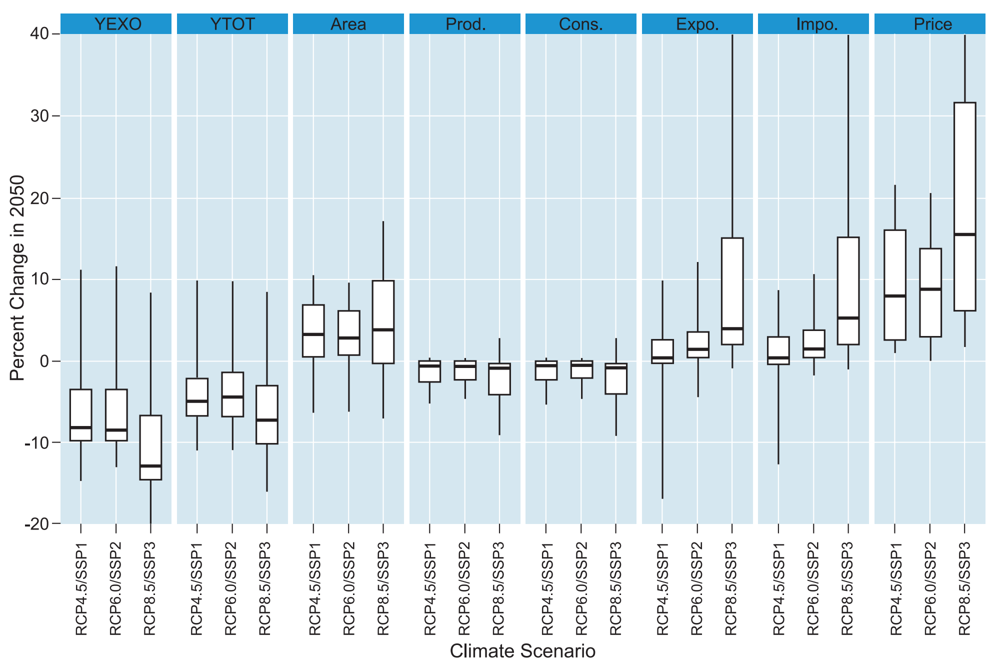


Figure 4.7 Climate-change effects under different SSPs and RCPs. *The "high-concentration/low-international cooperation" scenario (RCP 8.5/SSP3) shows much larger and more variable climate-change effects for the five commodities (coarse grains, rice, wheat, oilseeds, and sugar), with a more pessimistic development pathway, than the "medium-concentration/middle-of-the-road" (RCP 6.0/SSP2) and "low-concentration/sustainable-development" (RCP 4.5/SSP1) scenarios. Results are from three GCMs and five economic models, aggregated across 13 regions (n = 75). YEXO = yield effect of climate change without technical or economic adaptation, YTOT = realized yields after adaptation, AREA = agricultural area in production, PROD = total production, CONS = consumption, Expo = exports, IMPO = imports, PRICE = prices. Source: Adapted from Wiebe et al. 2015.*

to be larger for regions such as Africa and South Asia. These findings suggest that with largely integrated global markets and relatively free trade, the impacts of climate change are likely to be distributed around the world through the offsetting effects of the market and other economic adjustments.

As noted previously, the AgMIP global model intercomparison using nine models was extended to an analysis of RAPs that were designed to be consistent with three SSPs, each combined with a different assumed climate outcome (Wiebe et al. 2015): SSP1 with a medium level of climate change (RCP 4.5), SSP2 with somewhat more climate change (RCP 6.0), and SSP3 with a high level of climate change (RCP 8.5). Figure 4.7 summarizes the results of these projections for aggregate yield, area, production, consumption, trade and prices from five economic models. The results show that there are substantial differences between the "high-concentration, high-population growth, restrained-economic growth" scenario (SSP3/RCP 8.5) and the "low-concentration, low-population growth, high-economic growth" and "medium-concentration, medium-population growth, high-economic growth" scenarios (SSP1/RCP 4.5 and SSP2/RCP 6.0). The high-concentration, high-population, lower-economic growth scenario shows much larger climate-change effects than the lower-concentration scenarios, and also much larger differences across the models.

The high-concentration, high population, lower economic growth scenario shows much larger climate change effects than the lower concentration scenarios

Wiebe et al. (2015) project that yields would decline by a median of 7.2% in the high-concentration scenario, while area would increase by 3.8%, production and consumption would decline by 0.9%, exports and imports would increase by 4.0% and 5.3% (respectively), and prices would increase by 15.5%, all relative to a baseline projection for 2050 that does not include additional climate change between now and then. They also found that this scenario produced a wider range of price effects across crops and models than the two lower-emissions scenarios. Further analysis of the baseline scenarios suggests that the climate effects in 2050 of a high-emissions scenario are stronger than the differences between the underlying socioeconomic trends, at least at the global level.

Wiebe et al. (2015) also show that in the case of low international cooperation and high concentrations (SSP3/RCP 8.5), restricting trade results in higher prices, and thus more-adverse consequences of climate change, and a larger spread across models. This result is what economists would expect and shows that trade policy and other aspects of economic and political coordination are likely to play a role in determining the impacts of climate change on global and regional food security. However, it is important to note that the differences across scenarios cannot be attributed to any single factor, as both climate and socioeconomic conditions change.

4.6 Regional Modeling Studies

A number of regional (national or subnational) modeling studies have assessed the effects of climate on agriculture (Porter et al. 2014). These regional studies include statistical and process-based studies of crop productivity, similar to the GGCM studies discussed previously; regional econometric studies that focus on predicting how climate change may affect economic outcomes such as crop revenue or land values; and regional integrated-assessment studies, similar in design to the global modeling studies described earlier but focused on national or subnational regions.

4.6.1 Statistical, Econometric, and Integrated-Assessment Studies

Schlenker and Lobell (2010) used statistical models to evaluate the potential effects of climate change on crops in Africa. They combined historical crop-production and weather data into a model of yield response to climate change for several key African crops. By mid-century, the mean estimates of aggregate production changes in Sub-Saharan Africa are estimated to be −22% for maize, −17% for sorghum, −17% for millet, −18% for groundnut, and −8% for cassava, compared to a historical baseline period of 1961–2000. They also found that countries in this region with the highest average yields had the largest projected yield losses, suggesting that well-fertilized modern seed varieties are more susceptible to heat-related losses.

Econometric models have also been used to assess climate impacts on economic outcomes such as farmland values and revenues. A study by Mendelsohn and Dinar (2009) on a number of regions of the world suggest that agriculture in developing countries is more sensitive to changes in climate than agriculture in developed countries. This is consistent with the generally more-adverse effects of climate change on crop and livestock productivity in the tropics found in crop- and livestock-modeling studies. Rain-fed cropland is generally more sensitive to warming than irrigated cropland (Mendelsohn and Dinar 2009). The analysis shows that farmers are likely to make many adjustments to adapt to climate change, including switching crops and livestock species, modifying irrigation practices,

and alternating between livestock and crops. The results also reveal that effects and adaptations vary across landscapes, suggesting that adaptation policies must be location-specific. However, the focus of these studies on outcomes such as crop yields and farm revenues limit their ability to provide direct information and assessment of food-security outcomes.

Recent studies by Valdivia et al. (2012) and Claessens et al. (2012) illustrate the use of a disaggregated regional integrated-assessment approach and were the first regional studies to utilize RAPs to project impacts under future socioeconomic conditions. These studies assessed the effects and possible adaptation strategies on the incomes and poverty of farm households in two regions of Kenya. The studies showed that the adverse impacts of climate change could be largely offset by feasible adaptations involving new crops and intensification of livestock production. Like some of the global studies, these studies also demonstrated the important role that future socioeconomic conditions are likely to play in determining vulnerability to climate change and the value of adaptation. While these studies did assess the distributional effects of climate change on income and poverty, they did not directly incorporate all of the factors, such as regional food availability, utilization, and stability, that would be needed to assess climate-change effects and adaptations for food security.

4.6.2 Regional AgMIP Studies of Africa and South Asia

Regional assessments of climate-change effects in Africa and South Asia, currently two of the world's most food-insecure regions, have been conducted according to the methodology provided in Figure 4.2 and are summarized in Figure 4.8 (Rosenzweig and Hillel 2015, Valdivia et al. 2015). These assessments were carried out by regional teams that devised a RAP for each of the regions corresponding to the middle-of-the-road global socioeconomic scenario SSP2 (Valdivia et al. 2015). Climate change was represented by five GCMs selected to span the range of climate uncertainty in the IPCC CMIP5 data with RCP 8.5. The RAPs were generally optimistic, being based on the positive trends in productivity growth that were assumed in the AgMIP global model intercomparison study, as well as positive trends in agricultural prices due to increasing global food demand projected by the IFPRI IMPACT model. The variation in each indicator shown in Figures 4.7 and 4.8 is due to the variation in climate projections as well as regional differences in biophysical and socioeconomic conditions across the various study sites. Preliminary analysis of adaptation strategies is reported in Rosenzweig and Hillel (2015) but is not included in Figure 4.8.

The AgMIP regional studies produced indicators of (a) vulnerability (defined as the number of farm households that lose income due to climate change), (b) impacts on average (or net) per-capita income, and (c) changes in poverty; however, they did not include food-security indicators. Figure 4.8 demonstrates that there is a wide range of vulnerability to climate change under current socioeconomic conditions, averaging about 70% across study sites. The figure also shows that under the generally more-favorable future socioeconomic conditions defined by the regional RAPs, vulnerability to climate change averages less than 50%, demonstrating that positive socioeconomic developments could increase farm incomes and, in some cases, help to reduce vulnerability to climate change and to reduce poverty.

These studies have several important implications regarding the potential effects of climate change on the well-being of agricultural households. First, even in highly vulnerable regions, there is a range of household-level outcomes, with some households expected to lose and some to gain from climate change acting within the context of other socioeconomic changes. Second, preliminary analysis by the regional teams of possible adaptations of current systems shows that there are substantial opportunities to offset the adverse impacts and enhance the beneficial effects of climate change. Third, like other global and regional studies, these regional studies show the important role that socioeconomic conditions will play in determining vulnerability, impact, and adaptation potential.

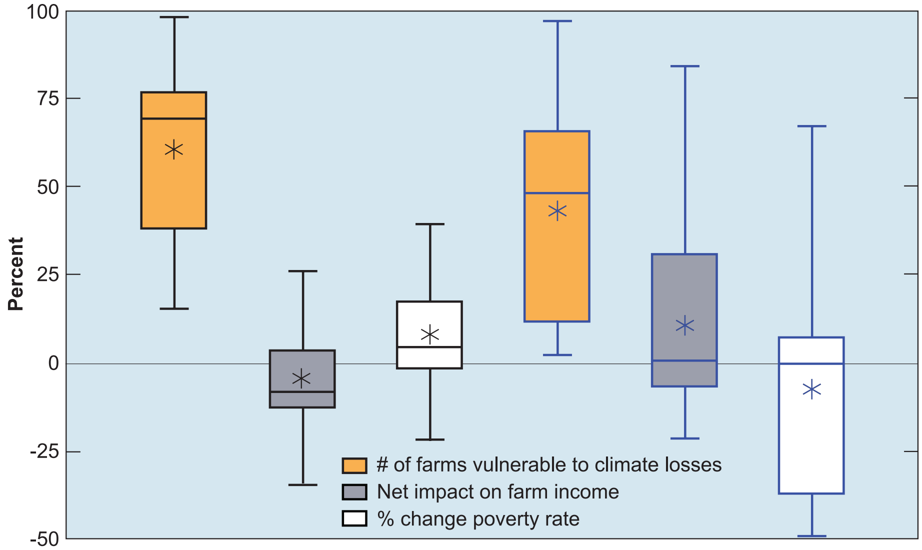


Figure 4.8 Summary of regional studies of climate-change impacts in West, East, and Southern Africa and South Asia under current and future socioeconomic conditions. *Adaptation is not considered in this figure. Bars show the range of outcomes from five climate scenarios, two crop models, and one socioeconomic scenario (current and future) for various study areas in Africa and South Asia; boxes indicate quartiles; asterisks are averages. Boxes outlined in black (left side) indicate current socioeconomic conditions; boxes outlined in blue (right side) indicate socioeconomic conditions in mid-century based on "middle-of-the-road" SSP2 and corresponding regional RAPs. Source: Wiebe et al. 2015.*

4.7 Conclusions

Climate-change effects on overall global food production are likely to be detrimental, particularly later in the century, but vary substantially by region. The most adverse effects are likely to be in the tropics and subtropics, and some benefits are possible at higher latitudes. Effective adaptation can help to offset climate-change effects. Detailed regional studies show that the regional differences in effects can be large, due to differing biophysical and socioeconomic conditions that determine both the effects of climate change and the potential for beneficial adaptation.

Global-scale food-system models can be used to assess climate-change effects on global and national food availability, but data are too aggregated to assess all of the important food-security concerns related to access, utilization, and stability. More detailed data and models and additional model intercomparisons are needed to assess climate-change effects on all dimensions of food security at subnational, local, and household levels.

Substantial differences in projections of price, production, and land-use changes by different models exist, implying a high degree of model uncertainty in impact projections. In addition to reducing these uncertainties, needed model improvements include a more-complete representation of risks to food production from pests and diseases and a more-complete and detailed representation of the food system beyond the farm gate, including food transportation, storage, processing, and distribution, and other parts of the comprehensive food system.

Technological, economic, and policy considerations also play a role in the global food system and future global food security, demonstrating that climate assessments need to be made in the context of plausible future socioeconomic scenarios. Many studies indicate that these technological and socioeconomic factors are likely to be at least as important to food security as climate change under low-to-medium emissions and concentration scenarios in the near term to mid-century. Under higher emissions scenarios and over the longer term, climate effects are projected to be equal to or greater than the effects of socioeconomic change.

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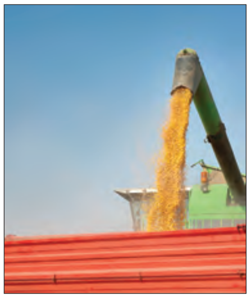


Chapter 5

Food Availability and Stability

Key Chapter Findings

- Climate change influences food availability and stability through many components of the food system.
- The natural-resource base and adaptive capacity each greatly influence food-availability and stability outcomes.
- Climate influences on food production depend on the relative balance of changes being experienced within localized conditions; at the global scale, however, such changes are increasing the challenges to food security.

The first component of food security, *availability*, addresses the question of whether food exists locally. This chapter defines food availability, relates it to important components of the food system, and identifies areas where changes in climate have already influenced and may in the future continue to influence food availability. The chapter addresses the stability of food availability, as well as adaptations for managing changing conditions.

What Is Food Availability?

Food availability requires that sufficient quantities of food be available on a consistent basis. It involves food production, processing, packaging, transport, storage, and all supporting trade systems involved in enabling those activities (FAO 1996, Schmidhuber and Tubiello 2007). This chapter focuses on food production, processing, packaging, storage, trade, and transport as each contributes to food availability.

Food production is the initial creation of food. Following production, all foods are processed to a greater or lesser degree. The foods are then traded and transported to consumers. These components—production, processing, packaging, storage, trade, and transport—work together in many possible combinations to make food available. The food system may be very short—such as a producer who consumes the eggs from chickens that she or, he has raised or it may be quite long and involve many intermediaries, such as produce imported from the Southern Hemisphere during the Northern Hemisphere winter. Both cases illustrate food availability.

5.1 Influences on Food Availability and Stability

Food availability and its stability through time are subject to multiple food-system activities. Where food is, or is not, is a function of production types, rates, and locations. The processing, packaging, and storage of food also contribute to food availability, as do trade and the transportation systems that enable it. Each food-system element is described below, along with climate influences.

5.1.1 Producing Food

Food production occurs through the cultivation of crops and livestock as well as foraging, fishing, and hunting outside of cultivated systems. The relationship of each to climate and weather variables, factors affecting their stability, and anticipated future changes are listed below.

5.1.1.1 Crop Production

Crop production forms the foundation of food availability, providing calories and nutrients for human consumption, as well as feed for animals that contribute to food supplies. At the same time, crop production is vulnerable to climate variability and change. For example, globally, rain-fed agriculture is practiced on 83% of cultivated land and produces 60% of all food (FAO 2002a). Yet this important form of production is exposed to risk resulting from fluctuations in precipitation.

Agricultural cultivation has expanded gradually over much of the past 10 millennia, but acceleration in productivity since the 1700s has enabled human settlement in most arable regions of the planet (Toussaint-Samat 1992). The subsequent green revolution of the 1960s resulted in the intensification of management, agrichemical, and technical inputs; growth in trade and economic output; changes in land use; and increased yields (Roberts 2008).

Historical production increases have been the result of greater yields (i.e., production per unit area) together with increases in the amount of overall land under cultivation (Funk and Brown 2009; Figure 5.1). Yields have increased globally by about 1.8% per year on average since 2000, resulting in a roughly 20% increase in global cereal production (FAO 2014b) over that time period. The amount of cultivated land per person has decreased by 9% over the same period. The combined effect of these trends has been an 8% increase in total per-capita cereal production since 2000. More recent yield trends are measurably smaller than those of the second half of the 20th century and may in part imply that such historical yield increases are becoming more difficult to attain. In addition, global averages can hide local and regional trends. For example, regions experiencing rapid agricultural expansion, which have strong overlaps with food-insecure regions, experience increased risk due to production expansion into more arid or other types of less-optimal land (Funk and Brown 2009).

Since 2000, food-production increases have been largely concentrated in countries such as Brazil and China, primarily a result of biotechnology (Paarlberg 2013). In sub-Saharan Africa, investments in agricultural research and wider adoption of new technologies can lead to improved production, though weak scientific capacity and support can hamper those efforts (Fuglie and Rada 2013), and the shrinking size of smallholder farms limits the viability of mechanization (Funk et al. 2008).

Global average yields for the four most-traded food crops (maize, rice, wheat, and soybeans) are stagnating or diminishing on 24%–39% of their growing areas (Ray et al. 2012), and the average global yield growth rates for each (1.6%, 1%, 0.9%, and 1.3%, respectively) lag behind the increases required to meet anticipated mid-century demands (Ray et al. 2013) of a 60%–100% increase in food production (FAO 2009a). Production trends differ in different locations. Eastern Asian rice and northwestern European wheat account for 31% of total global cereal production, but yields in these regions are declining or stagnating as they approach their biophysical limits and face pressures from land degradation, weather, and limits on fertilizer and pesticide use (Grassini et al. 2013). Annual yield increases in China, India, and Indonesia are 0.7%, 1.0%, and 0.4%, respectively (Ray et al. 2013). Annual increases at these levels would increase production by 67% for maize, 42% for rice, 38% for wheat, and 55% for soybeans by 2050 in these countries (Ray et al. 2013), which is generally inadequate to meet anticipated need. In the three largest wheat-producing nations—China, India, and the United States—yields have been increasing at annual rates of 2.7%, 1.1%, and 0.8%, respectively (Ray et al. 2013). The aggregate effects of these yield growth rates would see 2050 wheat yields of 154%, 47%, and 32% compared with current levels for each of these countries, respectively. Wheat yields are in decline across much of Eastern Europe (Ray et al. 2013). In contrast to plateauing yields in capital-intensive systems, slow growth or stagnation is occurring in many low-yield nations where farmers lack access to basic agricultural inputs (e.g., fertilizers), infrastructure, markets, and extension services (Grassini et al. 2013). Compared with major staple crops, less work has been done on the production of specialty crops such as vegetables, tree crops, fruit and ornamentals, livestock, or fish, which can be particularly important in developing regions (Zhang and Wilhelm 2011), and therefore represent an important area for future investigations.

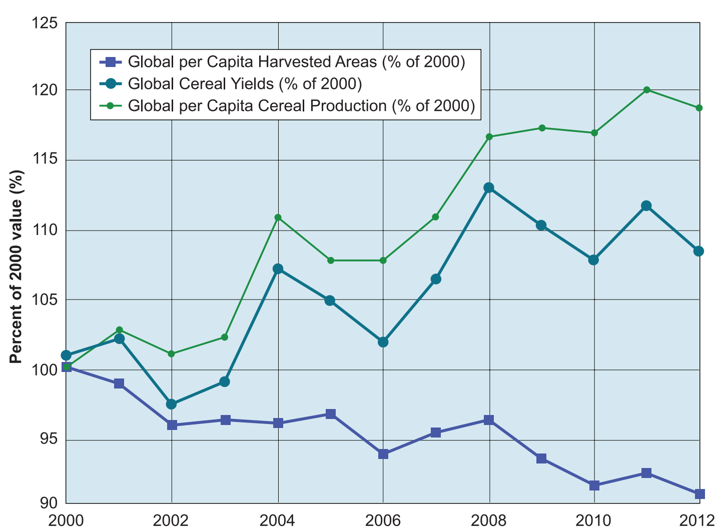


Figure 5.1 Global cereal production, yield, and harvested area relative to year 2000. *Global per-capita cereal yields have increased since 2000, even as the trend in per-capita harvested area has decreased. Source: FAO 2014b.*

Climate and weather influence food production. Climate and weather influence yields directly through physiological changes under varying temperature and moisture levels and indirectly by altering pest and disease pressures (Malcolm et al. 2012, Sexton et al. 2009, Sutherst 2001).

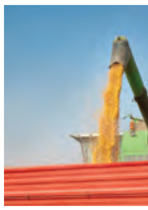
Temperature, precipitation, atmospheric CO_2 concentrations, soil moisture, and nutrient availability interact to determine how successfully a crop will germinate, flower, and produce seed (Badeck et al. 2004, Chmielewski et al. 2004, Tao et al. 2006). Different crop species and varieties have varying abilities to cope with differing stressors (Chaves et al. 2002); climate change and weather variability will therefore affect different crops, varieties, regions, and production systems in different ways.

Every crop and crop variety has a range of optimal growing and reproductive temperatures, as well as threshold temperatures beyond which the necessary physiological processes cannot occur, causing yields to suffer or cease (Walthall et al. 2012). While net global crop yields are increasing, the effects of recent climate trends may be slowing the rate of increase. Changes in climate may be diminishing rates of yield growth by up to 2.5% per decade, globally (Porter et al. 2014). Yields of corn, soybeans, and wheat in the United States have been shown to increase with temperatures up to 29–32 °C (depending on the crop), and then decrease sharply for all three crops (Schlenker and Roberts 2009). Increased temperatures in China between 1980 and 2008 appear to have reduced yield-growth rates for wheat and corn by approximately 1.5%, though had little effect on the yield-growth rates of rice or soybeans (Tao et al. 2012). In India, increasing minimum temperatures reduced rice yield-growth rates by more than 5% between 1960 and 2002 (Auffhammer et al. 2012).

Crops grown in warmer climates (e.g., tropical latitudes) are already closer to their physiological limitations, and are therefore at greater risk of exceeding temperature thresholds as temperatures rise (Gourdji et al. 2013, Teixeira et al. 2013). African corn yields decrease each day with temperatures above 30 °C, yields decreased by 1% under optimal moisture conditions and by 1.7% under drought conditions (Lobell et al. 2011). Warming leads to higher moisture losses from soils, exacerbating drought conditions and limiting growth in water-limited regions (Sheffield and Wood 2012).

Increased temperatures have led to an earlier start to, and lengthening of, the global growing season. The growing season increased by 10–20 days on average around the world over the 20th century (Linderholm 2006, Körner and Basler 2010, Sheffield and Wood 2012). Longer growing seasons can increase yields and allow for double-cropping, particularly in temperate latitudes, provided that sufficient water and nutrients to support additional growth are available, and provided that higher temperatures do not interfere with a crop's cold-temperature requirements for germination (vernalization; Sinclair 1992) or exceed physiological limitations. Warmer temperatures also increase rates of decomposition and may lead to greater soil-nutrient availability, which can, in turn, increase yields (Melillo et al. 1993, Kirschbaum 2004). Higher temperatures can shorten the time necessary for crop development, but in doing so, may prevent the completion of seed fill and, perversely, diminish yields (Harrison et al. 2011, Walthall et al. 2012). Early senescence (end of growing season), triggered by extremely warm temperatures (greater than 34 °C) poses a documented risk to tropical wheat harvests, for example (Lobell et al. 2012).

In some regions, however, higher temperatures lead to a shortening of the growing season and to reduced yields as physiological temperature or moisture thresholds are breached (Ericksen et al. 2011). In semiarid zones where temperature and moisture are already approaching biophysical thresholds, increasing temperature stress, an increasing number of dry days, highly variable seasonal rainfall, and increasing rainfall intensity are expected to lead to growing-season declines that are important to food-security outcomes (Ericksen et al. 2011). This is particularly true in developing regions where local and regional production have a major bearing on food availability.



Changing precipitation patterns and variability influence production and have been demonstrably influential in many corn-, soy-, rice-, and wheat-producing regions around the world (Lobell et al. 2011, Fallon and Betts 2010). In 2012, for example, the midwestern United States suffered a 13% drop in corn yields following an extremely hot summer coupled with severe drought (USDA NASS 2013). In both 2008 and 2013, severe flooding delayed corn planting in some areas of the midwestern United States and drowned already-planted crops (LeComte 2014). A shift to drier weather, together with expanded land area, in the summer of 2013 in the same region led to record-high U.S. corn production that year (USDA NASS 2009, 2014). In regions experiencing more rainfall, or more-intense rainfall events, increased rates of erosion lead to losses of organic carbon and nutrients in soil (Walthall et al. 2012). The net influence of such precipitation changes depends on a variety of soil characteristics, physiological crop characteristics, and the response of soil microbe communities (Nearing et al. 2005). Rates of erosion, however, appear to increase disproportionately with annual average rainfall by a ratio of approximately 1.7, indicating that the effects of soil erosion are likely to be important in affected regions (Nearing et al. 2005).

Changes in reliable crop-growing days, more-variable seasonal rainfall, temperature stress, and more dry days during the growing period increase instabilities in crop-production systems (Ericksen et al. 2011). As the climate-driven growth factors for crops (e.g., temperature, precipitation, pests, disease, extreme events) shift, the stability of production is likely to become more unpredictable over time and across geographical regions.

Elevated atmospheric CO_2 concentrations allow plants to keep their stomata closed for longer periods while still gaining sufficient CO_2 for photosynthesis, which results in improved water-use efficiency (Kirschbaum 2004). Elevated atmospheric CO_2 concentrations can also increase the levels of plant residue entering soils, increasing soil organic matter (van de Geijn and van Veen 1993), though this effect is mediated by increased soil-erosion rates brought on by more-intense precipitation in some regions, and more generally by diminished nutrient levels in plant tissues (Walthall et al. 2012).

Temperature, precipitation, and atmospheric CO_2 together interact to affect production by means additional to their individual effects described above. Higher average temperatures associated with longer growing seasons increase rates of evaporation and evapotranspiration, diminishing soil-moisture stores and increasing crop-moisture stress (Kirschbaum 2004, Trenberth 2011), even in regions where precipitation remains unchanged. The most severe droughts typically result from a combination of rainfall deficits and abnormally warm temperatures (Trenberth 2011); droughts occurring in a warmer climate are of a greater intensity (Trenberth et al. 2014). Of course, not all droughts are induced by climate change (Porter et al. 2014, Dole et al. 2011, Hoerling et al. 2014), as history demonstrates. However, climate change does appear to increase the probability of heat waves associated with drought events across much of the globe (Otto et al. 2012, Knutson et al. 2013, Diffenbaugh and Scherer 2013), perhaps by a factor of four (Otto et al. 2012, Rahmstorf and Coumou 2011, Knutson et al. 2013, Diffenbaugh and Scherer 2013). In East Africa, for example, the drought of 2011 (Funk 2012, Lott et al. 2013) and the low precipitation levels of 2012 (Funk et al. 2013) have been linked to changes in climate.

In addition to the direct physical effects, climate influences the range and infestation intensity of crop pests and pathogens.

These changing parameters directly affect crop yields. Individually, each has a range of possible effects on a crop. Together, the possible combinations mean that potential outcomes are highly specific and depend upon the relative balance of the changes being experienced within localized conditions.

In addition to having direct physical effects on food production, climate influences the range and infestation intensity of crop pests and pathogens. Many bacterial and fungal pathogens affecting staple, specialty, cash, and non-food crops are associated with climate variables (Anderson et al. 2004). Crop-eating insects, some of which are also disease vectors, also respond to changes in climate (Bale et al. 2002, Thomson et al. 2010). Milder winters, more and more-damaging severe-weather events, higher nighttime and overall temperatures, and increased humidity enable pest and pathogen growth, survival, and spread; extremes in drought and precipitation stress in plants make crops more susceptible to pathogens (Bale et al. 2002, Harvell et al. 2002, Kirschbaum 2004, Elad and Pertot 2014, Irey et al. 2006, Gregory et al. 2009). Weather is the primary driver of the emergence of 25% of crop-pathogen species; shifts in weather caused by climate change are therefore very likely to affect pathogen dynamics (Anderson et al. 2004), potentially reducing yields.

Production changes resulting from changes in underlying climatic conditions can also interact with stressors such as conflict, market stresses, or non-climate-related disaster conditions to alter the stability of food availability (Davis 2002, Watts 1983). In the 2011 Horn of Africa famine, for example, multiple lower-than-average rainy seasons diminished crop harvests and available forage in Ethiopia, Kenya, and Somalia. However, famine was declared in only one of those countries (Somalia), where a militant group interfered with attempts to deliver adequate relief (Hillbruner and Moloney 2012, Lautze et al. 2012, Maxwell and Fitzpatrick 2012, Menkhaus 2012). As a consequence of the induced scarcity, the number of people selling household assets in Somalia greatly outnumbered buyers, so that the assets were not effective sources of income—income that could have facilitated *access* to food through purchase rather than by direct production (Maxwell 1996, Watts 1983). When sold assets include livestock or other means of production, future food-production capacity is reduced, which can lead to diminished food-security outcomes long after the transitory initial cause has passed (Lybbert et al. 2004).

Estimates suggest that 30%–50% of total food production is lost globally as waste (Gustavsson et al. 2011). Similar levels of waste are observed in developed and developing nations, with differing causes in each case. As climate change increasingly influences the processing, packaging, storage, transportation, and trade of food, rates of food waste may increase in developing countries, where technological limitations prevent crops from being harvested quickly enough to avoid spoilage or to be managed properly afterward (Godfray and Beddington et al. 2010), potentially influencing food availability. In developed nations, such pre-retail losses are less significant; the issue is more one of utilization, and is discussed more fully in the "Food Utilization and Stability" chapter of this report.

5.1.1.2 Livestock Production

Livestock operations occur over approximately 30% of the Earth's ice-free land surface. Livestock operations provide a livelihood for over a billion people, including 600 million households in less developed areas (Thornton 2010).

Livestock operations may include cattle, dairy, swine, and/or poultry and may be part of farm operations that also grow crops ("mixed" systems). Mixed agricultural systems are common in low- to middle-income countries, where animals are commonly raised outdoors and fed with crops grown on-site, with forage, or a combination of the two (Sutherst 2001, Naylor et al. 2005). Livestock may also be raised separately, either indoors and fed with crops grown elsewhere (e.g., poultry houses) or outdoors on forage (i.e., grazing systems).

The livestock industry contributes over USD 1 trillion annually to the global economy (Thornton 2010). Since the late 1990s, livestock has grown more rapidly than other agricultural sectors and currently represents 33% of the GDP of developing countries (Thornton 2010). This growth is associated with urbanization and income growth in developing regions (Delgado 2005). In places like East Asia, poultry and swine production have expanded rapidly. The livestock sector plays an important role in agricultural systems and is a critical source of protein and micronutrients; however, comparatively little systematic assessment has been done relative to non-animal-based agriculture (Porter et al. 2014).

Risks to livestock systems are substantial and concern livelihoods, the provision of safe and nutritious food, and food security (Thornton et al. 2009, Walthall et al. 2012, McCarl et al. 2014). These risks, along with the increasing demand for animal-sourced foods worldwide, may lead to increased pressure on ecosystem services and natural capital of production areas (Herrero and Thornton 2013).

Heat stress from higher temperatures diminishes food intake and physical activity for livestock, leading to lower growth, survival, and reproductive rates, as well as lower production of meat, milk, and eggs (Nardone et al. 2010, Walthall et al. 2012, West 2003), though physiological acclimatization is possible to some extent over time (Kadzere et al. 2002, Saxena and Krishnaswamy 2012). Increasing temperatures require greater water intake; *Bos indicus* cattle, for example, require 3 kg of water per kilogram of dry-matter feed at 10 °C, but 10 kg of water per kilogram of dry-matter feed at 35 °C (Thornton et al. 2007). Indoor livestock (primarily poultry and swine operations in developed countries) face increased heat stress and associated mortality in a changing climate, absent adaptive measures to manage higher air temperatures (Turnpenny et al. 2001).

Climate change also affects livestock indirectly through disease and pests, quality and quantity of pasture and forage crops, and feed-grain production (Rötter and van de Geijn 1999, West 2003, White et al. 2003, Thornton et al. 2009, Nardone et al. 2010). Temperature increases and precipitation shifts may accelerate the development of certain livestock pathogens and parasites, along with distribution of their vectors, exposing livestock to novel pathogens (Harvell et al. 2002, Thornton et al. 2009, Pérez de León et al. 2012). At the same time, heat stress can weaken immune function in livestock. Together, these factors could require an increase in the use of veterinary medications (Nardone et al. 2010, Tirado et al. 2010).

Precipitation changes and warmer temperatures can lead to more forage for grazing livestock (Hanson et al. 1993). Changes in climate and atmospheric composition can also result in decreased forage-nutrient content and digestibility, and consequently, poorer livestock performance (Hanson et al. 1993, Klein et al. 2007, Baker et al. 1993, Tubiello et al. 2007, Thornton et al. 2009). The effects of climate on these indirect factors for outdoor livestock production are ecosystem-specific (Baker et al. 1993) and vary by location and operation type.

5.1.1.3 Fishery Production

Capture fisheries and aquaculture provide 3 billion people with almost 20% of their average per-capita intake of animal protein, with an additional 1.3 billion people obtaining 15% of their protein from this source (HLPE 2014). In some regions (e.g., West Africa, Cambodia, Bangladesh, Indonesia, Sri Lanka), fish make up over 50% of all protein consumed, making fish a highly important source of nutrition in food-insecure regions (FAO 2012b). 90% of fishers depend on small-scale capture fisheries; many of these people are food insecure (HLPE 2014).

Fisheries are dynamic social-ecological systems affected by many non-climate stressors that are particularly important for food security, including rapid market changes, exploitation, and governance (Daw et al. 2009). The combined effects of competition for resources, pollution, overfishing, habitat modification, acidification, temperature, and climate-driven changes on small-scale fisheries and aquaculture in these regions are likely to be damaging to fishery health and sustainability, resulting in decreased incomes for fishing families (affecting food *access*) and overall reductions in food availability for fishing communities (HLPE 2014). Current methods of analysis cannot distinguish the relative importance of each influence upon fishery health (IPCC 2014).

Climate-driven changes in water temperature, salinity, and dissolved-oxygen content affect the physiology and behavior of wild fisheries species, as well as that of their predator and prey species, affecting population dynamics and distribution (Walther et al. 2002, Roessig et al. 2004, Brander 2007, Brander 2010, Ottersen et al. 2001). Warmer weather caused by El Niño offers a glimpse into the potential effects of warmer weather on fisheries (Mysak 1986, Fromentin and Planque 1996, Wespestad et al. 2000). An increase in warmer-water fish species in response to higher water temperatures is observed at higher latitudes, and decreases in subtropical species have been observed in the tropics (IPCC 2014, Cochrane et al. 2009). Short-term changes in fish species type and population size result in changes in fishing opportunities, operational costs, and sales prices, with increased risks of damage or loss of infrastructure and housing for communities relying on marine resources (FAO 2008b). El Niño/La Niña events themselves may also be influenced by climate change (McGowan et al. 1998), making the changes described above more probable in the future as a result of more frequent oscillations.

Climate change has been linked to permanent shifts in the distribution of fish species in wild fisheries. For example, over a span of 25 years, Perry et al. (2005) found that of 36 species of North Sea deep-water fish, 21 had shifted their centers of distribution northward or to deeper waters to follow colder water. Temperature increases also affect the food sources of fisheries species by increasing productivity in cooler regions and decreasing productivity in warmer regions (Richardson and Schoeman 2004). Such changes diminish food availability and access for the 90% of capture fishers who are employed by small-scale fisheries (FAO 2012b). Aquaculture allows for a greater degree of control over growth conditions than capture operations in wild fisheries, but nonetheless remains vulnerable to climate pressures, including shifts in water temperature and chemistry, water availability, disease prevalence, damage from extreme events and sea-level rise, and changes in fishmeal availability as feed from capture fisheries (Brander 2007).

Elevated atmospheric CO_2 leads to higher levels of acidity in both wild and cultured fisheries. Higher acidity prevents the formation of calcium carbonate shells and skeletons in important fisheries species and their predators, leading to population declines with continued acidification (Cooley and Doney 2009).

5.1.1.4 Wild Game

Wild game is the primary source of meat and income for hundreds of millions of people in developing countries (Milner-Gulland and Bennett 2003). For the poorest households, wild game is a traditional safety net that protects impoverished rural households from chronic malnutrition during times of scarcity (Golden et al. 2011, Myers et al. 2013), including when livelihoods collapse and income sources disappear (Milner-Gulland and Bennett 2003). Wild game is consumed in rural areas by the poor and food-insecure, as well as in urban areas where it is obtained through trade by higher-income households (Brashares et al. 2011).

In addition to facing similar physiological pressures as those experienced by livestock, including the influence of high temperatures on meat, milk, and egg production; immune function; mortality; and reproductive rates, wild game is additionally subject to the effects of climate change on its food sources. Climate change affects the growth and seasonality of wild plants that serve as food for wild game, which influences the growth, survival, and timing of important life cycle events (e.g., reproduction) for those species (Ogutu et al. 2014, Kerby et al. 2012).

Much research to date has focused on game species in the Arctic, which is experiencing some of the most rapid and severe climate change on Earth and is home to a large community of subsistence hunters (Arctic Climate Impact Assessment 2004). In Greenland, for example, earlier spring warming has led to a mismatch between forage availability and caribou herds' arrival on their calving range, leading to higher offspring mortality (Post and Forchhammer 2008). Inuit communities that rely heavily on caribou as a food source have also observed changes in caribou migration patterns, body condition, and meat quality associated with changes in the Arctic climate (Wesche and Chan 2010).

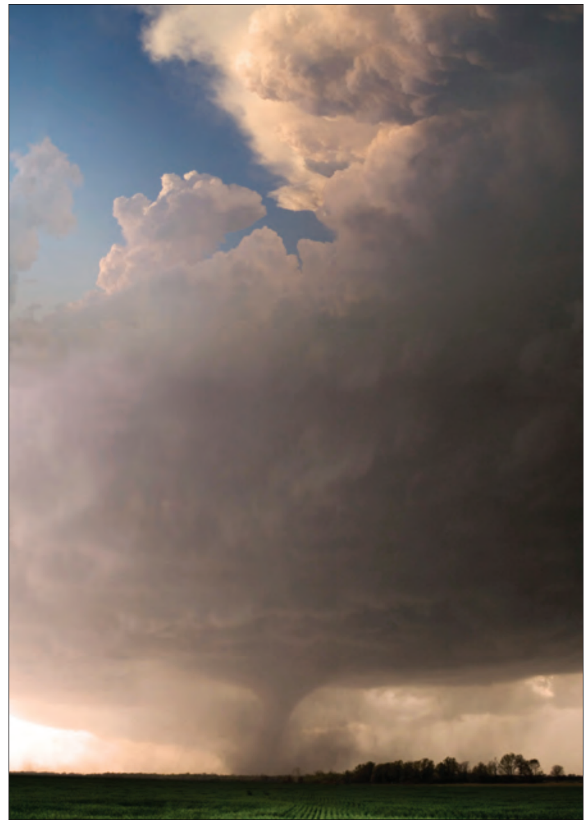
Pests and diseases of wild game species are spreading into new areas as regions experience milder winters (Kutz et al. 2009). For example, unseasonably warm winters in the northeastern United States are correlated with high tick loads that increase moose calf and cow mortality (Musante et al. 2010). It is likely that the effect of climate change on insect populations and parasite loads will extend to other important game species as temperate regions warm, allowing vector-borne diseases transmitted by ticks, midges, and mosquitoes to change in abundance, distribution, and infectivity (Harvell et al. 2002, Altizer et al. 2013).

5.1.1.5 The Natural-Resource Base and Food Production

Food production—agricultural, pastoral, aquatic, and wild—requires a wide range of functioning ecosystem characteristics and processes, particularly those related to soil and water resources (Power 2010). Changes in these characteristics and processes can occur through management, climate change, or numerous other activities and events. In developing regions, production systems are already challenged by current levels of natural-resource degradation combined with a lack of investment in infrastructure and technology (Nardone et al. 2010). In these cases, where there is adequate technological capacity, one or more of the natural constraints to production may be offset through management interventions such as irrigation, fertilizer application, or enhanced biological resources through selective breeding and use of improved varietals (Keeney and Hatfield 2008, Power 2010).

At the other end of the spectrum, indigenous and other communities that have close cultural and geographical ties to traditional or wild-food production systems are affected by changes in the natural-resource base. Shifts resulting from climate change affect the range and distribution of traditional food sources, leading to changes in food availability and the cultural appropriateness of available foods (i.e., food *utilization*; Lynn et al. 2013). Land management and administrative restrictions can hamper the harvest and production of food sources following geographical shifts in where food sources are available (Dougill et al. 2010).

Soils provide a substrate and nutrients for plant growth, while mediating water supply and quality; their health is therefore paramount to the underlying ability of ecosystems to produce food (Walthall et



al. 2012). A soil's nutrient levels, organic matter content, physical structure and depth, pH, microbial community, and contaminant load determine its productive capacity (Brady and Weil 2008). Each is subject to alteration through changing climatic conditions and management practices. Changing temperatures and precipitation patterns alter nutrient turnover rates and consequent plant availability. The level of organic matter in soil affects the provision of water to crops. Soil rich in organic matter better holds water and can provide more water to growing crops during drought conditions than soils low in organic matter (FAO 2005) and influences microbial dynamics and nutrient availability. More-intense rainfall events can erode and alter the physical structure and depth of soils, as well as reduce organic-matter concentrations (Walthall et al. 2012). Intensification of agricultural practices may further exacerbate these effects by affecting soil compaction, levels of soil organic matter and nutrients returned to soils, and the concentration of salts and other chemical constituents (Power 2010, Huang et al. 2011, Montgomery 2007).

The water cycle is also affected by climate change (IPCC 2007b, Haddeland et al. 2014, Rudorff et al. 2014, Barnett and Pierce 2009, Immerzeel et al. 2010, Elliott et al. 2014). Livestock systems are conditioned to respond to seasonally available moisture from precipitation, springs, or groundwater aquifers, or through management of water resources through various well and reservoir developments, and therefore respond to water-cycle changes. Seasonal availability of water may be affected by temperature trends that influence snowmelt timing and rapidity, as well as changes in the timing, amount, seasonality, type, and intensity of precipitation. Precipitation effects may be exacerbated by higher temperatures that increase moisture losses through evaporation and transpiration (Jiménez Cisneros et al. 2014).

Regions that use melting snow to supply water to growing crops are vulnerable to climate change as higher temperatures induce earlier peak flow, which leads to reduced water availability in summer and fall. In this situation, irrigation can help to regulate water supply where the necessary reservoir infrastructure exists, though such infrastructure is not without limitations. Irrigated Asian rice systems, for example, have experienced increased salinity in the soil and in irrigation water (Wassmann et al. 2009). Elliott et al. (2014) conclude that even where adequate irrigation-water supplies exist, they may be unable to offset greater warmth when combined with reduced precipitation. Changes in underlying conditions and the "natural" state of surrounding ecosystems therefore influence food production, even with adaptation (Zhang et al. 2007).

One review of 160 studies on the food-security benefits of soils and land management concluded that (1) land management that includes improved management of soil organic-matter, appropriate nutrient inputs in both time and space, and methods for reducing pests and diseases generally leads to increased yields, although the magnitude and variability of results varied by specific practice and agro-climatic conditions; (2) isolating the yield effects of individual practices is complicated by the adoption of combinations or "packages" of sustainable land-management options; (3) sustainable land-management generally increases soil carbon sequestration; and (4) rainfall distribution is a key determinant of the mitigation effects of adopting specific sustainable land-management practices (Branca et al. 2013).

Another study found that the effects of climate change on water availability and food security differ substantially among five important South Asian hydrological basins upon which 1.4 million people depend (Immerzeel et al. 2010). The study estimates that the food security of 60 million people dependent on these basins, particularly those dependent on the Brahmaputra and Indus, are susceptible to anticipated hydrological changes.

Agricultural production depends on soil properties and the availability of water, among other natural resources (Porter et al. 2014). Production systems are managed to alleviate stresses due to soil degradation, reduced soil fertility, pests and disease, and impaired water resources in order to enhance crop and animal sources of production. Land and water resources have been developed over centuries to meet regional and local needs (Vandermeer and Perfecto 2012). With the "green revolution" of the mid-20th century, agricultural production has been enhanced through technological advances (Pingali 2012). However, competition for land and water resources is emerging as a consequence of population growth (Lambin and Meyfroidt 2011, CNA Military Advisory Board 2014); climate change will affect production systems in ways that may exacerbate this competition (Porter et al. 2014, Hatfield et al. 2014). Intensifying agricultural production given available land and water resources, while managing multiple demands and reducing damage to the natural resource base, will be more challenging in a changing climate (Tschakert et al. 2008, Ojima et al. 2009, CNA Military Advisory Board 2014).

5.1.2 Processing, Packaging, and Storing Food

Processing, packaging, and storing are frequently prerequisites for food to reach its ultimate consumers. These activities are present in many food systems, enabling the provision of fresh and safe food to consumers who may be distant from agricultural areas. Food supply chains are becoming increasingly globalized, with retailers engaging with smallholders (farms with fewer than 2 ha) across countries and income levels (Lee et al. 2012).

Food processing preserves and adds value to agricultural products (Simon and Thirion 2013). There are two general categories of food processing: primary and secondary. Primary processing includes actions such as cooling to extend shelf life, and milling. Secondary processing makes agricultural products more readily edible. Secondary processing can also add significant economic value to harvested goods (Meléndez Arjona and Uribe 2012), for example, by creating bread from wheat (FAO 2004), corn meal from corn (Simon and Thirion 2013), oils from tree crops (Poku 2002), tomato sauce from raw tomatoes (Issahaku 2012), and hot sauce from peppers (Meléndez and Uribe 2012).

Food processing is directly sensitive to climate and must be suited to local conditions, as changing temperatures and moisture levels have different effects on foods depending on where they have been produced (Halford et al. 2015). An example is the cooling of fruits and vegetables following harvest to extend shelf life (Kurlansky 2012). Active cooling methods require considerable amounts of energy—more so with higher temperatures (Thompson 2002), which entail higher energy costs and raise consumer prices (Moretti et al. 2010). Increasing temperatures can in this way lead to strains on electricity grids that extend beyond the food system (FAO 2008d, Vermeulen and Campbell et al. 2012). Food systems with minimal packaging and processing, or with inadequate cold-chain continuity, are inherently more vulnerable to rising temperatures than those that respond to changing conditions by adapting food packaging (Lee et al. 2012, James and James 2010, Dangour et al. 2012).

Climate change may also affect the location of food-processing and packaging facilities, which are often located near the original food-production site for cost, convenience, and regulatory reasons (FDA 2006). As production shifts to reflect changes in climate, the location of processing facilities will also need to move (Hatfield et al. 2014). For example, growing corn in regions where it historically has not been cultivated requires the construction or expansion of nearby processing and transport facilities in order to handle the increased bulk (Petrolia 2008).

The effects of climate change on food processing are a function of multiple choices being made simultaneously among different actors within the food system, determined by the rapidity of climate change, structural changes within the food system, and changes in consumptive demands. From 1961 to 2007, global average per-capita food consumption increased from 2,250 kcal per person per day to 2,750 kcal per person per day; the biggest caloric increases were in the categories of cereals, vegetable oils, and animal products (Kastner et al. 2012). Changing dietary composition is also important and may become more important than population growth as a driver of agricultural expansion and trade in the near future (Kastner et al. 2012). Urban consumers in West Africa, for example, increasingly demand processed foods that are ready to use, are nonperishable, and do not require a great deal of preparation (Simon and Thirion 2013). These foods are often imported, and the lack of domestic supply has led to transitory supply shortages and influenced prices, which in turn results in declines in food intake and higher rates of food insecurity (Becquey et al. 2012).

Corporations are beginning to recognize the risk that climate change poses to supply chains and how that risk varies based on regulatory environment, energy prices, and temperature regime (CDP 2015). Packaging and logistics companies in some countries now collaborate with farmers and organizations that seek to reduce food waste at different stages of the food system to develop packaging that provides ventilation and temperature control, and enables flexible bulk transport to retail outlets (Verghese et al. 2013). New ways to monitor foods with sensors and electronic tagging to communicate harvest dates and to notify retailers when spoilage occurs are under development (Deloitte 2013).

5.1.3 Trading and Transporting Food

Following production, food is sold to off-farm interests and ultimately to consumers. The role of food trade has been growing. For instance, Japan now relies on imports to meet 75% of its annual cereal-consumption needs, compared to 26% in 1961 (USDA 2015). In this way, trade influences food availability. Global cereal and meat exports have climbed 27-fold since 1961 and are now worth approximately USD 192 billion a year, or 8%–10% of the total value of global production (Figure 5.2). Global trade linkages can provide consumers with access to non-local foods, while providing producers a means to earn money through geographically far-reaching trade networks (Bellemare 2012).

Food is transported primarily by international waters and rail (29% each), followed by truck transport (28%), and inland waters (10%; Weber and Matthews 2008). Cereals/carbohydrates comprise the greatest proportion of freight (14%), followed by red meat (10%), with nonalcoholic beverages, fats/sweets/condiments, non–red meat proteins, and processed food each responsible for about 6%–8% (Weber and Matthews 2008).

Transportation is an intermediate activity linking each food system activity. Multiple climate variables can influence transportation systems and the foods they carry. Transportation is particularly sensitive to extreme-weather events through damages to infrastructure, such as flooding and storm surge. While immediate effects on the transportation system may be temporary, disruptions can affect food availability and food safety, and impair just-in-time food-distribution networks (Wu and Olson 2008, Koetse and Rietveld 2009). Heat waves stress transport systems, as food needs to be moved faster and/or the cold chain needs to be strengthened to avoid spoilage.

Extreme weather can influence food transport in vulnerable locations (e.g., along coastlines, near rivers), particularly when maintenance has not taken changes in climate into consideration (Mashayekh et al. 2012). Vessels using inland waterways must reduce the weight of cargo that they carry when

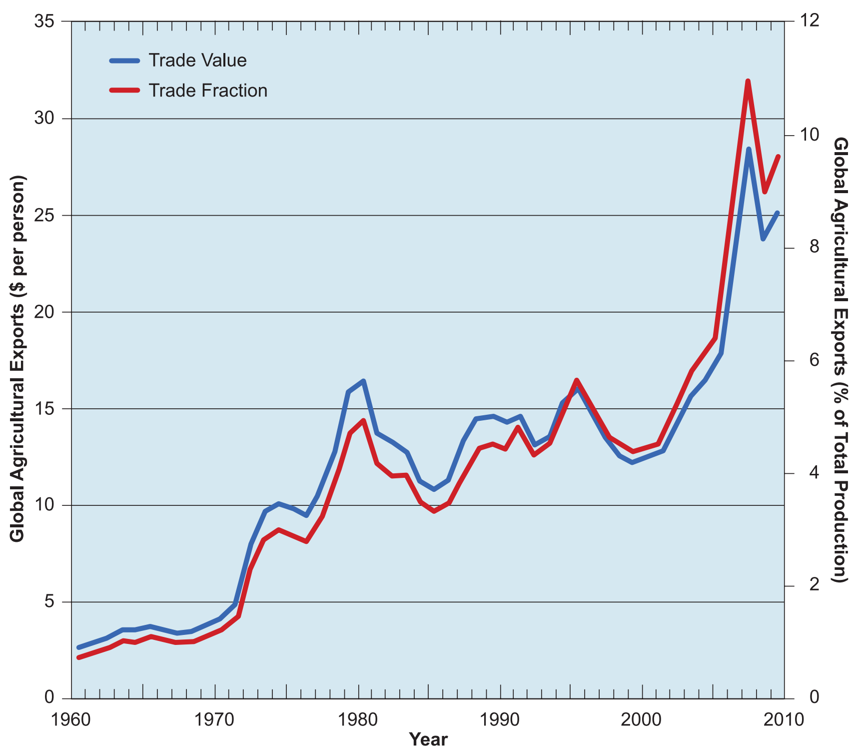


Figure 5.2 Historical trend in global per-capita cereal and meat exports. *Global per-capita cereal and meat exports have increased as a proportion of total production since 1961, reflecting the increased relevance of trade to food availability and stability. Source: FAO 2014d.*

water levels in rivers and lakes are low, leading to an increase in shipping costs and the number of trips they must make (Attavanich et al. 2013, Jonkeren et al. 2014, Millerd 2005 and 2011). Storm surge, river floods, and extreme weather affect food transportation and supply-chain integrity through effects on sea ports (Becker et al. 2013, Blake et al. 2013). For perishable foods, lack of a cold chain or refrigerated transport can result in large losses due to spoilage, particularly under higher temperatures (Choudhury 2006, Mittal 2007). Intense precipitation increases accident frequency in land transport and decreases traffic speed (Maze et al. 2006, Brijs et al. 2008). Heavy rains lead to flooding of transportation infrastructure (e.g., roads, railways) and mudslides that can interfere with continued food availability (McGuirk et al. 2009).

Regional and national disparities in production, whether chronic or generated by shocks, have resulted in an increasing trend, particularly in less-developed nations, to adopt international trade for overcoming food deficits (Jafry 2012). When an area experiences a food shortage, prices rise. This shortage attracts food from areas of surplus production, helping to improve food availability in the area of the shortfall (OECD 2013). Consumers benefit from increases in trade through a greater variety of foods, increased competition, and lower prices. Trade benefits agricultural producers as well by supporting their income through sales of surplus production and by improving productivity by providing lower-priced or more-varied production inputs, such as seed, fertilizer, pesticides, and machinery (Hebebrand and Wedding 2010, OECD 2013). On a broader scale, trade also helps generate economic growth, boosting households' income and their means to purchase food, while enabling countries to earn foreign exchange for food imports (Schiavone 2010, Cline 2004).

However, such a highly linked system also means that distant events, including climate and weather events like heat waves and droughts, can generate local food shocks that are far removed from the site of the original disturbance (Abbott and Battisti 2011). Rapid urbanization compounds this possibility, as millions of people have become more dependent on markets for their primary food supplies (Berazneva and Lee 2013, Porkka et al. 2013). Flooding and temperature extremes (IPCC 2012) are examples of climate and weather influencing the stability of food *availability* by hindering the movement of food from its place of production to consumers, by altering food prices in response to changes in the price of transportation (*access*), and by increasing the likelihood of food contamination (*utilization*).

The linkage between climate change and trade is indirect. When adverse climate reduces production of an agricultural commodity, prices for that commodity can increase, leading governments to sometimes adopt restrictive measures on trade (Schiavone 2010, World Bank 2008a). Disruptions in regional and international markets can result, leading to further price increases. These consequences may also spread to other commodities for which production remains unaltered, due to spillover effects (Zhao and Goodwin 2011, Slayton 2009). An example of this is the 2008 food price crisis, in which world rice price tripled in four months primarily as a result of trade restrictions imposed by some of the largest rice-exporting countries in reaction to rising prices of other commodities, during a time of record rice production and ample stocks (Slayton 2009). In Burkina Faso in 2008, high food costs, due in part to global price increases, led to protests and riots in a number of regions, despite above-average domestic agricultural production that year (FAOSTAT 2015a, Bush 2009). This is an example of the issue of scale when managing food security: it is not a matter of simply considering multiple scales, but of considering all scales, from the local to the global, at once. The Burkina Faso example demonstrates that global food prices can affect food costs in countries even without significant food imports (Aker et al. 2010, Haggblade 2013). The Burkina Faso situation could not have been predicted based upon local conditions or choices; knowing what was happening globally was necessary in order to properly interpret those events.

Storm surge, river floods, and extreme weather affect food transportation and supply chain integrity through effects on sea ports.

5.2 Adaptation for Food Availability and Stability

Adaptation in this report refers to actions that lead to "mean reductions in risk and vulnerability by the adjustment of practices, processes, and capital in response to the actuality or threat of climate change" (Porter et al. 2014).

Adaptive capacity is mediated by a broad set of socioeconomic drivers (Morton 2007). It is limited by the physiology of crops and livestock, research and development, technology adoption, the ability to convey timely and appropriate information to stakeholders, and social issues (Kane and Yohe 2000, Kates 2000). These factors suggest a wide variety of potential strategies to respond to changes in climate, including insurance, engineering responses, land-use allocation changes, management and policy responses, and research and development solutions (Kandlikar and Risbey 2000). Depending on income level and access to resources through government and institutional supports, individual actors in the food system may respond to different drivers and prioritize different actions, with climate being just one of many challenges needing to be overcome at a particular time (Risbey et al. 1999).

Factors affecting on-farm adaptive capacity under climate change include access to varietal traits that thrive in changing environmental conditions, soil characteristics that improve water retention and storage, access to water for irrigation, and information (Porter et al. 2014). Producers invest in new agronomic practices and genetic resources with the goal of buffering detrimental climate effects or taking advantage of changes to remain profitable (Zilberman et al. 2004, Kurukulasuriya and Mendelsohn 2008, Crane et al. 2011). Indicators that specific elements of the food system are not adequately adapting to climate and other stressors (Lemos et al. 2013, Zhu et al. 2013) include soil degradation, falling productivity, and movement beyond ecosystem thresholds that alter functionality (Le Houerou 2002, Moseley 2003, Wessels et al. 2004, Berry et al. 2009).

Constraints in one component of food security may often be compensated through another—e.g., food insecurity may be avoided when production decreases *(availability)* are substituted with food acquired through purchase *(access)*. Alternatively, constrictions at one point within the food system may be so severe, or have no feasible alternative possibilities within a local context, that food security may be compromised—e.g., a country with ample food production but inadequate transport conduits has more-limited capacity for food purchases by remote populations. As a consequence of these interactions and dependencies, a systems-based approach is needed to understand the implications of climate change.

Challenges to food availability and its stability have already been observed as a result of climate variability and change—food production, processing, packaging, storage, transport, and trade can all be affected by changes in temperature and precipitation (Vermeulen and Aggarwal et al. 2012). Food-system actors participate within specific environments, using specific tools and crop or livestock varieties suited to a particular environment and available within their means. Because production systems are "optimized" in this way, changes in the surrounding circumstances will require adaptation and altered management practices. As climate change accelerates, greater challenges are expected in responding to changing patterns of yield and productivity, production costs, and resource availability to ensure sufficient food availability (Walthall et al. 2012). The food system will require significant investment to adapt crop-production technologies or apply these technologies in new places (Malcolm et al. 2012). Similar challenges are expected for other elements of the food system that support food availability—processing, packaging, storage, transportation, and trade (Ericksen 2008).

Farmers have already adopted practices and strategies to reduce the damaging effects of drought, floods, high temperatures, and other phenomena related to climate change on food production (Malcolm et al. 2012). Farmers also have significant technical flexibility to adapt to changes in local weather, resource conditions, and price signals by adjusting crop types, locations, rotations, structural modifications, and management practices (FAO 2011b). That said, the existence of technical fixes to maintain or improve food availability under changing conditions is not a guarantee of their use, since use may be limited due to lack of knowledge of a technology, social constraints to its application, or financial limitations that prevent a producer or other food-system actor from obtaining or maintaining it (Kane and Yohe 2000, Kates 2000, Affholder et al. 2013).

The "yield gap" refers to the difference in crop yields obtained from capital-intensive agricultural systems in the developed world and labor-intensive agricultural systems in the developing world (FAO 2011b). Adaptation holds considerable promise for minimizing yield decreases from changes in climate and increasing yields in regions that currently produce only a fraction of potential yields (Nin-Pratt et al. 2011). Valdivia et al. (2012) and Claessens et al. (2012) demonstrate in two regions in Kenya that the use of new crop varieties and intensive agricultural systems could raise overall productivity and ameliorate climate change through higher yields, even in a high-emissions scenario. There is considerable potential for similar types of improvements using existing technologies (Funk and Brown 2009).

Smallholders represent 85% of all farms in food-insecure nations, of which 87% are located in Asia (Nagayets 2005, FAO 2013a). Smallholder farmers, in addition to the landless and urban poor, are one of the most disadvantaged and vulnerable groups, with the least ability to respond to climate change and severe weather events through investment in new crops, insurance mechanisms, and inputs to maintain production (IFAD 2001, Majid 2004). Investments in agricultural research, a wider adoption of new technologies, and policy reforms can lead to improved production; support for these innovations remains generally low in many areas where smallholders are predominant (Fuglie and Rada 2013).

Geographic shifts in production areas are expected as a result of climate change (Lobell et al. 2008). It is not necessarily the case, though, that production increases in some regions (e.g., northern latitudes) can fully compensate for production decreases elsewhere (e.g., tropical latitudes; Funk and Brown 2009, Gourdji et al. 2013).

Maintaining a diversity of crop varietals can be one adaptive approach to managing shifts in the underlying environmental conditions of food production. Successful breeding enabled the rapid expansion of hard red winter wheat across substantial climatic gradients—hot, dry, and cold—in North America during the 20th century (Easterling et al. 2004). Unexploited germplasm can continue to push environmental margins for maize production (Easterling et al. 2004, Carena 2013); for example, much research has focused on improving drought and salt tolerance in food crops (Parida and Das 2005). Attempts are underway to collect and protect the genetic diversity of a portfolio of plants that have the characteristics required to adapt food crops to climate change (Dempewolf et al. 2014). Such gene banks are critical to the success of future breeding aimed at expanding plant abiotic tolerances. In livestock systems, a delicate balance must be preserved between mining the genetic diversity of native species through breeding programs to develop animals that are better suited to meet expected drought and nutrition challenges, while at the same time maximizing feed-conversion efficiencies (Hoffmann 2010).

Genetically modified (GM) organisms may also be used toward these ends, as one of multiple solutions aimed at meeting the world's food needs while managing biodiversity, recreation, and ecosystem services (Godfray and Beddington et al. 2010, Borsari et al. 2014). Commoditized monocropping in much of the globalized food system has resulted in a narrower genetic base for plant and animal production, which may consequently be more susceptible to climate-related threats (Knudsen et al. 2005, Young 2013). Enhancing genetic resources, whether through better use of genomics or genetic modification, is important to increasing on-farm resilience to climate change and weather extremes. A range of strategies including GM organisms, enhanced breeding systems, and multicrop management schemes have the potential to enhance

resilience to changes in climate (Jacobsen et al. 2013, Lin 2011).

Not all adaptive strategies are universally applicable, however. Heat-abatement technologies for livestock are myriad, but costly from infrastructure and energy perspectives. Those costs increase under higher-emissions scenarios (do Amaral et al. 2009, Key et al. 2014). Solar radiation, wind, stocking rate, and design will determine the capacity of a livestock-production operation and its livestock to adapt to weather fluctuations and a changing climate (Cooper et al. 1998). The magnitude of improvements needed will vary geographically, and in some cases improvements will not prevent considerable economic loss or will be cost ineffective. For instance, in the United States, heat abatement is economical for poultry layers, but not for broilers (St-Pierre et al. 2003). The economics of various adaptation strategies for livestock production vary based on the livestock type, location of the operation, and economic circumstances of the situation under consideration. The rapid development of livestock systems in developing countries presents a number of challenges due to a combination of intensified environmental effects and the need for enhanced infrastructure to accommodate the increase in livestock production, especially with swine and poultry (Herrero and Thornton 2013). Recent attention has been focused on developing and implementing sustainable intensification practices

Transportation of food commodities can be highly vulnerable to climate variability and change, but substantial adaptive capacity exists to manage those risks, particularly in developed countries.

associated with expanding animal-sourced products. The demands for maize and soybean as animal feed to support beef and swine production highlight some of the challenges faced by intensification efforts (Herrero et al. 2013, Eshel et al. 2014).

Competition for resources may also diminish adaptive capacity. Competition among different end-users for water resources (e.g., agriculture, urban areas, and industry) likely diminishes available water in regions that depend heavily upon irrigation for crop or livestock production (Elliott et al. 2014). This type of competition reduces adaptive capacity, particularly in arid regions.

Food waste represents an area of much potential improvement for food availability in regions where food spoils before it can be sold or consumed. When food is cultivated and raised in adequate quantities but then lost to spoilage between the farm gate and the market or table, this production is effectively lost to the consumer. In the Southern Hemisphere, rates of loss to spoilage reach as high as 40% of all production for vegetables; losses are lower for grains (Parfitt et al. 2010, Kader 2005). Standards and regulations for food processing and packaging are key ways that large retailers engage with producers as a means to increase food-safety and quality standards in response to elongated food chains (Lee et al. 2012). In labor-intensive food systems, where a short supply chain is more likely, food is traded with little or no packaging (Lee et al. 2012). Systems with minimal packaging and processing, or that have inadequate cold-chain continuity, are inherently more vulnerable to rising temperatures than those that can respond to changing conditions by adapting food packaging (Lee et al. 2012, James and James 2010). Cooperative investment in infrastructure along with improved support, standards, and sustainability could result in improved food availability by reducing food waste (Parfitt et al. 2010).

Transportation of food commodities can be highly vulnerable to climate variability and change, but substantial adaptive capacity exists to manage those risks, particularly in developed countries. Alternative transportation routes, for example, have at times allowed for compromised or disrupted routes to be bypassed, saving producers who had access to those alternatives from significant financial losses while maintaining food-distribution functions that generate food availability (Changnon 1989). The use of containers in food trade offers significant advantages over other bulk methods by improving loading efficiencies and allowing products to remain untouched from origin to destination, representing a potential adaptation in ports where container ships may dock given changing conditions (O'Reilly 2012).

Maintenance and infrastructure improvement can reduce vulnerability to extreme events (Canning and Bennathan 2000). In some countries, infrastructure has been constructed that allows for storm surge and sea level rise without significant losses or a change in the location of maritime transportation infrastructure (e.g., Love et al. 2010). Adaptation capacity may also be significant in developing nations under some circumstances. In Bangladesh, for example, efforts have been successful to reduce vulnerability to sea level rise (Adger et al. 2007, Rawlani and Sovacool 2011). 63% of 93 global port facilities have at least one policy that specifically addresses potential climate change effects (Becker et al. 2012).

Proper food processing, packaging, and storage can protect food from spoilage. Regulations address appropriate temperature conditions for a food product to minimize spoilage and appropriate packaging to maintain food safety (WHO 2003b). As temperatures increase, the challenges and expenses of food processing, packaging, and storage are expected to increase as well. Refrigeration of food consumes an estimated 15% of global electrical consumption, a figure that may be expected to increase as rising temperatures increase the amount of cooling required to maintain food safety (Coulomb 2008).

Corporations have taken notice of the effects climate change can have on food production and the life of a product from farm to consumer. Their assessments are often given in reports to their shareholders and through other public documents. The J.M. Smucker Company ("Smuckers"), for example, which purchases coffee from 25 million farmers worldwide and is one of the four largest coffee companies globally, announced in 2012 a sustainability plan focused on addressing the challenges of climate change on coffee production and for the underlying ecosystem services that support it (Smuckers 2012). In another example, McDonalds Corporation's 2012–2013 Corporate Social Responsibility and Sustainability Report, states that it is committed to maintaining safe food temperatures through careful food handling (McDonalds 2014), representing another mechanism for adaptation within the food system.

An emerging issue for food availability involves adaptation at the international scale through the transnational acquisition of land resources. After adverse weather (Headey and Fan 2008), increasing demand, and rising fuel prices combined to rapidly raise food prices around the world in 2008, leading many corporations and governments to acquire property rights in foreign countries (Cotula et al. 2009), in part as a hedge against unfavorable climate conditions in any one region. Such property right transfers have the potential to influence food availability both in the countries selling the land rights and in the purchasing countries (Rulli et al. 2013).

Another means of meeting the challenges to food availability is sustainable intensification (Tilman et al. 2002)—producing more food while minimizing the environmental effects of doing so (Garnett et al. 2013). Sustainable intensification is based on three premises: (1) increased production through (2) higher yields rather than land conversions and (3) long-term environmental sustainability on equal terms with higher productivity. The concept does not specify the techniques to be employed. Under sustainable intensification, diverse approaches, including capital-intensive, labor-intensive conventional, high-tech, agro-ecological, or organic food-production systems, are to be rigorously assessed, with biophysical and social contexts taken into account (Garnett et al. 2013). An example of sustainable intensification is management that promotes long-term increases in soil organic matter and relies on landscape-scale strategies such as rotational diversity, cover crops, and perennialization (Gregorich et al. 2001).

5.3 Measuring Food Availability and Stability

There are two general methodological categories for assessing food availability. One category involves large-scale production and import/export estimates, the balance of which is then scaled to population. This can provide a high-level indicator of food shortages or excesses but cannot identify distributional discrepancies at the subnational scale, and also misses important food-insecurity indicators as a consequence. The second measurement category involves household-level surveying to identify consumption patterns and shortages. These methods better represent food availability at the highly relevant household and community scales, but cannot always account for within-household distributional discrepancies, and tend to underestimate overall consumption. The resource-intensiveness of survey methods limits the ability to maintain continuous records, and samples may not always scale to accurately reflect broader conditions. Each measurement type is discussed in further detail below.

At the national level, food availability includes products from either domestic or foreign sources (i.e., domestic production or imports), as well as any carryover stock from the previous year. Production can be used for food or nonfood purposes, including fuel, fodder, and fiber (Maxwell 1996). Because food availability is composed of many different food-system components acting and reacting simultaneously, the measurement of food availability typically must integrate several different measures.

Remote sensing of yields and production area, including satellite-based observation, is growing for food-production applications (Funk and Budde 2009, Funk and Brown 2009). Estimates of harvested area may use a combination of high- and low-resolution satellite imagery (Marshall et al. 2011, Grace et al. 2012). Modeling based on satellite observations of rainfall, such as the Water Requirement Satisfaction Index, may also be used to generate production estimates (Senay and Verdin 2003, Verdin and Klaver 2002). Much of the satellite data collected are then distributed through programs such as the Famine Early Warning Systems Network (FEWS NET) to developing and low-income countries to anticipate crop failures and food shortages (Brown 2008).

At the national scale, additional information can be provided by low-tech agricultural surveys and area-frame sampling. There has been a recent recognition of the need to strengthen these systems, and the Global Strategy to Improve Agricultural and Rural

Statistics has been developed with participation from international organizations, national governments, and donors (SPARS 2014).

While food production is critical to food availability, how that production is used requires additional consideration in order to have a measure of actual availability. Domestic supply of a given food item is the amount available for consumption once other uses (e.g., animal feed, biofuel production, starch manufacturing, industrial processing, and waste) are subtracted. When divided by the total population, the domestic supply estimates the per-capita food consumption of each food item.

This measure of food supply provides an overall average estimate of per-capita food consumption, but cannot account for distributional effects or variations within a population. To understand differences in availability *within* countries, regions, and even communities, food availability is usually estimated through short-term food-consumption surveys or by looking at food production and food stocks and assuming that the difference between the two represents food consumed (Maxwell 1996). There are several challenges associated with the measurement of food availability within populations. First, the differences observed within a given population, particularly at subnational levels down to the community or household level, are often a product of access limitations rather than availability. Separating the influences of access and availability on food-security outcomes requires site-specific investigation. Further, even the best surveys tend to underestimate consumption and produce estimates that are quite sensitive to survey design (Deaton 1997); this is especially true of household-expenditure surveys (Smith et al. 2014, Godfray and Crute et al. 2010). In contrast to household-expenditure surveys, individual and household food-intake surveys are somewhat more accurate, though they still tend to underreport actual intake (FAO 2003, Frankenberger 1992, Smith et al. 2006, de Weerdt et al. 2014). Finally, few countries have reliable estimates of intra-household food waste; this is particularly true of low-income countries (Godfray and Beddington et al. 2010).

The challenges of estimating domestic food availability are important, as estimates of per-capita consumption of calories and nutrients are constructed from these supply estimates. For example, the FAO's Food Balance Sheets (FAO 2001) estimate the per-capita supply of dietary energy, protein, and fat provided by each food item and by all food items combined. Measuring food supply in terms of energy (calories) and focusing

the analysis on staple foods such as coarse grains rather than documenting nutritional composition and adequacy of food is common. However, particularly as incomes grow, dietary composition shifts from coarser grains toward finer grains or from finer grains toward other items such as meat, fish, and dairy (Bennett 1941, Becquey et al. 2012, Popkin 1998, Drewnowski and Popkin 1997). Consequently, the FAO's Food Balance Sheets become increasingly uninformative as populations become more affluent.

One-sixth of total global agricultural production is traded internationally (Anderson 2010), making trade an important contributor to food availability. Official trade statistics are available from individual countries, international organizations such as the UN and WTO, and commercial database producers such as Global Trade Information Services (GTIS; Pagell and Halperin 1999). These sources are based on official trade data at the country level, usually collected by customs agencies or national statistics agencies. Of these, GTIS is recognized as the most comprehensive and current (Pagell and Halperin 1999), as it compiles monthly official merchandise import and export data of over 80 countries/regions (GTIS 2015) that covers more than 90% of total international trade (IHS 2014).

Trade is typically measured in volume and value. These metrics have their limitations in that they do not reflect nutritional composition. Analyzing FAOSTAT's country-reported trade data, MacDonald et al. (2015) converted volume of traded food commodities to calories and found that wheat, soybeans, and maize make up 50% of calories traded but only 21% of nutritional value. Meat and horticultural products, on the other hand, account for a much larger share (44%) of the traded monetary value but a far lower proportion of calories. In addition, the more processed a product is, the higher its value in trade, though the underlying nutritional composition may not be much changed (MacDonald et al. 2015). The current metrics thus provide an incomplete measurement of trade in nutrition.

Assessing carryover stock is challenging when compared with production and trade. Grain stocks stored on-farm or in traders' and millers' warehouses cannot be measured with any degree of reliability, as producers tend to hold on-farm stocks in the hope of obtaining higher prices later in the season, while private companies are unlikely to report the information for commercial reasons (Lynton-Evans 1997). In addition to private stocks, many countries also hold state reserves. China, the world's largest grain stock–holding country, has never released any official data about its reserves and considers this data to be a state secret (Hsu and Gale 2001, Su 2015).

While official trade is relatively straightforward to track, informal cross-border trade is much harder to capture. Exchange is difficult to monitor in small markets that do not participate in international commodity trading (Fafchamps 2004). Informal, or unofficial, unreported trade could represent a significant portion of total trade in some regions, particularly Sub-Saharan Africa. For example, Nkendah (2010) found that Cameroon's unrecorded, informal agricultural exports to neighboring countries in 2008 totaled 38 billion CFA francs, or 96% of the country's official trade. In other words, almost half of the total (official plus unrecorded) agricultural exports from Cameroon were not captured by official trade data. And in Somalia, despite closed borders with both Kenya and Ethiopia, unofficial trade in cattle continued and expanded between 1990 and 2003 (Little 2005). Exchange can also occur within families or ethnic groups in different countries, without being reflected in standard international trade-monitoring mechanisms (Aker et al. 2010, Fafchamps 2004).

Missing trade data not only skews national accounts but can undermine efforts to formulate appropriate policies on issues such as food security, due to incorrect information (Nkendah 2010). The opacity of food exchanged beyond formal bilateral trade mechanisms makes a full evaluation of food availability difficult (Fafchamps 2004).

5.4 Conclusions and the Future

Food availability is determined by a number of factors described in this chapter. Despite the inherent difficulties, it is feasible and prudent to anticipate that the factors determining food availability will not operate in a static fashion, nor will they operate independently of one another. The inclusion of climate change in this discussion adds another set of interacting conditions that precludes highly specific predictions. However, there are tendencies that can be used to understand the pitfalls, barriers, and/or opportunities that a simple, single, path-dependent analysis would not alone allow for, due to the complex set of interconnected operations and processes at work in food systems globally.

This section addresses lessons and conclusions about the future of food availability and its stability, based on the available literature investigations. Subsection 5.4.1 combines information from the rest of this chapter with the shared socioeconomic pathways described in Chapter 3 of this volume, allowing the report's authors to identify sensitivities under climate change given a range of development pathways.

While official trade is relatively straightforward to track, informal cross-border trade is much harder to capture.

Food availability and its stability over time and space are already being influenced by changes in climate. Food production from crops, livestock, fisheries, and wild game each have climate and weather dependencies that are poised to change, influencing raw food supplies. Packaging, processing, and storage specifications are sensitive to temperature and humidity, and therefore also likely to be influenced. Transportation systems that support trade are subject to climate disruptions as well, limiting the ability for production deficits in one location to be compensated by production excesses elsewhere. When interrupted by climate or other factors, trade disruptions can influence food supplies and their variability. At the same time, large-scale average changes can mask pronounced effects and significant variability at smaller scales (Challinor et al. 2015). Even in scenarios where national agricultural production totals, for example, are unchanged, the conditions experienced by individual producers and consumers can change profoundly.

Food availability and its stability are highly dependent on relatively stable climatic conditions. Changes in the occurrence of weather and climate extremes are already detectable in many regions (Zhang et al. 2011, Coumou and Rahmstorf 2012, Donat et al. 2013, Zwiers et al. 2013, Coumou and Robinson 2013), and even under lower-emissions scenarios, higher frequency of some extremes such as very hot days, very dry days, and intense rainfall events may be anticipated (Tebaldi et al. 2006, Kharin et al. 2007, Wuebbles et al. 2014), which can influence the seasonal availability of food. Variability in food supply is most likely to affect populations that have less capacity to absorb food shortages over short periods of time, potentially increasing the prevalence of transient food insecurity, particularly if increased variability occurs in the absence of increased incomes to compensate for reduced availability through trade mechanisms (Tiwari et al. 2013, Grace et al. 2013, Cornia et al. 2012).

The effect of climate change on crop productivity is projected to be mixed in the near term, with detrimental effects becoming more pronounced and geographically widespread over the longer term and with higher emissions rates (Schlenker and Lobell 2010). A recent meta-analysis of over 1,700 studies found that in the absence of adaptation, losses in aggregate production are expected for wheat, rice, and maize in both temperate and tropical regions at 2 °C higher average growing season temperatures, with adaptive measures improving outcomes substantially (Challinor et al. 2014).

Regional variation is expected and important to food availability. Crop production is expected to increase in high latitudes and decline in low latitudes (Snyder et al. 2001, IPCC 2007c, IPCC 2007a, Ericksen et al. 2010). The geographic center of U.S. production of maize and soybeans, for example, shifted northward by 160–225 km between 1950 and 2010 (Attavanich et al. 2014), and other regional northward shifts have also been observed (Reilly et al. 2003, Olesena et al. 2011, Tolliver 2012). Significant yield decreases are likely in mid-latitude regions of Africa and South Asia, however, particularly under high-emissions scenarios (Schlenker and Lobell 2010, Knox et al. 2012). Hotter average temperatures affect crops by accelerating rates of crop development and evapotranspiration, but extreme temperatures can cause damage that is not typically captured by models, particularly during flowering and the reproduction phase (Gourdji et al. 2013). Mid-latitude regions that already have a high mean temperature may also experience yield reductions if they experience heat waves during the critical period of a crop reproductive cycle (Teixeira et al. 2013).

Fish protein will remain important in coming decades, particularly for low-income and vulnerable populations

Regions that already require high water inputs to grow crops are likely to be the first to experience yield reductions where precipitation is reduced (Hornbeck and Keskin 2014). Changes in the distribution and infestation intensity of weeds, insects, and disease will exert additional influence beyond direct temperature and precipitation effects (Chen and McCarl 2001, Gan 2004, Hicke and Jenkins 2008, Walther et al. 2009, Robinet and Roques 2010). These indirect effects are largely uncaptured by models (Walthall et al. 2012) and affect an operation's anticipated outcomes and adaptive capacity.

All effects are likely to become increasingly pronounced in the latter part of the century, as cumulative emissions grow (Rosenzweig et al. 2014). To 2050, most studies show a small average crop yield decrease globally from a changing climate; this is true even for high-emissions scenarios, because over that relatively short timescale, projections are similar (Rosenzweig et al. 2014). Beyond that, the projections diverge demonstrably based on scenario and changes are more readily discernible, with more-detrimental outcomes expected for higher emissions scenarios (Challinor and Wheeler 2008).

Livestock operations in regions requiring high water inputs are likely to be the first to experience livestock production reductions associated with climate change (Hornbeck and Keskin 2014). Differing responses are expected in different types of livestock systems (Seré and Steinfeld 1996). Mixed crop/livestock systems may face trade-offs between land and water allocations for their crops and for livestock, including the need to supply feed that may have been grown and purchased elsewhere rather than grown on-site (Thornton et al. 2009). Such choices will be influenced by economic and cultural considerations, and prices and property ownership will alter available management alternatives. The design of animal-housing facilities may increasingly need to take disease and pest occurrences into account, and the nutritional needs of the livestock may shift. Trade-offs made between income, food security, and environmental objectives in the livestock sector will influence future outcomes (Thornton et al. 2009).

Fish protein will remain important in coming decades, particularly for low-income and vulnerable populations (HLPE 2014). As fishery management develops characteristics of terrestrial food production and relies increasingly on aquacultural methods over wild-caught fish, the ability to adapt to changes in climate is likely to improve (Boyd and Brummett 2012, World Bank 2013). The World Bank (2013) projects 2% annual average increases in aquaculture fish production between 2010 and 2030, though considerable uncertainties exist (Brander 2007).

The availability effects of changing fish distribution and abundance from changing water temperatures and chemistry in the coming decades therefore depends on the vulnerability of the communities who rely on the fish as a dietary protein source. Because poorer and less empowered countries and individuals tend to rely more heavily on fish protein, these countries and individuals are more vulnerable to climate effects on production, and the fisheries they rely upon are more likely to be overexploited (FAO 2007). Overexploitation of fisheries is a likely outcome of anticipated changes in climate, particularly fisheries that supply those who are poor and depend more upon fishery resources for food and incomes (FAO 2007).

Changes in the role of wild game as a food-security safety net in coming decades depend in large part upon the functioning of the natural-resource base in the forest, coastal, and savanna systems where wildlife lives (Dahdouh-Guebas et al. 2005, Patz et al. 2004). Where development is limited and wildlife populations remain viable, the harvest rates of wild game may increase, unless other forms of livelihood can be ensured (FAO 2008a).

The changing climate imposes new stressors on current and future food production in many important agricultural regions, possibly leading to an increase in production volatility. The most immediate effects will emerge in the low latitudes where interannual variability is comparatively low, causing changes in availability and pricing (Parry et al. 2004, Lobell et al. 2011). Temperature changes that lead to shifts in the location of optimal growing areas may lead to changes in the availability of certain food types, trade patterns, and pricing. Through mid-century, changes are not expected to be pronounced at the average global scale, regardless of the specific emissions trajectory. High-emissions scenarios are expected to result in disproportionate increases in damaging outcomes.

Land degradation, loss of ecosystem services, and increased vulnerability of rural communities have resulted in the overappropriation of the natural-resource base that forms the foundation of food production (Haberl et al. 2007, Power 2010, Lambin and Meyfroidt 2011, Eshel et al. 2014). A focus on individual goals to the exclusion of others can lead to perverse outcomes through the degradation of ecosystem services that undermine the sustainability of the land-use system, disrupt social structures, affect livelihoods, and lead to unintended consequences in other parts of the globe (Ojima et al. 2009). The degree of integration in land management in a world of rapidly growing human population and per-capita consumption of ecosystems services is highly context-dependent and will influence food production, livelihoods, and their sustainability (Haberl et al. 2007, Seto et al. 2012, Ojima et al. 2013, Tschakert et al. 2008).

Future food availability during climatic shifts and stresses is largely determined by adaptive capacity within the food system and dependent in many ways upon choices made by food-system actors. Climate-controlled food-storage infrastructure, road systems, and market structures that lack adequate supply during the months preceding harvest are important determinants (Vermeulen and Campbell et al. 2012, Hillbruner and Egan 2008, Handa and Mlay 2006), and how each is managed will influence outcomes. Lower-emissions scenarios with more moderate temperature increases would require fewer large-scale changes than higher-emissions scenarios.

Future food availability during climatic shifts and stresses is largely determined by adaptive capacity within the food system and dependent in many ways upon choices made by actors within the food system.

Much can be done to adapt to these changing conditions, as each of these sectors has a great deal of potential technical capacity for flexibility. However, adaptation may not be feasible due to informational, societal, or financial constraints, and overall adaptive capacity must be considered with respect to these considerations.

5.4.1 Food Availability and Stability in the Context of Shared Socioeconomic Pathways (SSPs)

Climate change affects food availability through its key food-system elements, with differing effects under differing socioeconomic trajectories.

Shared Socioeconomic Pathway	Production		Storing/Processing/ Packaging		Trade		Transport	
	P	W	P	W	P	W	P	W
SSP1	Medium/Low Risk	Low Risk	Medium/Low Risk	Low Risk	Medium/Low Risk	Low Risk	Medium/Low Risk	Low Risk
SSP2	Medium Risk	Medium/Low Risk	Medium Risk	Low Risk	High Risk	Medium Risk	Medium Risk	Medium/Low Risk
SSP3	High Risk	Medium Risk	Medium Risk	Low Risk	Very High Risk	High Risk	Medium Risk	Medium/Low Risk
SSP4	Very High Risk	Medium Risk	Medium Risk	Low Risk	Very High Risk	Medium Risk	Medium Risk	Low Risk
SSP5	Medium/Low Risk	Low Risk	Medium/Low Risk	Low Risk	Medium/Low Risk	Low Risk	Medium Risk	Low Risk

(P: poorer nations, W: wealthier nations)

Key
Low Risk
Medium/Low Risk
Medium Risk
High Risk
Very High Risk

Figure 5.3 Relative risks to key food availability elements for different SSPs. *The risks to food availability would be lowest under the economic conditions described by SSP1 and SSP5, with poorer nations at higher risk across all food production, distribution, and trade categories for all SSPs. Shading represents higher or lower risks for each SSP from climate change. Risks reflect the informed judgment of the authors of this report, based on the available literature.*

To illustrate the range of possible outcomes, this section considers food production, trade, transport, storage, packaging, and processing for each of the shared socioeconomic pathways (SSPs) introduced in section 3.4.1 of this volume. Many parts of the food system are not considered by the SSPs or by available modeling frameworks directly; however, this discussion reflects the informed judgment of this report's authors based upon the literature discussed previously in this chapter (Figure 5.3).

Producing Food

The risks to crop production posed by climate change would be greatest under SSPs 2, 3, and 4. Under these scenarios, as yield increases weaken due to reduced agricultural investment and increasing land degradation, extensification onto arid land and areas with more-variable climate is likely to continue or increase. This trend exposes producers to more-variable and limiting climate conditions. It is therefore likely that under SSPs 2, 3, and 4, variability in temperature and rainfall would increase challenges to local availability for some areas. Under SSPs 3 and 4, this challenge could be particularly pronounced, as those living in the poorest countries under these scenarios are likely to lack access to agricultural technologies that could offset some climate-variability effects on production in more-arid and marginal lands.

The risks posed by climate change to crops would be lowest for SSPs 1 and 5. Under these SSPs, gradual intensification would likely be the principal means of increasing yields. With technological investment and development seen as high priorities, extensification is unlikely to take place in a manner that results in increased production in arid or highly variable environments, lowering the overall exposure of crops to climate stressors under these scenarios.

Patterns of climate-related stress on livestock production under the different SSPs are similar to the patterns seen for crops, in part because livestock husbandry depends upon crops for feed in many regions. Wealthy countries, with robust economies and food-production systems would have livestock-production systems that are more resilient than those in poorer countries. Under SSP1, although incomes rise, the rate of increase in livestock production and consumption slows as society shifts toward less-resource-intensive means of generating calories. That shift, driven by broadly held societal goals of greater sustainability, leads to a livestock sector closely tied to locally available resources. Under SSP5, relatively open markets and strong investment in technologies to address climate-change effects would likely manage most anticipated effects on livestock production. However, the increased likelihood of climate-change effects that exceed technological solutions makes agricultural production under this scenario more precarious than under SSP1.

The remaining three scenarios present more-significant challenges for agricultural production and demonstrate that those in wealthy countries are not immune from potentially damaging climate-change effects. Under SSP2, imperfect markets and increasing environmental degradation would likely affect feed prices, making production of cattle and large ruminants less economically sustainable. Under SSPs 3 and 4, markets function even more poorly, making it nearly impossible to effectively smooth out the price impacts of climate shocks that affect local feed supplies. Such events may force at least temporary reductions in herd size and could result in the abandonment of the husbandry of particular animals.

Processing, Packaging, and Storing Food

Under nearly all SSPs, climate change is expected to have limited effects on the storage, processing, and packaging of food in wealthy countries. In poorer countries, however, different SSPs produce different outcomes. Under SSPs 1 and 5, investments in education and health generally lead to more-hygienic and reliable food storage, processing, and packaging. These outcomes appear more durable under SSP1, where the increased focus on human well-being creates broader societal conditions under which food storage, processing, and packaging are seen as important contributions to well-being, and investments in these processes and technologies outstrip the effects of climate change. Under SSP5, food-safety gains are predicated on the generation of wealth through the consumption of fossil fuels, which over time are likely to lead to significant climate changes and shocks that can undermine education and health investments under those pathways. In both cases, improvements to food storage, processing, and packaging can help to maintain or even improve food availability and stability, even with climate change.

Under SSP2, there are fewer investments in education or health, and a limited social emphasis on human well-being as a metric for successful policy outcomes. Investments in food storage, processing, and packaging proceed unevenly and slowly, exposing populations to increased levels of unsafe food. Under SSPs 3 and 4, investments in education and technology decline over time relative to other concerns. As poorer countries struggle to provide safe water, improved sanitation, and appropriate health care to their populations, the changing climate would expose weaknesses in food storage, processing, and packaging that contribute to unsafe or low-quality food. Under SSPs 2, 3, and 4, climate change is more likely to lead to higher rates of spoilage and contamination.

Trading and Transporting Food

Under SSPs 1 and 5, world markets would be highly connected and trade would flow easily between countries and regions. Under these scenarios, markets are likely to be able to facilitate the movement of food from areas of surplus to areas of deficit. This is likely to smooth food availability and stability challenges created by changes in climate under either of these scenarios.

SSPs 2, 3, and 4 all present different futures under somewhat constrained global trade. Under SSP2, stresses and shocks in availability are anticipated, and the semi-open globalized economy may not be open enough to facilitate the robust trade links needed for markets to effectively respond to these shocks. Under SSPs 3 and 4, this pattern is accentuated. These SSPs present a world where the wealthy enjoy strong trade connections through which they can access goods and resources, but have few connections to the global poor, and the poor have few connections between one another. As a result, markets would rarely respond fully to shocks and stresses on availability such that food can effectively move into deficit areas to address shortages. Under SSP3, poor market connectivity also exists among the wealthy of the world, though effects on food availability would almost certainly be less severe than among the poor because greater incomes allow for greater food access (Chapter 6). Under SSP4, high within-country inequality could create market-based challenges that diminish food availability for segments of the population within a country. For example, the consumption of meat and other resource-intensive foods under this scenario would divert food away from poorer populations, and low-functioning markets would inhibit trade to areas of deficit created by this pattern of consumption.

Under SSPs 1 and 5, high rates of economic growth facilitate the construction of transportation systems that enable effective food trade. Under SSP1, transportation systems would be designed with future climate conditions in mind for better robustness over time; under SSP5, some of the high-consequence impacts of climate change are considered in their design. Under SSP5, heavy reliance on fossil fuels to drive economic growth could accelerate observed changes in the climate over the next few decades, resulting in damage to physical infrastructure, such as flooded ports and roadways. Under such a scenario, poorer countries would have fewer resources and therefore a lower capacity to address impacts.

SSPs 2, 3, and 4 would see uneven transportation outcomes, with wealthier countries better able to maintain infrastructure, and poorer countries less able to finance needed improvements, repairs, or retrofits that might address climate change.

Chapter 6

Food Access and Stability

Key Chapter Findings

- Climate and weather have demonstrable effects on food prices, and consequently food access and its stability.
- Food access is influenced by multiple factors, both inside and outside the food system; within the food system, trade and wholesaling/retailing of food each act to alter food access and stability, and are sensitive to changing climate factors.
- The adaptive capacity of food access to changes in climate is potentially very high but varies enormously between high-income and low-income countries and individuals, and between urban and rural populations.

Food access addresses the question "If food exists (i.e., is available), can you get it?" This chapter defines food access, relates it to important components of the food system, and identifies areas where changes in climate have already and may in the future continue to influence food access. The chapter addresses the stability of food access, as well as adaptations for managing changing conditions.

What Is Food Access?

Food access requires having the resources necessary to acquire nutritious foods. It involves food prices (trading), proximity to food, retail outlets (wholesaling/retailing) or farmable lands (producing), and social and cultural norms that shape intra-community and intra-household food distribution and food preferences.

The existence of food *(availability),* even in abundance, is not a guarantee of food security. The causes of internal U.S. food insecurity, for example, have been detailed extensively elsewhere (Gundersen et al. 2011, Takle et al. 2013, USDA ERS 2013a). U.S. domestic agricultural production was approximately 30% greater (according to regression) in 2013 compared with the mid-1990s (Figure 6.1); the United States produces approximately 3,900 kcal per person per day as of 2006 (USDA ERS 2014b)—well in excess of domestic demand. At the same time, U.S. food insecurity is 14.3% (Coleman-Jensen et al. 2014). This is primarily the result of household-level economic conditions, that is, *food access* (Figure 6.1), and exemplifies the limitations of high production alone as a means of managing food insecurity.

6.1 Influences on Food Access and Stability

A number of long-term trends affect global supply and demand for food commodities, which in turn influence food access (Trostle 2008). Climate's influence on food access occurs primarily through effects on food prices, trade and transportation networks, and wholesaling and retailing, each of which is discussed below.

Food access requires having the resources necessary to acquire nutritious foods.

6.1.1 Food Prices

A backdrop to any discussion of food *access* is the trend in real food prices over the last century (Figure 6.2).

The real food price—that is, the price of food adjusted for inflation (a measure of the price of food relative to all other prices)—generally decreased over the second half of the 20th century. Except for a sharp increase between 1972 and 1974, the real food price steadily declined from the early 1960s until 2000, when the price of food was near an historical low. Since 2000, however, the real food price has been on an upward trend. The global averages displayed in Figure 6.2 are useful; however, the variability displayed is extremely important to poorer households and regions, whose ability to purchase food is highly influenced by these types of changes, even when such changes are transitory (Hnatkovska and Loayza 2005, FAO 2011a, Minot 2012). The food crisis of 2008 was the result of a price spike brought on by multiple factors, including weather-induced crop failures in important global exporting regions, changes in demand patterns, and policy shifts in both importing and exporting nations that led to an overall closing of supply relative to demand, driving up prices and resulting in food riots in parts of the developing world (Bellemare 2014, Headey 2011, Nielsen and Vigh 2012, Trostle 2008). Price shocks can exacerbate other causes of food insecurity, including chronic poverty, disease, and a

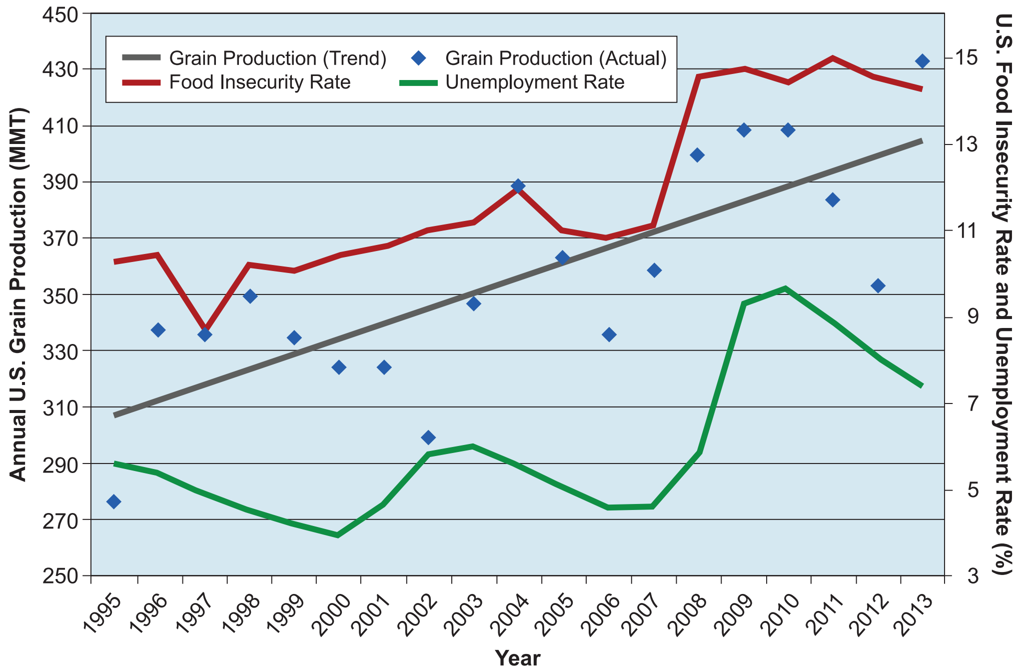


Figure 6.1 Trends in U.S. grain production, food insecurity, and unemployment. *Food availability and production increases alone do not necessarily determine food-security status. For example, in this case, food insecurity is driven by economic conditions more than by food production. Sources: USDA ERS 1996–2013, USDA NASS 1997–2013, and USBLS 2014.*

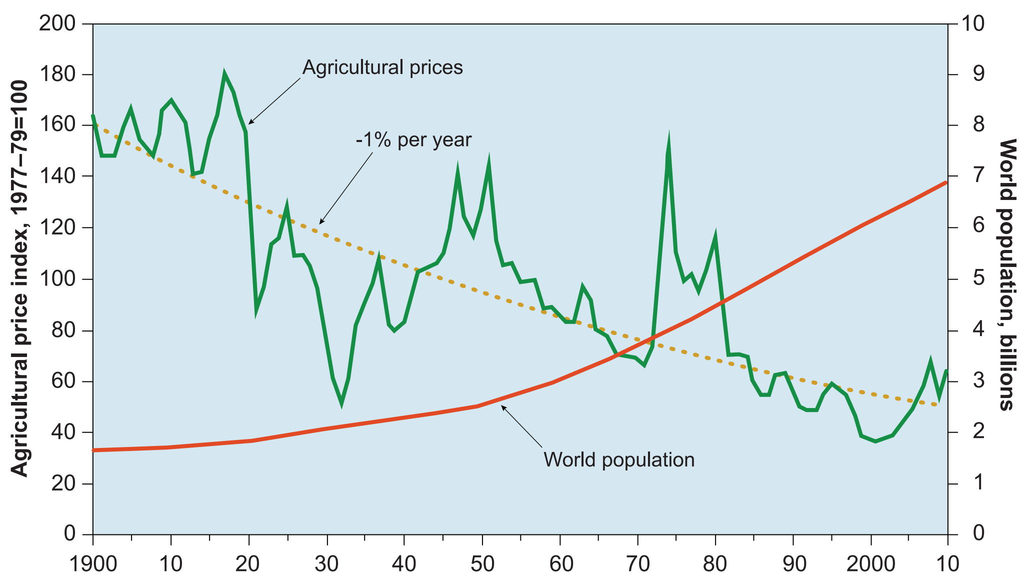


Figure 6.2 Historical trends in real agricultural commodity prices and world population. *As world population growth has increased since 1900, the price of food adjusted for inflation has declined. Source: Fuglie and Wang 2012.*

lack of access to a nutritionally adequate diet (Irz et al. 2001, Thirtle et al. 2003, Ravallion et al. 2007, Schreiner 2012).

The concept of affordability integrates food prices with the amount of disposable income an individual or family has to spend on food. As a key element of food access, changes in food prices affect human well-being by shaping poverty outcomes, education outcomes, education and health services, and the reserves of productive assets held by the poor (Grosh et al. 2008). Low-income households, whose food budgets represent a large portion of their incomes, are potentially more vulnerable to price spikes than middle- and high-income households because they do not have the economic reserves to manage sudden or extreme increases in food prices (Bellemare 2014).

For poor populations, droughts, floods and other events that destroy housing, reduce agricultural production, or increase the cost of food are major factors in their impoverishment or remaining in poverty (Cutter et al. 2007), thereby limiting food *access*. Weather shocks, in particular, are a key source of vulnerability (Hansen 2002, IFAD 2011, Vermeulen and Campbell et al. 2012). Poor people have low resilience because they have few assets to fall back on when shocks occur (Jayne et al. 2003). When shocks do occur, poor people may resort to incurring debt, selling assets, or foregoing educational opportunities for their children—all of which are adaptive strategies that leave them more vulnerable to future shocks (Kinsey et al. 1998, Prince et al. 1999, IFAD 2011, Gazdar and Mallah 2013). Furthermore, poor farmers with small land holdings may be unable to adapt to climate change due to a lack of resources, lack of social standing, and marginalization (IFAD 2011).

Because of the nature of economic-growth processes, poorer countries typically grow at a faster rate than wealthier countries (Acemoglu 2008), and this trend is expected to continue. For the same reason, growth rates in newly middle-income countries are likely to be more moderate going forward than they have been in recent decades (particularly in China). Growth in income creates changes in consumptive demand, as described previously.

A number of variables interact to determine the balance between food supplies and demands. Aggregate grain and oilseed production rose on average 2.2% per year between 1970 and 1990 but has declined to about 1.3% since 1990, mostly due to slowing growth in crop yields (Fuglie and Heisey 2007, Fuglie et al. 2012). The demand for energy increases the cost of agricultural inputs such as fertilizers and fuel, and diverts crop use from feed stocks to biofuels. Global population is expected to grow to 8.6 billion in 2050 (UN 2012), with the sharpest increases in developing countries. The FAO (2009a) estimates that world food production would need to increase by 60%–100% by mass to feed a larger, wealthier, and more urban population.

The combined effect of slowing growth in agricultural production *(availability)* and an increasing demand for food is higher food prices (Mankiw 2011). In many countries, economic access to food will benefit from increases in per-capita income (Mankiw 2011). If the rise in incomes surpasses the rise in food prices, overall access to food, even in developing countries and regions, can be expected to improve. However, higher food prices affect everyone, and some less developed countries may not experience a rise in per-capita income due to various obstacles to growth; in such cases, higher prices may cause a reduction in food access for large segments of the population. For example, while global yields grew by 2.4% annually between 2003 and 2012, this growth has been nearly matched by increased demands for cereals (Funk and Brown 2009). If population and economic growth double cereal demands between 2005 and 2050 (Tilman et al. 2011), and climate change slows yield growth (Porter et al. 2014), then overall access will be diminished.

The concept of affordability integrates food prices with the amount of disposable income an individual or family has to spend on food.

The volatility of global food prices *(stability)* has been increasing in recent years due to a combination of factors, including the widespread occurrence of extreme climate events (e.g., droughts), competition for land by fuel crops, and a change in the commodity markets as global demand for commodities from nonfood sectors increases (Bellemare et al. 2013, Haile and Kalkhul 2013).

6.1.2 Trading and Transporting Food

Trade in agricultural commodities and food can reduce price volatility and enhance predictability *(stability)* for both producers and consumers by integrating markets (OECD 2013). Unintended consequences can ensue from policy interventions, as illustrated by the 2008 food price crisis (Slayton 2009).

Damages to the transportation infrastructure that enables trade diminish food access for both consumers who have greater difficulty obtaining food and also for producers, who have fewer available options to sell their crops (Chamberlin and Jayne 2013). Current weather anomalies offer a preview into the possible effects of climate change on the transportation infrastructure that enables trade. These events influence food access by hindering food's movement from its place of production to consumers, altering the price of food in response to changes in the price of transportation and disrupting the timing and operation of logistical supply systems (IPCC 2012). Extreme temperatures can physically damage roadways and railways (Nemry and Demirel 2012). Heavy rainfall, sea-level rise, and storm surges can damage ground transportation and shipping infrastructure in coastal and low-lying areas (Schweikert et al. 2014). Severe drought can disrupt barge shipping in rivers when water levels get too low (Changnon 1989, Yu and Fuller 2005).

Extreme temperatures, storm surge, river floods, and other types of extreme weather physically damage transportation infrastructure and the supply chain (Koetse and Rietveld 2009, Becker et al. 2013). For example, in 2012, Hurricane Sandy led to a week-long shutdown of one of the largest container ports in the United States, generating economic damages estimated as high as USD 66 billion (Blake et al. 2013). Low water levels in rivers and lakes force inland waterway vessels to use only part of their maximum capacity, which leads to an increase in shipping costs and the number of trips they must make (Attavanich et al. 2013, Jonkeren et al. 2014, Millerd 2005 and 2011). In the United States, Attavanich et al. (2013) estimate that lower water levels in the Great Lakes, across which many goods (bulk freight, including agricultural products) are transported by barges, reduce the ability of U.S. farmers to export their grain to international markets. These transportation changes will affect both the ability of farmers to get their goods to market as well as the access of consumers to the goods.

6.1.3 Wholesaling and Retailing Food

With increased urbanization has come the rise of supermarkets and other highly efficient retail outlets in developing countries.

Food for consumption is sold to distributors for onward sale through large supermarkets, small vendors, or directly to consumers. Infrastructure is susceptible to damage from climate and weather, and through the influence of climate on economic drivers by affecting consumer traffic or increasing local demand during times of crisis (Burrus et al. 2002, Murray et al. 2010). More than half of the world's population lives in urban areas (Seto et al. 2012). With increased urbanization has come the rise of supermarkets and other highly efficient retail outlets in developing countries (Reardon et al. 2003, Pingali 2007). In coastal cities, imported food that caters to changing urban dietary preferences competes with food supplied by inland producers (Pingali 2007). Capital-intensive and labor-intensive production systems frequently coexist in developing economies, and most agrifood sectors include food from both. The result is a diverse exposure to climate and weather shocks, for which the retail sector has increasingly assigned risk to the producer (Lee et al. 2012).

Expansion of large-scale retailing will also affect producer prices as integration and consolidation occur, particularly for specialty crops such as cocoa and coffee (Kaplinsky 2004). Both high and low food prices on the world market challenge food security (Swinnen and Squicciarini 2012). Low prices, underpinned by producer subsidies in North America and Europe, make it difficult for farmers in developing countries to compete with farmers in developed countries on the world market, thus reducing the former's domestic capacity (Anderson et al. 2013). Alternatively, high prices make it difficult for low-income populations to purchase adequate food supplies when their own food production cannot meet their needs (Nin-Pratt et al. 2011).

6.2 Adaptation for Food Access and Stability

The effects of climate and food price changes depend upon vulnerability; the ability to effectively respond to shocks depends on adaptive capacity, which varies greatly within and across societies. The future evolution and distribution of vulnerability and adaptive capacity will strongly influence the effects of climate change on food access (Dunford et al. 2015, Krishnamurthy et al. 2014).

With respect to climate change, the adaptive capacity of the food system depends upon how effectively risk is managed to minimize its effects on the overall supply chain. Risk and uncertainty take many forms in the food chain: weather and climate, biological processes critical to successful production, financial risk, geographical separation of production and consumption, market cycles, and the political economy of food systems (Krishnamurthy et al. 2014, Vermeulen and Campbell et al. 2012). The degree to which different aspects are sensitive is very case-specific (Johnson and Brown 2014, Murphy et al. 2012, Cole et al. 2009). In some situations, a severe storm can destroy crops in the field and hence lead to local food shortages and price increases. More-widespread food insecurity may arise if a larger region depends on a critical element of infrastructure (e.g., rail) that can be destroyed by a major flood. Although it is not possible to pinpoint a specific risk to the food system from climate change that applies universally, the interdependence of different food-system activities means that effects on post-farm-gate activities can outweigh farm-level production effects (Rosenzweig et al. 2001).

Food prices are affected by access to markets and by trade decisions. In an extension of previous AgMIP research, five global economic models extend their analysis to look at the effects of trade (Wiebe et al. 2015). Four scenarios drawn from this work are shown in Figure 6.3. Scenarios 1 and 2 assume relatively low emissions (RCP 4.5) and high levels of international cooperation in adapting to and mitigating climate change (SSP1). Scenarios 3 and 4 make the opposite assumptions: high emissions (RCP 8.5) and low levels of international cooperation in adapting to and mitigating climate change (SSP3). Each scenario differs in its assumptions regarding trade. Scenario 1 assumes moderate levels of global trade, Scenario 2 assumes freer trade, Scenario 3 assumes very restricted trade, and Scenario 4 assumes restricted trade, but trade that is less restricted than under Scenario 3.

Relative to a world where the climate remains fixed under current conditions, the low-emissions/high-international-cooperation scenarios (1 and 2) exhibit smaller price increases compared with the high-emissions/low-international-cooperation scenarios (3 and 4); however, prices do increase in each case relative to a scenario where current climate conditions remain constant until 2050 (a “no climate change” scenario). The freer-trade scenarios (2 and 4) result in lower price increases relative to the restricted-trade scenarios (1 and 3).

The scenarios are limited in that they are based on models that primarily represent production of major agricultural grain commodities and do not fully characterize the food system beyond the farm gate, thereby missing important food system elements that affect food access. They also represent consumer behavior in relatively simple terms, with highly aggregated data that do not fully reflect some demographic changes or changes in the distribution of income. Yet, the influence of climate change to increased prices, regardless of socioeconomic scenario, is consistent.

The opportunities of a more resilient food chain depend upon location and product (Kaplinsky 2004, Lee et al. 2012). Participation in agricultural markets is often uncertain, risky, and conducted on unfavorable terms for smallholders in rural areas (IFAD 2011). There is a positive relationship between average farm size and the level of economic development: the higher the per-capita GDP of a country, the larger the average farm size (Eastwood et al. 2010) and the greater the adaptive capacity

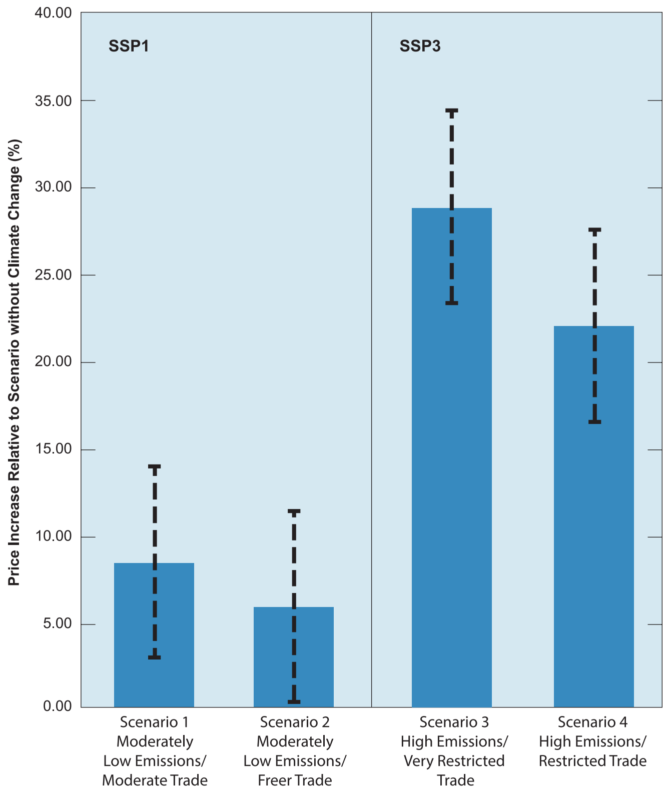


Figure 6.3 Projected mean food price changes in 2050. *Food prices from five global model projections for four scenarios, with error bars representing the uncertainty in results. The scenarios depicted here are relative to a projected 2050 baseline price when climate conditions are held constant at current levels. Scenario 1 projects moderately low emissions (RCP 4.5) and moderate levels of trade. Scenario 2 also projects moderately low emissions, but with freer trade than Scenario 1. Scenario 3 projects high emissions (RCP 8.5) and very restricted trade. Scenario 4 projects high emissions with restricted trade, but trade that is less restricted than under Scenario 3. All scenarios demonstrate increased prices under climate change. Freer trade results in smaller projected price increases for both low emissions (Scenario 2) and high emissions (4) scenarios. Adapted from Wiebe et al. 2015*

(Brooks et al. 2005). Differences in adaptive capacity can drive households to grow their own food instead of buying it at local markets or to limit their production to market-oriented crops (Nin-Pratt et al. 2011). If remunerative and reliable produce markets are available, farm households can increase their incomes and reduce their vulnerability during poor production years (Lloyd et al. 2011), though the risks of market participation are context and value-chain specific (IFAD 2011, Zant 2013, Haile and Kalkhul 2013). However, it is generally a challenge for poor rural people to seize rewarding opportunities in produce markets and cope well with the attached risks (Reardon et al. 2003, Neven et al. 2009).

Participation in agricultural markets is often uncertain, risky, and conducted on unfavorable terms for smallholders in rural areas.

The capacity of the urban poor to adapt to changes in climate and consequent effects upon food access

depends on many factors. Climate change is one stress among many that cities face (Leichenko 2011). Cities in many places often have common vulnerabilities that can be ameliorated with adaptive responses operating at different scales, such as engineering solutions to floods, waste management, and disaster planning (UNISDR 2004, Cutter et al. 2007, Shepherd et al. 2013). The urban poor, however, have the greatest exposure to flooding, high temperatures, and other hazards likely to occur with a changing climate (Douglas et al. 2008). Better understanding of the relevant interactions between urban development and the climate system, and turning the hazards resulting from human pressures into sources of opportunities and innovations, is indicated for improved food-access outcomes in urban settings (Romero-Lankao and Dodman 2011).

For wholesaling and retailing activities, adaptation might take a number of forms. Adaptation to higher temperatures may be accomplished with increased refrigeration, though that would likely come at increased costs for industry (James and James 2010). Disruptions in delivery systems due to extreme events also may also require adaptive adjustments. “Just-in-time” logistical systems, which match the rate of food production to the rate of food consumption to avoid the need for large storage areas and maintenance, may be at greater risk under more-severe climate extremes, though it appears possible that adaptive measures, such as greater supply-chain redundancy, may be one possible approach (Stecke and Kumar 2009, Altay and Ramirez 2010). Repairs, modifications, changes to shipping logistics, and transportation substitutions (e.g., switching from barge to rail transport) may be applied to a greater degree, as well, to adapt to changing conditions (Brown et al. 2013, Rodrigue 2013).

6.3 Measuring Food Access and Stability

The measurement of food access generally focuses on economic access using price and income information (Deaton 1989). However, it is difficult to track basic food prices on a global scale (Brown et al. 2012). Data issues are compounded by social norms that are frequently geographically specific and cannot be easily applied to other locations.

Information on household and intrahousehold access to food can be combined with per-capita food-consumption statistics to develop national-level measures of undernourishment, such as those found in the FAO’s Prevalence of Undernourishment Indicator (FAO 2014c). No comparable indicator is available for access to nutrients, though some information can be gleaned from dietary composition, as assessed by food-intake data.

Because of the heterogeneity of food items, and because access depends on cost, the real rate in the growth of food supply is typically measured in monetary terms. A money metric for real growth involves correcting for price variation over time (i.e., changes in the general price level) within a country and for differences in exchange rates and purchasing power across countries. To account for these factors, international food-production statistics are usually expressed in terms of a reference currency (e.g., the U.S. dollar, or USD). For instance, FAO data on the value of food production currently use average producer prices for each product and country for the period 2004–2006 as converted into USD at purchasing power parity (PPP) conversion rates (FAO 2014d). Income statistics in PPP dollars are also available from the United Nations (UN) International Comparison Program and included in the World Bank’s World Development Indicators (World Bank 2014). Indicators of monetary access to food based on these or other figures, however, are not currently available, except for some specific places and times. The closest substitutes are poverty rates, which measure the purchasing power of households relative to the cost of covering their food requirements and other basic needs (Deaton and Dupriez 2011).

A compilation of survey-based income and consumption distributions across households is maintained by the UN University as part of the

WIDER-WIID project (Chotikapanich et al. 2007). The measurement of income and consumption distributions across households requires estimating the mean and variance of the distribution of per-capita household income. Income variance data are usually taken from household income or expenditure surveys; average income data may be taken from the same surveys (which usually involve some underreporting of income) or from national sources (which also suffer from measurement error). In either case, the indicator is not restricted to food but rather covers all expenditures, although many surveys now specifically collect detailed data on food expenditures (Deaton 1997).

6.4 Conclusions and the Future

Climate change presents challenges to food access and its stability in a highly connected world. This section addresses lessons and conclusions about the future of food access and its stability, based on the available literature. Subsection 6.4.1 below combines information from the rest of this chapter with the shared socioeconomic pathways described in Chapter 3, allowing the report's authors to identify sensitivities under climate change given a range of development pathways.

Price

Food-access stability depends on relatively stable climatic conditions. Changes in the occurrence of weather and climate extremes are already detectable in many regions (Zhang et al. 2011, Coumou and Rahmstorf 2012, Donat et al. 2013, Zwiers et al. 2013, Coumou and Robinson 2013), and a higher frequency of very hot days, very dry days, intense rainfall, and changes in the growing season can occur even under lower-emissions scenarios (Tebaldi et al. 2006, Kharin et al. 2007, Wuebbles et al. 2014, Menzel et al. 2003, Robeson 2002), which can affect food prices.

There is high uncertainty about future real food prices, even in the absence of climate change (Figure 6.2). Some models project substantial price increases, while others project substantial price decreases, each in the absence of climate-change effects. The addition of climate change to those projections increases prices in either case (Figure 6.3), however, implying that climate change is likely to diminish gains in food access that might be achieved under any socioeconomic-development scenario.

Rapid increases in food prices due to extreme events are more likely in the future and have been demonstrated to reduce food affordability and consumption (Webb 2010). Low-income households, for whom food represents a larger portion of income, are more vulnerable to price spikes than middle- and high-income households (Bellemare 2014).

Food allocation among different groups (e.g., ethnic, gender) can also be affected by changes in food prices, resulting in increased vulnerability to food insecurity by more marginalized segments of a population (Raleigh 2010).

Food-price increases are most likely to affect segments of the growing population with lesser capacities to absorb food shortages, even over short periods of time, potentially increasing the prevalence of transient food insecurity, particularly in the absence of increased incomes (Becquey et al. 2012, Hillbruner and Egan 2008, Handa and Mlay 2006).

Trade and Transportation

Trade of agricultural commodities in a changing climate, and the physical transportation system that enables that trade, can alter vulnerability to changes in food access. Effects are context-specific, and changes in large-scale average conditions depend greatly upon actions and choices made outside the food system itself.

Trade can allow greater food access through a more diffuse supply base, stabilizing food prices and compensating for regional shortfalls (Schmidhuber and Tubiello 2007). Food trade can also expose import-dependent communities to changes in climate occurring in distant regions through supply disruptions and price fluctuations (Godfray and Beddington et al. 2010).

Increased food prices can benefit the agricultural producers who generate a surplus (Swinnen and Squicciarini 2012). However, price variability can create food-access difficulties for food producers, even when prices are on average increasing, due to the greater challenges in managing uncertain and fluctuating income levels (Brown et al. 2009). The frequently low production levels of food-insecure populations reduce the ability of these populations to benefit from a productive agriculture sector elsewhere (Brown et al. 2009). These concerns are particularly acute where population growth outstrips food production and imports become increasingly necessary using scarce foreign capital (Alexandratos and Bruinsma 2012). Population expansion and urbanization are projected to continue through the 21st century, particularly in lower income regions (Ezeh et al. 2012); thus, the need for imports is likely to increase (Godfray and Garnett 2014, Masters et al. 2013).

Damage to transportation infrastructure can diminish food access for consumers as it becomes more difficult to obtain food (Kneafsey et al. 2013) but also for producers who have fewer available options for selling their crops (Emran and Hou 2013). Repairs, modifications, changes to shipping logistics, and transportation substitutions (e.g., switching from barge to rail transport) can improve food access (Omamo 1998, Koetse and Rietveld 2009). Increased refrigeration during transport can keep food unspoiled but increases costs (James and James 2010). The smaller the changes in climate, the lower the costs are likely to be.

Wholesaling and Retailing

Food wholesaling and retailing plays an important role in the provision of food to consumers (Ericksen 2008). This sector is undergoing expansion in the form of supermarkets in much of the developing world, alongside more traditional systems, driving an evolution in procurement systems to source foods from long distances (Reardon et al. 2003). Such structural changes within the sector expose it to climate risks (Crush and Frayne 2011, Lee et al. 2012). Contract farming, purchasing agreements, and continued expansion of supermarket-type wholesaling and retailing are expected to continue and form an important backdrop for any effects that changes in climate may have (Barrett et al. 2012, Collier and Dercon 2014).

The rapidity of adaptive changes in the sector will be affected by changing climate effects upon trade and transportation systems and vulnerabilities along the supply chain, particularly under higher-emissions scenarios over the longer term and operating in

Shared Socioeconomic Pathway	Price	
	P	W
SSP1	Medium Risk	Medium/Low Risk
SSP2	High Risk	Medium/Low Risk
SSP3	Very High Risk	Medium Risk
SSP4	Very High Risk	Medium/Low Risk
SSP5	Medium Risk	Medium/Low Risk

(P: poorer nations, W: wealthier nations)

Key
Low Risk
Medium/Low Risk
Medium Risk
High Risk
Very High Risk

Figure 6.4 Relative risks to food access for different SSPs. *The risks to food access would be lowest under the economic conditions described in SSP1 and SSP5, with poorer nations at higher risk across almost all food affordability and allocation categories for all SSPs. Shading represents higher or lower risks for each SSP from climate change. Risks reflect the informed judgment of the authors of this report, based on the available literature.*

tandem with changes in consumptive demand. The nature of these changes can only be fully understood by working in cooperation with industry, which is a fundamental food system actor, but whose internal data, metrics, and indicators are not often available for peer-reviewed analysis to inform this discussion.

6.4.1 Food Access and Stability in the Context of Shared Socioeconomic Pathways (SSPs)

The influence of climate change upon food access and its stability depends on responses by each of the key food-system elements under differing socioeconomic trajectories. Food access is shaped by prices and affordability, trade and transportation, and wholesaling and retailing. Each of these factors is highly context-specific. Many parts of the food system are not considered by the SSPs or within available modeling frameworks directly, but applicable lessons emerge from the exercises that have been conducted. For these reasons, this section focuses on price as a principal shaper of future food access, considered for each of the SSPs introduced in section 3.4.1 of this volume. Trade significantly influences food prices, but anticipated effects of climate change on trade were discussed in detail in Chapter 5 (section 5.4.1) and are not reiterated here. Figure 6.4 reflects the informed judgment of the report's authors on the relative risks that contribute to food access and stability for each of the five SSPs.

Under SSPs 1 and 5, the existence of highly connected trade networks suggests that climate change is unlikely to generate exceptional price shocks that might widely compromise food access and stability. Under both scenarios, markets effectively facilitate the movement of food from areas of food surplus to areas of food deficit, helping to ameliorate high food prices and price shocks. Additionally, both SSPs anticipate substantial economic growth that would improve purchasing power and make food more affordable, in both poor and wealthy contexts. The fossil-fuel-intensive pathway of SSP5, however, could result in significant climate disruptions to transportation networks and create barriers to trade, diminishing some of these benefits, particularly in poorer countries where resources to invest in infrastructure improvements and repairs are scarce. It is therefore possible that under SSP5, climate change could make food less affordable for people in poorer countries.

Constrained trade under SSPs 2, 3, and 4 has price, and therefore food-access, implications. SSP2 would likely lead to many stresses and shocks, and while the semi-open globalized economy may allow for trade links that prevent severe price shocks and affordability challenges in this SSP, it may not be open enough to facilitate the robust trade links needed for markets to effectively respond to the more severe shocks. Under SSP2, it is likely that price increases would be more prevalent in poorer countries. Under SSPs 3 and 4, this pattern and outcome are accentuated. These SSPs present a world where the wealthy enjoy strong connections but are disconnected from the global poor, who are disconnected from one another in different geographic locations. As a result, markets would rarely respond to food shocks and stresses such that food can effectively move into deficit areas to address shortages and higher prices. Under SSP3, ineffectual trade connections can also exist among the world's wealthy, potentially compromising food prices and affordability, though these effects would almost certainly be less severe than among poorer nations. Food prices and affordability would be at risk in all SSPs, but SSPs 2, 3, and 4 exhibit the greatest risks to food access and its stability.

Chapter 7

Food Utilization and Stability

Key Chapter Findings

- Biological contaminants in the food supply are highly sensitive to changing temperature and humidity, affecting food spoilage rates and human health.
- The adaptive capacity of food-system activities that influence food utilization and its stability is potentially very high but is also highly variable.
- Climate variability has already affected the stability of food utilization through extreme-weather events and their associated emergency responses.

Food *utilization* addresses the question "If food exists (i.e., is *available*), and you can get it *(access),* can you then make use of it?" This chapter defines food utilization, relates it to important components of the food system, and identifies areas where changes in climate have already and may in the future continue to influence food utilization. The chapter addresses the stability of food utilization, as well as adaptations for managing changing conditions.

What Is Food Utilization?

The principal measures of food utilization capture nutritional effects, focusing on an individual's ability to use the food that is both available and accessible. These outcomes are expressed in terms of malnutrition, which manifests as undernutrition or overnutrition (WHO 2003a). Shocks can also exacerbate causes of food insecurity outside the food system, including chronic poverty and disease (Irz et al. 2001, Thirtle et al. 2003, Ravallion et al. 2007, Schreiner 2012). Standards and regulations for processing and packaging are a key means to improve safety (and utilization potential) at multiple stages along the food system (Lee et al. 2012).

The term undernutrition captures the outcomes of inadequate caloric and/or nutrient intake (WFP 2012). These outcomes include stunting (short for one's age), wasting (thin for one's age), and micronutrient malnutrition (deficient in needed vitamins and minerals). Undernutrition is related to inadequate diet, care, feeding, and health practices, and/or compromised sanitation and hygiene. These factors can lead to infection, weight loss, nutrient depletion, and immunosuppression, which decreases the body's ability to fight infection and further reduces the absorption of nutrients, leading to a cycle of undernutrition and infection (Kau et al. 2011). For example, deficiency in vitamin A can lead to immunosuppression and blindness; iron deficiency can lead to anemia; and iodine deficiency can lead to goiter (Ramakrishnan and Semba 2008, Semba and Delange 2008, West and Darnton-Hill 2008).

In 1980, the prevalence of child stunting in the developing world was approximately 47% (de Onis et al. 2000). By 2010, the prevalence had decreased to 29.2% and is expected to decrease to 23.7% by 2020 (de Onis et al. 2012). In the developed world over the same time period, the prevalence of stunting has remained at about 6% (de Onis et al. 2012). While the developing world has seen an overall decrease in stunting and other measures of undernutrition over time, vast regional differences have been observed (Black et al. 2008). With the exception of North Africa, most regions of Africa have maintained a consistent level of child and maternal undernutrition (with stunting at 38%–40%). Asia and Latin America have seen the most dramatic decreases and are expected to reduce their stunting levels to 19% and 10%, respectively, by 2015 (de Onis et al. 2012).

Overnutrition refers to the consumption of too many calories or specific nutrients relative to the required levels for normal activities and/or growth and can manifest, for example, as an increase in weight or mineral poisoning. Overnutrition has been attributed to increased urbanization as well as changing lifestyles and diets (specifically, an increase in the consumption of processed foods, animal-source foods, fats, and sugars), and it is associated with diabetes, heart disease, and stroke (Kennedy et al. 2006, Popkin 2006, UN Standing Committee on Nutrition 2010, WHO 2003a). Although studies in the United States have shown conflicting results on the link between food insecurity and overnutrition (Dinour et al. 2007, Lohman et al. 2009, Martin and Ferris 2007), in developing countries undergoing a nutrition transition (e.g., Brazil, China, Guatemala, Indonesia, Vietnam, Russia, the Kyrgyz Republic), there has been a rise in the double burden of undernutrition and overnutrition occurring in the same populations and even in the same households (Doak et al. 2005, Kennedy et al. 2006).

Trends in overweight children have only recently been documented and are limited by available data, but they suggest that the prevalence of obesity since 1970 has increased for all developed countries and for a number of developing countries (Wang and Lobstein 2006). North America and Europe report the highest prevalence of obese and overweight children (as high as 30%, with the expectation that this figure could increase to 46%). Southeast Asia and much of Africa report the lowest prevalence of overweight children and the slowest rate of obesity (Wang and Lobstein, 2006). Some countries that have experienced rapid economic development are now coping with both childhood undernutrition and overnutrition, particularly among the lowest socioeconomic groups (Jones-Smith et al. 2011, Wang and Lobstein 2006).

Trends in overweight children have only recently been documented and are limited by available data, but they suggest that the prevalence of obesity since 1970 has increased for all developed countries.

In addition to these types of individual manifestations reflecting food utilization, there are societal elements as well. Individuals may place high value on locally produced food, culturally important food, or food that they themselves produce (Altieri and Toledo 2011, Rosset 2008). Alternatively, they may have limited knowledge regarding the preparation of unfamiliar food types. These issues of cultural appropriateness, individual values, and preparation skill may be particularly acute for women, who are often the household food preparers (Ibnouf 2009, Quisumbing et al. 1995). Changes in the geography of food production, and/or changes in trade patterns that may make some familiar foods less available or accessible and/or increase the availability or accessibility of unfamiliar foods, may alter utilization patterns.

7.1 Influences on Food Utilization and Stability

Climate has a number of potential and observed effects on contamination of the food supply, on the nutritional composition of food, and on a body's ability to assimilate the available nutrients, all of which influence food utilization and each of which is discussed below.

7.1.1 Food Safety

Climate change can affect food safety throughout various stages of the food supply chain (Jacxsens et al. 2010, Tirado et al. 2010). Food safety is a critical means by which changes in climate can affect the utilization of food by influencing vectors of food contamination and levels of toxins in food. Elongated supply chains expose food products to greater risk of potential contamination and make it harder to verify the quality of the products at various stages (Swinnen 2007), but also allow more diversity in consumption and more stability over time.

Vulnerability of transport infrastructure to extreme events (IPCC 2012) can affect utilization by hindering the movement of food from its place of production to consumers and increasing the likelihood of food contamination. Temperature increases have been associated with illness from Salmonella and Campylobacteria, which may be related to poor food storage and handling practices in the supply chain. In general, increased temperatures are known to cause an increase in diarrheal diseases (which can lead to malnutrition); bacterial foodborne diseases grow and reproduce faster at elevated temperatures (Bandyopadhyay et al. 2012, Tirado et al. 2010). For example, in one study in Peru, the incidence of diarrheal diseases increased by 8% for every 1 °C increase in temperature (Checkley et al. 2000). However, some viruses, such as noroviruses, which can be transferred when contaminated foods or liquids are ingested, show an increased prevalence in children in winter, particularly during times of low immunity in the population and the emergence of novel genetic variants (Velázquez et al. 2004, Levy et al. 2009, Cook et al. 1990, Tirado et al. 2010). A decrease in infection rates could therefore result from warmer winters. These health challenges are not confined to low-income countries. For instance, a study in England found that for every 1 °C increase in temperature, there was a 5% increase in the number of reports of Campylobacter enteritis, up to a threshold of 14 °C (Tam et al. 2006).

Fungal infections of crops, particularly of the genus *Aspergillus,* can have severe effects on human health and nutrition whether consumed directly or through the milk produced by livestock who have themselves consumed infected crops (Wagacha and Muthomi 2008, Williams et al. 2004). Aflatoxin, a potent mycotoxin, is produced by *Aspergillus* and is known to lead to cancer, as well as developmental and immune-system suppression; in severe cases it can lead to death (Williams et al. 2004, Wu et al. 2011). Fungal contamination is a result of pre-harvest practices; timing of harvest; handling of produce; moisture levels during harvest, storage, transportation, and processing; and insect damage (Wagacha and Muthomi 2008, Cotty and Jaime-Garcia 2007, Miraglia et al. 2009, Tirado et al. 2010). Climate change can affect crop contamination, which can increase during the warm and dry periods of crop development, as some mycotoxin-producing fungi grow best in warmer temperatures (Paterson and Lima 2011, Sanders et al. 1984, Schmitt and Hurburgh 1989). Crops such as maize and peanuts, staple foods for large populations, can be affected, though effects vary depending on the region and temperature and rainfall changes within the region (Paterson and Lima 2011). In low-income countries, the problem of mycotoxin contamination in food and feed due to lack of refrigeration or climate-controlled containers is becoming more widely recognized (Groopman et al. 2008). A synergistic effect between mycotoxin exposure and some critical diseases in Africa, such as malaria, kwashiorkor, and HIV/AIDS, is also suggested by several studies (Wagacha and Muthomi 2008, Williams et al. 2010).

Aquatic and fishery food sources are important, both as sources of protein and for income generation (FAO 2009b). The warming of the upper ocean and uneven changes in the nutrient density of the water (Barange and Perry 2009) can promote harmful algal blooms, which produce toxins that contaminate seafood and can cause illnesses such as paralytic shellfish poisoning, diarrhetic shellfish poisoning, and neurotoxic shellfish poisoning in humans. In addition, climate-related fluctuations in sea salinity can cause a more rapid uptake of toxic chemicals by fungi, bacteria, mollusks, and crustaceans and an increased uptake and bioaccumulation by crustaceans and mollusks (Marques et al. 2010).

7.1.2 Nutrition

The body's utilization of macro- and micronutrients, required vitamins and minerals, and related dietary compounds is a critical component of food utilization. Micronutrients are nutrients that are needed in relatively small quantities in the diet. They play important roles in sight, immune function, and cellular signaling, among other biological processes.

Climatic factors can potentially affect the availability and use of micronutrients in several ways, which can lead to micronutrient deficiencies (Loladze 2002). One study found that the concentration of iron and zinc found in staple grains and legumes is reduced under elevated atmospheric carbon dioxide, a driver of climate change (Myers et al. 2014). Another study found that protein (a macronutrient) content in milk declined with increased temperature and humidity above threshold values (Bahashwan 2014, Nardone et al. 2010, Renna et al. 2010). Other nutritional effects are more uncertain under changing climate (Renna et al. 2010). Evidence of climatic effects on nutrient content in fruits and vegetables, for example, remains limited (Burke and Lobell 2010).

The nutritional quality of a number of staple foods is diminished by elevated atmospheric CO_2 concentrations

The nutritional quality of a number of staple foods is diminished by elevated atmospheric CO_2 concentrations (Ceccarelli et al. 2010). Under increasingly high concentrations of atmospheric CO_2, nitrogen concentration, a proxy for protein content, appears to diminish by 10%–14% in the edible portions of wheat, rice, barley, and potato, and by 1.5 % in soybeans (Müller et al. 2014, Taub and Wang 2008). Mineral and micronutrient concentrations in the edible portions of crops are also likely to diminish under elevated CO_2 concentrations (IPCC 2014). The overall nutritional quality of many important food sources is therefore diminished in a changing climate.

One result of the historical focus on additional calories as the primary means of achieving food security has been the increased production of high-yielding rice, maize, and wheat crops. The result has been a reduction in micronutrient (iron and zinc) concentrations, as well as protein content, in the overall mix of crops produced. This has resulted in lower nutrient availability for portions of the population who rely on cereals as their main food source (DeFries et al. 2015).

7.1.3 Environmental Enteropathy

Climate also affects utilization through changes in nutrition-*sensitive* factors. For example, a review of nutrition-related interventions undertaken in 36 countries demonstrated that food-utilization outcomes are shaped not only by nutritional inputs, but also by factors such as disease burden; women's empowerment; and water, sanitation, and hygiene (Bhutta et al. 2008).

These wider climate-sensitive factors affect utilization through environmental enteropathy (EE), a subclinical condition associated with intestinal infections, altered gut morphology, chronic inflammation, and increased gut permeability, and in turn, increased entrance of bacteria into the body and poor nutrient absorption, leading to undernutrition (McKay et al. 2010). Increasing waterborne diarrheal diseases, including cholera, that are among the causes of EE are associated with extreme-weather events, particularly in areas with poor sanitation (Confalonieri et al. 2007). EE itself is associated with stunting and wasting (Campbell et al. 2003). The climate change to EE to diminished food utilization chain of events has not yet been studied in an end-to-end fashion; however, the relationships established between climate variables and EE causes, and EE's association with diminished food-utilization capacity, imply that climate change may influence the prevalence of EE and, ultimately, undernutrition.

7.1.4 Storing, Processing, and Packaging Food

Food storage, processing, and packaging often include both capital-intensive and labor-intensive systems coexisting in the same region, with each system having different vulnerabilities to weather and climate (Lee et al. 2012). Poor storage is a major cause of food loss, and proper packaging prevents damage and contamination. In developing countries, there are significant post-harvest losses due to financial and structural limitations in harvest techniques, inadequate or poorly managed storage and transport infrastructures, and climatic conditions favorable to food spoilage (FAO 2013a). Higher temperatures can also prolong damage by pests (e.g., rodents, insects) after harvest, absent appropriate storage methods (Magan et al. 2003, De Lima 1979). Post-harvest losses vary by region and industrial process, as losses are dependent on the specific conditions and local situation in a given country or region. For example, lack of appropriate storage facilities for food crops can lead to pest infestations or mold growth that render the crops inedible (Parfitt et al. 2010). As temperatures rise, post-harvest losses may increase in regions without appropriate processing and storage facilities.

Food-safety issues increase when the agricultural product-processing sector lags behind broader agriculture growth, which has been the case in many food-insecure countries (Byerlee et al. 2005). Modern packaging and storage facilities are currently deficient in most developing countries (IAASTD 2008). Higher temperatures can affect food packaging by degrading the plastics, rubber, and wood materials over time (Andrady et al. 2003). In low-income countries, lack of cold storage on farms and in wholesale and retail outlets can result in loss to pests and rotting (Vermeulen and Campbell et al. 2012). In east and southern Africa, for example, grain is often stored outside or in open-air sheds and may be affected by weather shocks (Stathers et al. 2013). Unusually wet weather in the dry season can significantly harm grain stored for future use (Nukenine 2010).

7.1.5 Consumption and Disposing of Food

The final stage in the food system is consuming food, which involves buying, preparing, and eating food at the individual or household level (Ericksen 2008). Food consumption has increased over the past 50 years by 400 kcal per person per day, with dramatic decreases in the prevalence of hunger in many areas (Kearney 2010). Large increases in the consumption of vegetable oils (199%), meat (119%), and sugar (199%) in low-income countries between 1963 and 2003 reveal significant expansion of food availability across all income brackets (Alexandratos and Bruinsma 2012). At the same time, declines were seen in the consumption of pulses and roots over these four decades (Kearney 2010). These changes have been driven largely by technological and socioeconomic factors, and how climate change will further affect these changes is uncertain.

Food consumption has increased over the past 50 years by 400 kcal per person per day, with dramatic decreases in the prevalence of hunger in many areas.

The marked rise in available food energy observed globally has been accompanied by changes in dietary composition that have affected overall food demand (IAASTD 2008). The extra calories come from cheaper foodstuffs of vegetable origin in both developed and developing countries (Kearney 2010, Smil 2000). Income growth, urbanization, and increasing demands on people's time that might otherwise be used for food preparation together result in larger proportions of the diet being composed of prepared foods that are high in fats, sugar, and salt, resulting in adverse health consequences (Popkin 1999). Increasing demand for meat and dairy from urban populations is further straining the agricultural system (IAASTD 2008).

Estimates suggest that 30%–50% of total food production is lost globally as waste (Gustavsson et al. 2011). Similar levels of waste are observed in developed and developing nations, with differing causes in each case. In developing nations, the absence of adequate food-system infrastructure is a primary cause of food waste (Godfray and Beddington et al. 2010). This issue was discussed in the "Food Availability and Stability" chapter of this report. Waste in retail, food service, and at home accounts for the majority of food waste in developed regions (Parfitt et al. 2010).

7.2 Adaptation for Food Utilization and Stability

Diminished food utilization or utilization stability can result when the food system fails to adapt to changes in climate. Vulnerabilities are particularly apparent during extreme-weather events when time is critical (Ericksen 2008, Hillbruner and Moloney 2012, Lautze et al. 2012). A number of options exist for adaptation to better enable food utilization and stability that may be appropriate under differing circumstances.

A variety of techniques exist to reduce post-harvest losses resulting from food spoilage and include varietal selection, biological control, storage structures, chemical treatments, botanical and inert dusts, and improved handling and processing (Affognona et al. 2015). Additional monitoring for food pathogens and contaminants will be adaptive under higher temperatures and humidities as a means of managing food safety (Gregory et al. 2009). Prerefrigeration methods of food storage (e.g., drying, salting, pickling) may be used effectively in a changing climate (Shepherd 2012, Gitonga et al. 2013). Reduced intervals between harvest and storage can diminish the faster rates of spoilage that occur under higher temperatures and humidity. Cold storage is another possible adaptation, though costs increase with additional refrigeration (James and James 2010). High levels of food processing can reduce the need for cold storage (Young 2013) and may consequently represent a means of adaptation that ameliorates refrigeration costs.

Disruptions in delivery systems may become more probable in a changing climate (Stecke and Kumar 2009), with implications for "just-in-time" logistical supply systems, which attempt to match the rate of food production to the rate of food consumption to avoid the need for the maintenance of large storage areas. Greater supply-chain redundancy may be one productive approach (CDP 2015, Altay and Ramirez 2010) and becomes more economically feasible under more-rapid levels of change (Global Commerce Initiative 2009).

As the nutritional value of food diminishes under elevated atmospheric CO_2, adaptations might include greater cultivation of protein-rich crops (Linnemann and Dijkstra 2002), the inclusion of animal protein sources (Golden et al. 2011), or cultivation protein sources that are less familiar for some, such as insects (Shockley and Dossey 2014), particularly in cases where inadequate protein limits food-security status. Such adaptations might require the economic means to purchase animal-protein sources, farmland for additional leguminous crops, or a willingness to eat unfamiliar protein sources. Feedbacks from this adaptation might include potential changes to other components of food security, such as overall global food demand in cases where grains are used as feed (Kearney 2010, West et al. 2014).

Estimates suggest that 30%–50% of total food production is lost globally as waste.

Changing production geography may make familiar foods less available or accessible in some cases, and unfamiliar or less familiar foods may take their place. This can result in reduced utilization, perhaps transient, due to lack of familiarity with preparation methods for the new food types (Axelson 1986). Reduced utilization may disproportionately affect women (Ibnouf 2009, Quisumbing et al. 1995). The greater the change in familiar foods as a consequence of changes in climate, the greater the adaptation required, whether that entails paying more for familiar foods that are grown at a greater distance, purchasing the less-familiar foods and learning how to prepare them in a culturally appropriate way, or a combination of multiple adaptive habits.

Increased disease prevalence and distribution in a changing climate may lead to increased use of veterinary drugs or pesticides, bringing with it the possibility of higher residue concentrations in food and possible effects on consumption choices (FAO 2008a, Tirado et al. 2010, Cooper et al. 2014). This illustrates that where adaptation is possible, it may have consequences of its own.

7.3 Measuring Food Utilization and Stability

Food-utilization outcomes, expressed by anthropometric, clinical, or biochemical indicators of nutritional status, are usually measured by health and nutrition surveys carried out every 4–6 years, and thus do not always reflect seasonal and annual situations (Grace et al. 2014, Shively et al. 2015). Both poverty and undernourishment indicators refer to habitual consumption, usually over the span of a year (or the average of a 3-year period), and can help to identify issues where utilization of food is impaired.

Undernourishment is intended to measure chronic or habitual insufficiency of dietary energy, rather than short-term consumption fluctuations. For children under the age of 5, habitual insufficiencies can be measured by estimating the proportion of children with a low height-for-age (stunting). Short-term fluctuations can be measured for both adults and children by estimating the proportion of individuals with a low weight-for-height or low mid-upper-arm circumference as a measure of wasting (Gorstein et al. 1994) and can be used in combination with body mass index to estimate food insecurity. Overnourishment is measured by body mass index (James et al. 2004, Mathers et al. 2009).

The rapid expansion of food transport to supply supermarket-type retailing structures lengthens the period of time between harvest and consumption, potentially exposing food to conditions that may result in higher rates of contamination.

Seasonal or other short-term changes in consumption (stability) are common in agrarian settings where the timing of production and employment affect food-security status and is difficult to measure, as it requires high-frequency (i.e., monthly or seasonal) data that is highly spatially variable (de Haen et al. 2011). Few countries have systems in place for such a purpose. Where seasonality is an important component of food utilization, survey data are generally poor sources of information (de Haen et al. 2011). Despite the relevance to climate change, there is virtually no widely used source of data on seasonal variation of consumption or other factors related to food utilization and its stability at a household or community level (Barrett 2010).

7.4 Conclusions and the Future

Food safety and utilization have strong relationships to temperature and humidity; changes in these parameters are therefore likely to result in greater food-safety challenges, including the potential to alter human health outcomes from foodborne illness (D'Souza et al. 2004). Influences on food utilization—food safety and nutrition; food processing, packaging, and storage; and food consumption and disposal—are likely to be increasingly challenged by changing climatic conditions.

Fruit and vegetable crops harvested with higher pulp temperatures require more energy for proper cooling (Moretti et al. 2010). Higher temperatures and humidity generally cause increased mycotoxin accumulation (Magan et al. 2003, Fandohan et al. 2003, Rossi et al. 2001, Coakley et al. 1999). While exceeding a fungus's biophysical temperature threshold will reduce mycotoxin-related food spoilage, fungal populations can adapt to local conditions (Coakley et al. 1999). The need for refrigeration and dehumidification to reduce fungal growth can lead to strains on electricity grids (James and James 2010) and comes at increased cost. Managing food-security outcomes requires a comprehensive understanding of the interactive effects of adaptive choices throughout the food system and indicates that single-point adaptation itself may not, in many cases, be a panacea for managing systemic food-security outcomes (Ludwig 2011).

More-frequent food pathogen and contaminant monitoring may also be indicated in a changing climate (Gregory et al. 2009). At this time, monitoring surveys tend to be large-scale and prone to miss regional granularity food-safety threats, which may be addressed, at least in part, by more frequent monitoring of food from or in regions undergoing more rapid environmental change or adaptation (Lake et al. 2012).

The rapid expansion of food transport to supply supermarket-type retailing structures lengthens the period of time between harvest and consumption, potentially exposing food to conditions that may result in higher rates of contamination (Ercsey-Ravasz et al. 2012). As a consequence, some food products may require updated processing, packaging, and storage or may require protective packaging for the first time (Parfitt et al. 2010). Industry addresses food processing, packaging, and storage requirements to meet legal trade and food safety specifications (CDP 2015, WHO 2003b), but such data are not often available for scientific analysis. Documented relationships between food safety and climate variables that are expected to change, however, imply an increased need for adaptation in food processing, packaging, and storage (Parfitt et al. 2010).

Food-storage techniques such as drying, salting, and pickling are effective under increased temperatures and humidity, and may be used more widely or more rapidly after harvest to reduce the risk of food spoilage under higher temperatures (Affognona et al. 2015).

More-highly processed foods may be consumed more frequently in the future, helping to ameliorate both potential food-safety concerns and higher energy costs, though introducing other variables into the human health equation (Monteiro et al. 2011).

7.4.1 Food Utilization in the Context of Shared Socioeconomic Pathways (SSPs)

The influence of climate change on food utilization and its stability depends on how key elements of the food system respond to changes in climate under differing socioeconomic trajectories. Many parts of the food system are not considered by the SSPs or by existing modeling frameworks; Figure 7.1 reflects informed judgments of the authors on the relative risks to food safety and environmental enteropathy from climate change for different development pathways, based on inferences from the available literature on the subjects.

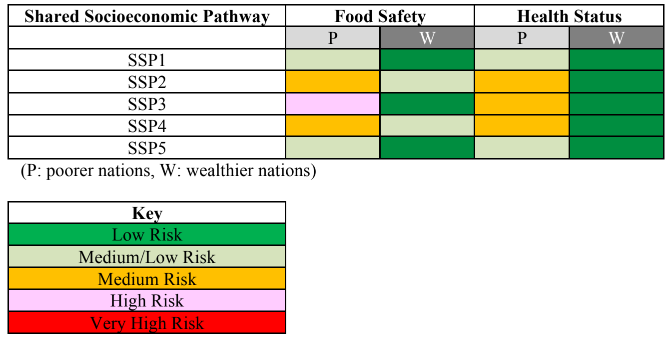


Figure 7.1 Relative risks to food utilization for different SSPs. *The risks to food utilization would be lowest under the economic scenarios described in SSP1 and SSP5, with poorer nations at higher risk across all food utilization categories for all SSPs. Shading represents higher or lower risks for each SSP from climate change. Risks reflect the informed judgment of the authors of this report, based on the available literature.*

Food Safety

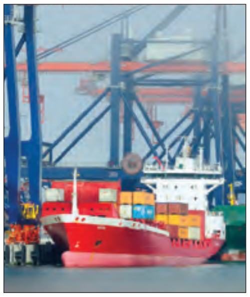
Across all SSPs, in wealthy countries where effective controls exist, food safety is not likely to be significantly affected by climate change. Poor countries, however, could experience significant variability in food safety across the SSPs. Economic growth and technology transfer under SSP1 is likely to ameliorate the effects of changing temperatures on food safety in poorer countries. Similarly, high rates of economic growth under SSP5 might produce income increases and increase expectations of improved food safety.

Under SSP2, technology transfer and economic growth would be somewhat lower than under SSP1, but the globalized trade regime might compel investment in or transfer of food-safety technologies due to international certification requirements, limiting significant food-safety impacts. Another possibility is that more-globalized trade could facilitate the movement of unsafe food into wealthy countries at higher rates than occur today. Under SSP3, more-modest economic growth would limit additional education and infrastructure developments that might otherwise contribute to improved food safety. Technology transfer, which is expected to be low under this scenario, would not fill that gap. In SSP4, poor countries would experience similar challenges as under SSP3, given low rates of economic growth and low technology transfer. However, the globalized trade regime might compel the international transfer of food-safety technologies to meet international certification requirements, which would address food-safety challenges in these countries. If not, food exports from these countries could result in more unsafe food consumption in importing countries.

Environmental Enteropathy

Given existing infrastructure and levels of public health, wealthy countries are likely to maintain low rates of EE under all SSPs in a changing climate. Rates of economic growth are expected to be high, and environmental quality would be expected to be high or improve in poor countries under SSPs 1 and 5, expanding their ability to manage climate change and respond quickly to disasters that would otherwise allow cholera and similar conditions to spread, contributing to EE.

Environmental quality is expected to deteriorate under SSPs 2, 3, and 4. For these SSPs, changing patterns of climate-related disasters are more likely to result in higher rates of EE-based diseases in places with little capacity to address them. Under SSP4, high levels of intracountry inequality could produce highly variable outcomes within a country, with the wealthy largely insulated from EE-related stressors and the poor experiencing increasing exposure.



Chapter 8

Global Food Security, Climate Change, and the United States

Key Chapter Findings

- Many important connections that the United States maintains with the rest of the world, including trade, food and developmental assistance, and technological development, are essential for global food security and will be challenged by climate change.
- Climate change has the ability to disrupt food security by making it more difficult to get food from one region that is able to produce food to another region that wants to consume it, due to vulnerabilities in transportation infrastructure and related trade arrangements.
- The United States. will likely be directly and indirectly affected by changing global conditions and is expected to maintain strong food imports, exports, and assistance programs and be a source of innovative new technologies for addressing global food insecurity.

Achieving and maintaining global food security is in the best interest of the United States (CCGA 2013). According to the CCGA (2013), improvement in food security in low-income countries assists the United States in its humanitarian goals of helping improve quality of life, promotes global stability, and helps create future trading partners. To these ends, the United States makes significant contributions to global food security and provides key resilience to climate change through trade, assistance programs, technology transfer, and export of on-farm agribusiness management principles and management of off-farm waste streams and other indicators of sustainability.

Changes in food security are occurring globally and are expected to continue based on changes in climate conditions, food systems development, and external factors such as incomes (Smith et al. 2000). Because the global food system is highly integrated, the United States is not independent of these changes (Walthall et al. 2012).

Changes at the global scale are therefore likely to be reflected domestically, within the United States. This may be reflected in whom the United States exports to, what types of exports are in demand on the world market, the geographical origins and qualities of imported foods, the demands placed on assistance programs, changes in the domestic infrastructure necessary for moving food products, and considerations for the natural resource base within the United States in meeting these changing circumstances. These global influences occur even as climate change itself directly influences U.S. production patterns, agricultural management, and food-system structures, and as the world changes in important ways that are independent of climate change altogether. The potential for domestic change is therefore high, though the current state of scientific inquiry raises more questions than answers at this time.

This chapter explores the ways in which the United States relates to the global food system and how climate change modifies those linkages. It goes on to assess the means by which the changing global picture may feed back into the U.S. food system.

Changes in food security are occurring globally and are expected to continue based on changes in climate conditions, food systems development, and external factors such as incomes

8.1 The United States as a Global Food-System Actor

The U.S. food system operates within a global system of interconnected markets. It has become increasingly integrated in international trade as both a major exporter and importer of food (Walthall et al. 2012). In that regard, the U.S. food system has become highly responsive to the main drivers of change in global food demand, which are population and income growth (Alexandratos and Bruinsma 2012). Growth in global population, although historically large, is expected to slow in the coming decades, bringing with it a broader lowering of the growth rate of food consumption globally (Alexandratos and Bruinsma 2012). However, demand in many low-income countries, especially in sub-Saharan Africa where consumption rates are presently low, will continue to grow rapidly. Rising per-capita incomes in many low-income countries will decrease poverty and increase food consumption, although incomes will remain low enough in the lowest-income countries and subpopulations of other countries that significant food insecurity will persist (Alexandratos and Bruinsma 2012).

The role of U.S. food exports in the future is unclear. Alexandratos and Bruinsma (2012) anticipate more-vigorous international food trade in future decades, with more low- to middle-income countries becoming major food importers. However, they see several traditionally major exporting countries, such as the United States and Canada, conceding market share to rising exporter nations, such as the Russian Federation and Ukraine. For the United States, markets for exports will continue to grow, although the picture of future U.S. export growth is unclear as demand slows.

Three major challenges to achieving broader global food security (Godfray and Beddington et al. 2010) that are likely to involve the U.S. food system are: (1) closing yield gaps, (2) increasing production limits, and (3) reducing food waste.

8.1.1 Food Production

Increasing food production is a key to providing continued upward growth in food supplies at regional and international scales (Godfray and Beddington et al. 2010). Yield gaps are the difference between the realized crop productivity of a place and what is attainable using the best genetic material, technology, and management practices (Godfray and Beddington et al. 2010). The realized crop yields of some low-income countries are estimated to be approximately 60% of their potential (Godfray and Beddington et al. 2010). Ameliorating this gap with existing technologies and methods offers a significant opportunity to increase food production for the food insecure. Yield gaps are typically caused by lack of access to contemporary technology and management knowledge. Food-insecure nations can narrow yield gaps through effective technology transfer and management training (Godfray and Beddington et al. 2010).

Concern exists that many countries, including the United States, are divesting agricultural research focusing on increasing crop yields (World Bank 2008a). Very little of the total genetic material from original varieties is actually exploited in today's crops (Godfray and Beddington et al. 2010). Preserving heretofore unused genetic material is important to pushing yield limitations. International collections and gene banks are valuable repositories of genetic variation. The United States is a major repositor of landraces and other genetic material. The USDA's National Center for Genetic Resources Preservation (NCGRP; Williams 2005) is one of the world's largest collections of seeds, genetic material for livestock, microbes, and endangered plants. The mission of the NCGRP is to act as genetic and germplasm conservator into the future to protect the nation's and world's ability to develop new traits, especially those oriented toward increasing food supplies (Williams 2005).

Modern genetic techniques combined with a better understanding of crop physiology allow greater specificity in cultivating a suite of desired traits in crops and livestock (Godfray and Beddington et al. 2010). The first USDA-approved field releases of GM crops in the United States occurred in 1985, with four releases (Fernandez-Cornejo et al. 2014). By 2013, nearly 12,000 releases had been approved for corn, soybeans, cotton, and potatoes in the United States. Most of the companies producing GM crop seeds are U.S.-owned. Land planted with GM crops in the United States has rapidly eclipsed land planted with non-GM crops (Fernandez-Cornejo et al. 2014). Fernandez-Cornejo et al. (2014) found that consumers in many low-income countries were willing to pay more for certain GM crops over conventional counterparts, an inducement for producers in those countries to grow GM crops. This suggests that sales of GM seeds in many low-income nations could increase in the future, thus exporting technological advances that are needed to increase production limits in those nations. Cost, consumer demand, and other considerations, however, imply that the use of these particular technologies for adaptation in the food system to changes in climate is among the many choices facing decision makers in a changing climate (Azadi and Ho 2010, Scoones 2008, Masip et al. 2013).

8.1.2 Food Waste

Globally, 30%–50% of food is lost to waste (Gustavsson et al. 2011, Godfray and Beddington et al. 2010). Causes differ between high- and low-income countries. In low-income countries, the majority of waste occurs on-farm and in transporting and processing food. In high-income countries, most waste occurs in home consumption and very little is lost on-farm or in transportation and processing. Food waste at home by consumers in high-income nations primarily takes the form of discarding usable food because of qualitative deficiencies or failure to consume food within a certain period of time, regardless of its continued edibility.

Three global trends are posited to influence rates of waste in the food supply chain (Parfitt et al. 2010). The first trend is urbanization and the contraction of the agricultural sector. Nearly 50% of the world's population now lives in urbanized areas, and this number is expected to grow to 70% by 2050. This trend will lengthen food supply chains, which places food at increased risk of wastage due to added exposure during transportation, processing, and final consumption. The second trend is dietary transition. As incomes rise in many currently low-income countries, diets are changing. The food share of starchy staples declines as income increases (Parfitt et al. 2010). Higher incomes are accompanied by increased consumption of fresh fruit and vegetables, dairy, meat, and fish. Those foods tend to have shorter shelf lives and contribute to increased waste. The third trend is increased globalization of trade. International trade is leading to increased imports of high-quality foods that undercut domestically produced equivalents in many countries. Those imports are marketed in major supermarkets that dispose of large quantities of edible food for reasons of freshness and appearance.

The past seven decades have seen technological advances, such as improved genetics, fertilization, and mechanization, which have greatly increased total agricultural capacity and productivity in the United States. Many of those advances also helped increase the resilience of the U.S. food system to weather and climate extremes. For example, Tester and Langridge (2010) point out that recent transgenic crop modifications aimed at increasing yield stability have improved resistance to abiotic stresses such as drought. The advent of high-efficiency irrigation systems has improved water conservation, making more irrigation water available during droughts than was possible with lower-efficiency systems. Such technological advances, many of which are piloted in the United States, are likely to play a significant role in helping the nations across the globe deal with the consequences of climate change for food security for their citizens.

8.2 Climate and Weather Effects on U.S. Agriculture

The USDA sponsored an assessment report entitled "Climate Change and Agriculture in the United States: Effects and Adaptation," published in 2012 (Walthall et al. 2012). The information in this section is drawn from that recent work, unless otherwise cited.

As a large, mid-latitude nation with complex topography, the United States has widely varying climate conditions, ranging from very high precipitation coupled with very cool average temperatures (due to very long and cold winters) in Alaska to high precipitation and warmer average temperatures throughout the year in Florida. The Southwest has warm summers with low annual precipitation, whereas the Northeast has warm summers with high annual precipitation.

All regions of the United States have experienced climate change during the last century. Alaska has changed the most, with average temperatures increasing by 1–2 °C. Average temperatures have also increased in the northern Midwest, and the Southwest has also become warmer. The only region in the United States that cooled over the last century is the Southeast, although it has also experienced temperature increases during the last several decades. In most regions, summer has warmed more than winter, and spring is also warmer in most places (Walthall et al. 2012). In the United States, as in most other parts of the globe, the observed number of record highs during each year is now about three times the number of record lows (Meehl et al. 2009). Much of the Northwest, Central, and Southern United States now receive more precipitation than 100 years ago, while parts of the Eastern Seaboard, the Rocky Mountains, and the Southwest receive less. The intensity of precipitation has also increased in most areas of the United States. Increases in precipitation totals and intensity do not necessarily mean that additional water is available for agriculture. More intense rain leads to faster runoff, and higher temperatures increase evapotranspiration losses to the atmosphere, both of which result in less moisture retention in soils.

The entire United States is projected to warm substantially in the future. Even under a scenario of limited emissions increases and GHG concentrations (e.g., RCP 2.6), average temperatures are likely to increase by 1–2 °C over the next 40 years, which is substantially faster than the rate observed over the last 100 years (Figure 8.1). Temperatures would then remain at about this level throughout the rest of the century. If emissions follow a higher scenario (e.g., RCP 8.5), average U.S. temperatures could increase by 2–3 °C by mid-century. Looking ahead to 2100, a high-emissions scenario results in warming of 4–5 °C in most regions and 5–7 °C in parts of the interior West and Midwest. This widespread warming could increase the length of the growing season by a month or more and lead to 20–40 fewer frost days per year in most areas.

The picture of future precipitation shows more geographic variation (Figure 8.2). Over the next 40 years under a low-emissions scenario, most of the United States is projected to see increased average precipitation with some notable exceptions. Increases are greatest in the East. Only parts of the Southwest and the Pacific coast are projected to become drier. If emissions remain on a low trajectory, these conditions do not change significantly by 2100, except for a switch from drying to slightly increased precipitation in some parts of the Southwest. Under a high-emissions scenario, the pattern of change is similar in the near term but with larger increases in precipitation in much of the eastern United States and larger decreases over a slightly larger area of the Southwest. Over the longer term, there is a further increase in precipitation in more of the eastern United States, with the exception of Florida, which is projected to see decreased precipitation.

The changes in precipitation and temperature outlined above are extremely likely to have direct effects on U.S. agricultural production. Crops and livestock are sensitive to direct effects of climate changes, such as changing temperatures and precipitation. Exceeding optimum temperatures for crops steadily reduces productivity up to a threshold, after which productivity decreases sharply, and increases animal stress, especially when coupled with high humidity. Precipitation decreases can make it difficult to store and deliver adequate water to crops at the right time, while increased overall precipitation, and particularly increased intense precipitation, requires improved drainage to avoid crop and soil damage.

Agriculture is also sensitive to indirect effects, such as increases in diseases and pests, and degradation of the natural-resource base, such as high quality soil and water, upon which agriculture depends. Climate change is projected to increase the growth and range of many weeds, insect pests, and pathogens

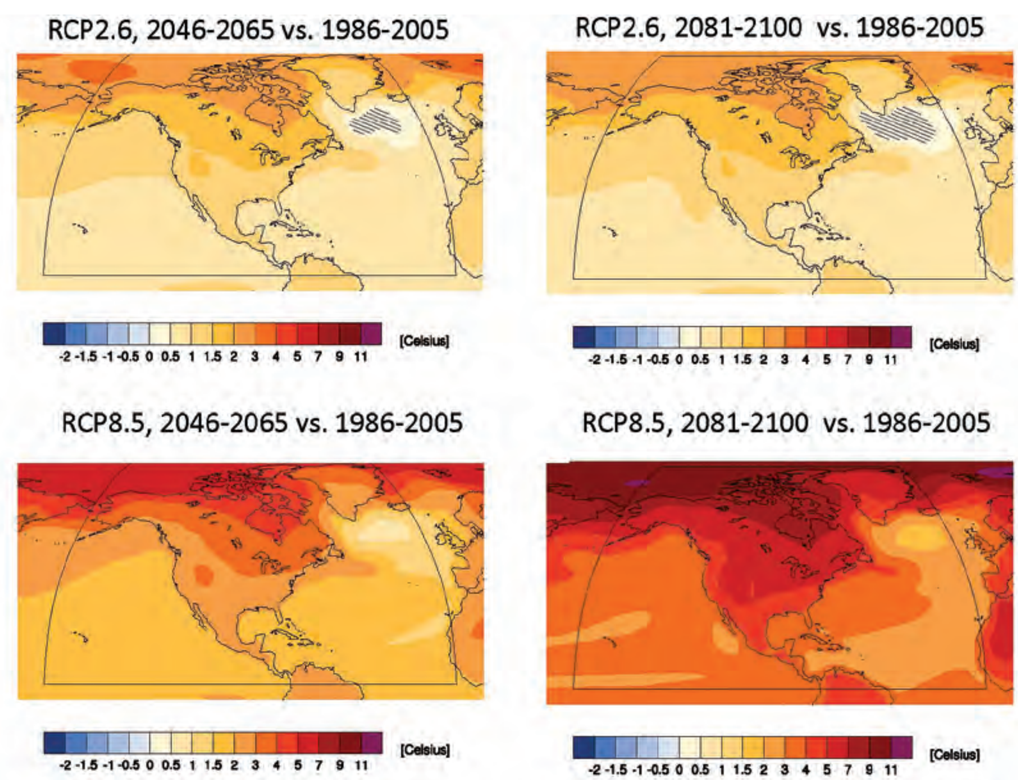


***Figure 8.1 Projections of U.S. surface temperatures.** U.S. average surface temperature projections for the low-future-GHG-concentration scenario (upper panels) for mid-century (left panel) and end of century (right panel). Lower panels show projections based on high GHG concentrations for mid-century (left) and end of century (right). Plots show multimodel ensemble means, with gray dashes indicating areas where changes are small (less than one standard deviation) compared to natural variability. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

harmful to agriculture, although the ranges of some invasive weeds could decrease. Projected increases of intense precipitation coupled with increased drying of soils from higher temperatures increases the risk of accelerated erosion of soils in many areas, which both degrades soil quality and increases the runoff of agricultural chemicals. Projected changes in precipitation are also likely to increase water-management challenges in agriculture. For example, the combination of decreased snowfall and snowpack, increased rainfall (from less precipitation falling in frozen form and more in liquid form), earlier snowmelt, and decreased summer flows in streams and rivers could increase the need for water storage in many areas of the western United States.

Overall, the U.S. food system is expected to be fairly resilient in the near term due to its capacity to undertake adaptive actions such as increased irrigation, shifting of crop rotations and acreage devoted to specific crops in some regions, and alteration of nutrient inputs and other management practices. As climate change continues and temperature increases of 1–3 °C are coupled with changes in precipitation timing and intensity, yields and farm returns are projected to decline. The continued changes expected between 2050 and 2100 under high-emissions scenarios are expected to have overall detrimental effects on most crops and livestock. Finally, it should be recognized that there is a significant chance that current projections underestimate potential declines, because most analyses exclude production constraints arising from increased pest pressures, extreme events, and decreased ecosystems services (Walthall et al. 2012).

8.3 The U.S. Role in a World Adapting to Climate Change

Climate change will occur at a pace and magnitude that will require adaptation (Porter et al. 2014). As part of the global food system, the United States is expected to participate in actions to adapt to climate change domestically and abroad. Four key areas in which the United States can be expected to play a role in adapting food systems to climate change abroad are (1) international trade, (2) food assistance, (3) development assistance, and (4) technology and information assistance. These are discussed below.

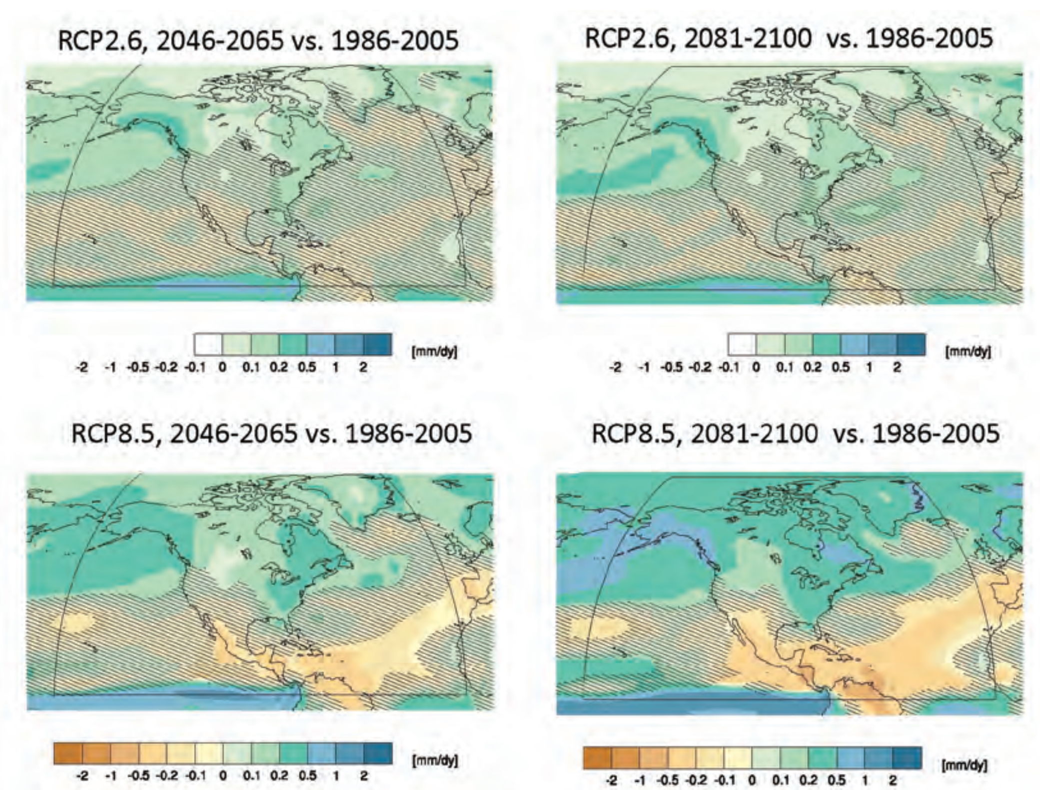


Figure 8.2 Projections of changes in U.S. precipitation. *U.S. precipitation changes for the low-future-GHG-concentration scenario (upper panels) for mid-century (left panel) and end of century (right panel). Lower panels show changes based on high GHG concentrations for mid-century (left) and end of century (right). Plots show multimodel ensemble means, with gray dashes indicating areas where changes are small (less than one standard deviation) compared to natural variability. Source: This figure was produced using CMIP5 model output through the web application "Climate Explorer," available at http://climexp.knmi.nl/.*

8.3.1 Trade

Information in this section is drawn from Walthall et al. (2012) unless otherwise cited.

International trade connects areas of resource surplus and deficit, lowers demand for land resources on a global level (Qiang et al. 2013), and stabilizes food availability and prices, to the benefit of many food producers and consumers (CCGA 2013). The United States contains 11% of the world's arable land, one of the highest endowments of any country (FAOSTAT 2014c). The United States produces about one-fifth of the world's grain and soybeans, and roughly one-sixth of the world's beef, pork, and poultry (USDA 2015).

An estimated 20% of U.S. agricultural production (based on volume) is exported (USDA ERS 2012), making the United States the largest food exporter in the world, responsible for 16% of global agricultural exports (GTIS 2015). The United States is the largest producer of corn in the world, responsible for over one-third of the world's corn crop, which is grown on over 400,000 U.S. farms (U.S. EPA 2013). More than 275,000 farms in the United States produce soybeans, making the United States the largest producer of that commodity as well (U.S. EPA 2013). The United States is also among the world's top wheat and rice suppliers and is responsible for one-quarter of the world's meat exports (USDA 2015).

Top markets for U.S. agricultural products include China, Canada, Mexico, Japan, and the European Union (USDA ERS 2014a). China is one of the fastest-growing agricultural markets, driven primarily by its burgeoning demand for soybeans and limited arable land base. Since international trade can contribute to global land savings if trade flows from a relatively efficient country to a less efficient country, it is estimated that China's import of land-intensive crops led to a global land savings of 3.27 million ha annually, on average, during 1986–2009 (Qiang et al. 2013). The United States' comparative advantage in land has enabled it to be the largest agricultural supplier to China, thus contributing to global land savings. In terms of global crop trade, the United States, Canada, Australia, and Argentina are net virtual land exporters, while some Asian and Mediterranean countries are net importers (Qiang et al. 2013, Fader et al. 2013).

Mirroring China's rise in market size, import demand for food and other agricultural products is generally expanding faster in developing countries than developed, reflecting more dynamic population and economic growth. Developing countries (defined by FAO to include all countries in Africa except South Africa, all countries in Asia except Israel and Japan, all countries in Oceania except Australia and New Zealand, and all countries in the Western Hemisphere except Canada and the United States) are expected to become more dependent on imports to meet their increasing demand, which is outstripping production (FAO 2002b). In 2014 about two-thirds of U.S. agricultural exports went to developing countries, compared with 48% in 1994 (USDA FAS 2015b). Demand growth in developing countries is expected to create additional opportunities for U.S. agricultural exports, although the United States will continue to compete with other major exporting countries (USDA 2014).

U.S. production affects global food security by influencing global commodity prices. In the summer of 2012, for example, a severe drought affected 80% of cropland in the U.S. Midwest (USDA ERS 2013b). Largely as a result of the diminished U.S. corn and soybean crop production, international prices for these commodities increased by 25% and 17%, respectively (World Bank 2012a). The influence of U.S. exports makes world food commodity prices dependent on weather and other supply-and-demand effects within the United States (USDA ERS 2015a). Weather and climate events in the United States also affect planting decisions in other countries. Farmers in Brazil and Argentina—both large corn and soybean exporters—react to prevailing U.S. prices and plant their crops accordingly (USDA ERS 2015a).

A significant aspect of U.S. agricultural trade with respect to climate change is the ability of the United States to export virtual water in the commodities being traded. Virtual water refers to the water that is embodied throughout the entire production process of a traded commodity (Hoekstra and Chapagain 2008). Many regions of the world where the risk of food insecurity is high are likely to simultaneously experience severe climate changes in the form of diminished precipitation and drought, including especially the tropics and semiarid tropics (Porter et al. 2014). Water will be a key limiting factor for food production in those areas. Konar et al. (2013) estimate that by 2030, if climate change causes moderate crop yield decreases globally, the United States would lead the world by a large margin in the amount of virtual water embedded in exported commodity crops. It is worth noting that only minimal global yield decreases are likely by 2030 (Porter et al. 2014). However, it can be inferred from the Konar et al. (2012) estimates that as global yield decreases become moderate later in the century, the

United States might maintain or even strengthen its role as a major exporter of food, especially commodities that require water (for production, processing, or transporting). Yet it is important to recognize that agriculture in some parts of the United States, particularly the arid West, may be as constrained by reduced precipitation and increasing demands on nonagricultural uses of water as other parts of the world (Walthall et al. 2012).

Trade is beneficial to the U.S. domestic economy. It is estimated that each dollar of U.S. farm exports stimulates an additional USD 1.22 in U.S. economic output (USDA ERS 2015b). Agricultural exports create additional economic output due to their effect on other nonagricultural industries. Farmers purchase additional machinery, durable goods, or other inputs to produce the exportable agricultural commodities. These purchases generate jobs, income, and wages for other sectors of the U.S. economy. In 2013, the most recent year for which trade-impact analysis is available, the USD 144.38 billion U.S. farm exports supported almost 1.1 million jobs, three-quarters of which were in nonfarm sectors (USDA ERS 2015b). In addition to direct, on-farm employment, agricultural exports also support economic off-farm activities associated with procuring production inputs such as fertilizers and fuel, processing, packaging, manufacturing, transporting, and financing and logistics activities. Similarly, agricultural imports generate economic output through transporting and retailing food (Paggi et al. 2012), though the multiplier effects are more difficult to quantify (USDA ERS 2015b).

U.S. imports play an indirect role in global food security. The United States is the third-largest food importer in the world; it imported USD 112 billion of agricultural products in 2014, including coffee beans, cocoa, fresh fruit, and rubber, as well as an additional USD 20 billion of fishery products (USDA FAS 2015b). The United States is the world's largest importer of edible seafood products, with an edible seafood trade deficit of approximately USD 15 billion in 2014 (NOAA Fisheries 2014). Imports generate income for overseas producers through export sales of surplus production, and, in some cases become the main source of income for farmers who have limited options. For instance, the United States is the largest importer of Guatemalan coffee, buying about 40% of the country's exported coffee beans (GTIS 2015). Coffee production supports 150,000 full-time and 300,000 part-time jobs in Guatemala, contributing 1.5% of that country's total GDP (USDA FAS 2015c). About 70% of the coffee production there is concentrated at high altitudes, where few alternative agricultural options are available. For a discussion on the importance of coffee to the Central American economy, the region's food security, and how climate change affects both, see Box 8.1. U.S. food imports from all regions are growing to meet consumer demand for variety, quality, and convenience (USDA ERS 2015a). Retailers and processors also seek low-cost ingredients sourced from all over the world, raising concerns about the safety of supplies from far-flung locations that have different safety standards and quality control (Gale and Buzby 2009). Food import refusal reports indicate that vegetables and vegetable products, fishery and seafood products, and fruits and fruit products are among the top imported food categories refused due to safety and other violations under FDA law, which includes sanitary, pesticide, labeling, and packaging violations (Buzby et al. 2008). Improved safety in imported food is likely to entail higher costs, as exporting countries invest in sanitary facilities, equipment, water treatment, worker hygiene, changes in production processes, and third-party certification (Gale and Buzby 2009).

The U.S. is the third-largest food importer in the world; it imported $112 billion of agricultural products in 2014, including coffee beans, cocoa, fresh fruit, and rubber, as well as an additional $20 billion of fishery products.

The AgMIP projections described in Chapters 3 and 4 of this volume can also be used to describe some possible climate change effects on food production in the United States. With the exception of domestic U.S. food prices, the effects of varying climate scenarios on U.S. imports and exports can be studied using AgMIP data. Within the models, the United States is classified as a region, and the effects of climate change can be assessed specifically for the United States (Valin et al. 2014). Several results from these projections provide additional information on the domestic climate change effects; changes in domestic U.S. food prices are not possible to glean from these models, however. The models use global commodity prices to determine when supply equals demand, which then calculate prices and other outputs for future commodities. Therefore, prices in the United States are the same as those observed in other regions of the world, except for costs associated with transportation, tariffs, and other trade-related price adjustments.

Table 8.1 provides information from the publicly available AgMIP data for U.S. imports and exports (Valin et al. 2014, Nelson and Valin et al. 2014). The table reports the average results of six different economic models to more clearly illustrate the effects of changes in agricultural imports and exports under different climate scenarios. The baseline scenario maintains the 2005 climate, while the alternative scenario is the average change based on four similar climate scenarios, all of which use emissions and

Box 8.1
Central American Coffee, the United States, and Climate Change—A Case Study

U.S. food imports provide an income source to exporting countries and can be important to the production choices, economic condition, and food security of those nations. High-value crops such as tropical fruits (e.g., bananas, pineapple) and coffee are examples. Coffee has recently demonstrated a sensitivity to changes in climate in Central America, the consequence of increasing temperatures and large production losses brought about by infestation of the fungal *Hemileia vastatrix* pathogen (coffee rust or *la roya*; Avelino et al. 2015).

Coffee was the eighth most traded agricultural commodity in the world in 2011 (FAOSTAT 2015b) and is important to many developing tropical economies. Global Exchange, a human rights organization, estimates that about 25 million people in 50 countries around the world currently depend upon the cultivation of coffee for their livelihoods (Global Exchange 2015), disproportionately represented by rural households.

Coffee leaf rust, Hemileia vastarix. (Smartse/Wikipedia Commons.)

The United States purchases over 40% of Central America's exported coffee, and as such, represents its primary market (USDA FAS 2015a). Imports from the combined countries of Central America (Guatemala, Costa Rica, Nicaragua, Honduras, El Salvador, and Panama—USD 1.05 billion) are approximately equivalent to those from Brazil (USD 1.1 billion), the largest individual source country of U.S. coffee (USTR 2015). Coffee is among the top three agricultural exports from each Central American country; the relative importance of agriculture to each economy and the domestic employment rate is listed in table below.

Changes in climate may have severe long-term effects for those who depend on coffee production. Arabica coffee, the most common variety, grows only in narrow climate conditions that require relatively constant temperatures and substantial rainfall. These conditions have existed in the mountainous regions of Central America, though climate projections suggest that farmers will be unable to continue to cultivate coffee in the same locations. In the short term, farmers may grow coffee at higher altitudes, tracking changing temperatures. Over the longer term, much of the suitable habitat in the region is expected to be lost entirely (Vermeulen et al. 2013).

Climate factors have been important drivers of the Central American *H. vastatrix* infestation. Temperature (a decrease in the diurnal thermal amplitude; Avelino et al. 2015), the seasonality of precipitation (Avelino et al. 2015), and higher humidity levels (Helfer 2013), consistent with anticipated changes in climate, are each implicated. Plants at higher altitudes were more vulnerable than in the past due to higher minimum daily temperatures (Avelino et al. 2015). Many operations may have been simultaneously more vulnerable to infection due to lower management investments, the result of low coffee prices on the world market, and the affordability of fertilizer and fungicides (Avelino et al. 2015).

Country	Coffee Exports to the U.S. (USD Million) (2013)	Agriculture Value Added (% of GDP) (2012)	Employment in Agriculture (% of Total Employment) (2012)
Costa Rica	204	6	13
El Salvador	91	12	21
Guatemala	420	11	32
Honduras	159	15	35
Nicaragua	165	18	32
Panama	7	3	17

Sources: Coffee Exports to the U.S. – USTR 2015; Agriculture Value Added – World Databank 2015a; Employment in Agriculture – World Databank 2015b.

(Box 8.1 continued)

The long time period required for coffee shrub establishment makes shifting plantations difficult, even in cases where land purchases are possible. Even in the shorter term, the effects on farmers are significant. Lost sales income is difficult to recover and damaging to farmers' food security (Avelino et al. 2015). Because of the high degree of economic dependence upon coffee cultivation in the region, lower production levels have affected the livelihoods of thousands of Central American smallholders and harvesters (Avelino et al. 2015). The Inter-American Institute for Cooperation on Agriculture estimates that over 17% of the region's agricultural employees were displaced in 2012–2013 as a consequence of coffee rust (IICA 2013). In 2013, the World Food Programme supplied emergency food assistance to more than 53,000 families in Guatemala, Honduras, and El Salvador due to food insecurity brought about by coffee rust (WFP 2013b).

Record production levels anticipated for Honduras in 2015 reflect more recent plantings with rust-resistant varieties (USDA FAS 2015a). There are multiple adaptation possibilities for managing *H. vastatrix*, including agronomic practices (Avelino et al. 2011, Lasco et al. 2014), biological controls (Haddad et al. 2009), chemical applications (Belan et al. 2015), and genetic breeding (Rozo et al. 2012, Silva et al. 2006), as well as monitoring and alert systems to acquire and disseminate actionable information (e.g., FEWS NET et al. 2014, SATCAFE 2015). Some adaptations may be quickly implemented; others may take decades to develop. Many will depend upon producers having the means of acquiring production inputs, new information, or technologies—means that have been measurably diminished by these events.

The example of Central American coffee production highlights several important concepts embodied within this report: the influence of trade on a nation's food systems and production choices; the importance of global production to the U.S. food supply; and the relevance of climate—present and future—for strategic management at all levels, from individual producers through the integrated global food system.

concentrations from RCP 8.5. The AgMIP data use 2005 as a base year, and for this table agricultural imports and exports are normalized to their 2005 values. Under both the baseline and climate scenarios, global population is expected to reach 9.3 billion people in 2050 and global GDP is expected to exceed USD 147 trillion (Valin et al. 2014). Over time, the table shows large increases in imports and exports for both scenarios. By 2050, agricultural imports to the United States are projected to increase by 67% under the baseline scenario (relative to 2005). Under a scenario that includes climate change, imports into the United States would increase by almost 73% relative to 2005. Similarly, exports are also expected to increase substantially, by 85% in 2050 under the baseline scenario and by 91% under a scenario that includes climate change.

While agricultural imports and exports are expected to increase over time, regardless of climate change, Table 8.2 shows the changes in agricultural imports and exports from climate scenarios expected relative to the baseline scenario in 2030 and 2050. Agricultural imports increase in a world with climate change relative to the baseline scenario. In 2030, the average increase in imports is almost 5% above agricultural imports relative to a world where climate is held constant at 2005 levels (the

Table 8.1 U.S. Agricultural Imports and Exports (AgMIP Projections). *AgMIP projections show increases in U.S. imports and exports in the years 2030 and 2050. Units are multiples of the 2005 baseline import and export volume. The climate scenario results are the average of six economic models over four different climate scenarios. The climate scenarios are generated from all possible pairings of two crop models and two general circulation models, and all use RCP 8.5. Source: Adapted from Nelson and Valin et al. 2014.*

	% Change in Imports Relative to 2005		% Change in Exports Relative to 2005	
Year	Baseline (No Climate Change)	Climate Scenario Average	Baseline (No Climate Change)	Climate Scenario Average
2005	---	---	---	---
2030	31.42%	37.18%	62.74%	65.61%
2050	66.75%	72.64%	85.24%	91.13%

Table 8.2 Change in U.S. Agricultural Imports and Exports Relative to Constant 2005 Climate. *When only climate change influences are considered, U.S. imports and exports are both expected to increase in the years 2030 and 2050. Units are percentage changes relative to the import and export volumes in 2030 and 2050 in a world where climate is held constant at 2005 levels. The climate scenario results are the average of six economic models over four different climate scenarios. The climate scenarios are generated from all possible pairings of two crop models and two general circulation models, and all use RCP 8.5. Source: Derived from Valin et al. 2014.*

	Imports		Exports	
Year	Baseline (No Climate Change)	Climate Scenario Average	Baseline (No Climate Change)	Climate Scenario Average
2030	---	4.38%	---	1.77%
2050	---	3.53%	---	3.18%

baseline). Agricultural exports also increase, with slightly smaller increases in exports relative to the baseline scenario. The U.S. agricultural balance of trade would therefore be expected to change based on these projections by 2050, with imports increasing slightly more relative to exports under the climate change scenario.

While the AgMIP results continue to show an increase in U.S. agricultural trade, the models do not account for potential vulnerability in transportation infrastructure. To be able to export and import goods, infrastructure such as ports and roads are necessary. AgMIP results focus on economic growth, population growth, and trade and are unable to model changes in infrastructure. Other studies demonstrate that it is a valid concern and influences whether U.S. and global infrastructure will be resilient to a changing climate (Nicholls et al. 2008). Therefore, it is important to discuss current major agricultural trading partners with the United States and port infrastructure to get food into and out of the country.

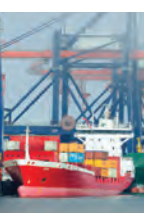
Major destinations for U.S. agricultural exports are presented in Table 8.3. Currently, the second- and third-largest U.S. trading partners are Canada and Mexico, which have common borders with the United States. However, the remaining major agricultural trading partners are distributed around the world, with the majority located in Asia, Europe, and South America. For the United States to exchange goods with trading partners, there must be adequate infrastructure in both the United States and its trading partners and that goods be exchanged in a timely manner to prevent food waste as well as the excessive costs associated with perishable goods storage.

In assessing the vulnerability to climate change, one report estimates that three of the largest U.S. ports (by volume) are at significant risk (Nicholls et al. 2008). As major export and import hubs, this vulnerability could directly affect the agricultural export capabilities of U.S. farmers and limit the ability of the United States to receive food imports. Table 8.4 lists the international ports most vulnerable to sea level rise; many are in countries that are major importers of U.S. agricultural products. Therefore, climate change has the ability to disrupt food security simply by making it more difficult to get food from one region that is able to produce the food to another region that wants to consume that food.

Table 8.3 Top 15 Countries for U.S. Agricultural Exports

Rank	Country (Region)	Value (U.S. Dollars)
1	China	25,880,644,237
2	Canada	21,326,516,722
3	Mexico	18,098,808,744
4	Japan	12,138,761,149
5	European Union-28	11,857,780,593
6	South Korea	5,135,962,712
7	Hong Kong	3,852,064,120
8	Taiwan	3,088,863,591
9	Indonesia	2,823,768,279
10	Philippines	2,509,046,614
11	Turkey	2,148,734,476
12	Vietnam	2,128,330,507
13	Brazil	1,906,663,898
14	Egypt	1,651,981,562
15	Venezuela	1,545,396,029

Source: USDA ERS 2014a.



8.3.2 U.S. Foreign Assistance

In addition to helping countries meet agricultural development and long-term food-security objectives, U.S. foreign assistance, including both development and international food assistance, is an important instrument for meeting the needs of vulnerable populations, including those experiencing food shortages brought on by drought and other climate-related factors (Rosen et al. 2014). Food assistance will likely continue to be a major tool for ameliorating food insecurity in the early stages of climate change, when many low-income nations are just beginning to experience rising incomes (Barrett and Maxwell 2005). Increasing emphasis is being placed on building resilience to recurrent crises in order to reduce the need for humanitarian assistance over the longer term (see, for example, Executive Order 13677 2014). Both emergency food assistance and longer-term development programs are important to building more-resilient, food-secure communities. The consequences of climate change for food security in different regions globally likely will influence, and be influenced by, development efforts.

In a changing climate, the multiple actors driving engagement between the U.S. food system and global food security include the U.S. government; U.S. civil society, including nonprofit organizations, philanthropic foundations, voluntary organizations, faith-based groups, and academic institutions; and private-sector actors, including large corporations and small businesses.

U.S. government international food-security programs analyze climate risks and aim toward climate-resilient outcomes (Executive Order 13677 2014). Global food security also represents a strategic priority for the United States, as food insecurity in weakly governed areas is considered to be a potential national security threat (Clapper 2014). International food assistance is provided by USAID's Office of Food for Peace and USDA's Foreign Agricultural Service (FAS). FAS administers two food-assistance programs with agricultural-development and long-term food-security objectives: the McGovern-Dole International Food for Education and Child Nutrition program and the Food for Progress program. Food for Peace, administered by USAID, provides flexible emergency programming through interventions such as local and regional procurement and cash transfers and food vouchers to optimize response time during emergencies, as well as *in-kind* food from the United States. Each is described in greater detail in this section.

Table 8.4 Top 20 Port Cities With Severe Potential Impacts From Sea-Level Rise and Tropical Storms.

Rank	Country	City	2005 Assets at Risk	2070 Estimated Assets at Risk
			(Billions, U.S. dollars)	(Billions, U.S. dollars)
1	United States	Miami	416.29	3,513.04
2	China	Guangzhou Guangdong	84.17	3,357.72
3	United States	New York–Newark	320.2	2,147.35
4	India	Kolkata (Calcutta)	31.99	1,961.44
5	China	Shanghai	72.86	1,771.17
6	India	Mumbai (Bombay)	46.2	1,598.05
7	China	Tianjin	29.62	1,231.48
8	Japan	Tokyo	174.29	1,207.07
9	China	Hong Kong	35.94	1,163.89
10	Thailand	Bangkok	38.72	1,117.54
11	China	Ningbo	9.26	1,073.93
12	United States	New Orleans	233.69	1,013.45
13	Japan	Osaka-Kobe	215.62	968.96
14	Netherlands	Amsterdam	128.33	843.7
15	Netherlands	Rotterdam	114.89	825.68
16	Vietnam	Ho Chi Minh City	26.86	652.82
17	Japan	Nagoya	109.22	623.42
18	China	Qingdao	2.72	601.59
19	United States	Virginia Beach	84.64	581.69
20	Egypt	Alexandria	28.46	563.28

Source: Nicholls et al. 2008.

USAID delivers both foreign humanitarian and development assistance. USDA provides non-emergency food-assistance programs to help meet recipients' nutritional needs and support agricultural development and education. Each of these assistance programs, combined with trade capacity–building efforts, support long-term economic development and can help countries transition from food-assistance recipients to commercial buyers. Programs focus on the world's poor, particularly those living in rural areas and dependent on agriculture for their livelihoods. These programs and initiatives address the nexus of climate change and global food security, and have implications for U.S. food systems. They include alternative livelihoods programs; the Food for Peace development food-assistance programs authorized primarily by the Agricultural Act; the U.S. government's Global Climate Change Initiative; and the U.S. government's flagship global hunger and food security initiative Feed the Future.

Feed the Future seeks to reduce poverty and improve nutrition through agriculture-led growth and incorporates several cross-cutting themes, including nutrition, gender, and climate change. Feed the Future addresses climate resilience to achieve higher productivity and incomes, adapt to climate change, and mitigate GHG emissions, where appropriate. Feed the Future programs create new opportunities for the most-vulnerable households through various program goals, including agricultural and nonagricultural development; maternal and child health and nutrition activities; promotion of water, sanitation and hygiene; infrastructure development; and rehabilitation of the natural resource base.

Such programs can help increase food security and improve maternal and child health. Programmatic assessment indicates that Feed the Future and other U.S. government–led efforts have contributed to reductions in poverty and child stunting in the areas of Bangladesh where Feed the Future operates, a 9% reduction in stunting in Ethiopia over the most recent 3-year evaluation period, a 33% reduction in stunting in Ghana, and a 55% increase in the average Honduran income between 2012 and 2014, which elevated 36,000 above the 1.25 USD per person per day poverty threshold (Feed the Future 2015 Progress Report). The 5-year USAID-funded development food assistance program (through Food for Peace) Shouhardo II implemented a number of agricultural and maternal and child health activities in Bangladesh from 2010–2015, and demonstrated a significant increase in the number of months of adequate household food provisioning, from 5.9% at the start of the program to 11% in the final evaluation, and an 81% increase in the average household dietary diversity, an indication of household socioeconomic status in the target area. In addition, the program saw a significant decrease in stunting of nearly 21% in children 6–59 months (from 61.7% to 48.8%) and a significant increase in the percentage of women receiving antenatal care, from 47.1% to 85.3% (TANGO 2015). In another example, the WALA program produced a significant reduction in stunting of 12.5% in Malawi among children 6–59 months from the start of the program to final evaluation and an increase in the proportion of deliveries attended by a skilled health professional, from 78% to 88.5%, in target areas. In addition, the WALA program enabled an increase in the modified household incomes of 14% between the start of the program and final evaluation, and a decrease in the proportion of households that reported losses of livelihood assets due to shocks and stresses, from 7.8% to 6.8% (CRS 2014). Finally, USAID funds the Famine Early Warning System Network (FEWS NET). Every 3 months, FEWS NET analysts conduct scenario-building exercises to estimate food security outcomes for the coming 6 months. The situation in areas of concern is assessed and assumptions are made about the future in order to consider how those assumptions might affect food and income for poor households. Then, the most likely scenario is determined and the expected level of food insecurity is classified. Finally, major events or changes that could affect the outcome, including climate-related events, are identified to inform decision makers and contribute to emergency response planning. FEWS NET has used scenario building to assess the impact of drought on poor farming households in Somalia and project the impact of extensive flooding in Nigeria on the regional market (Husak et al. 2013).

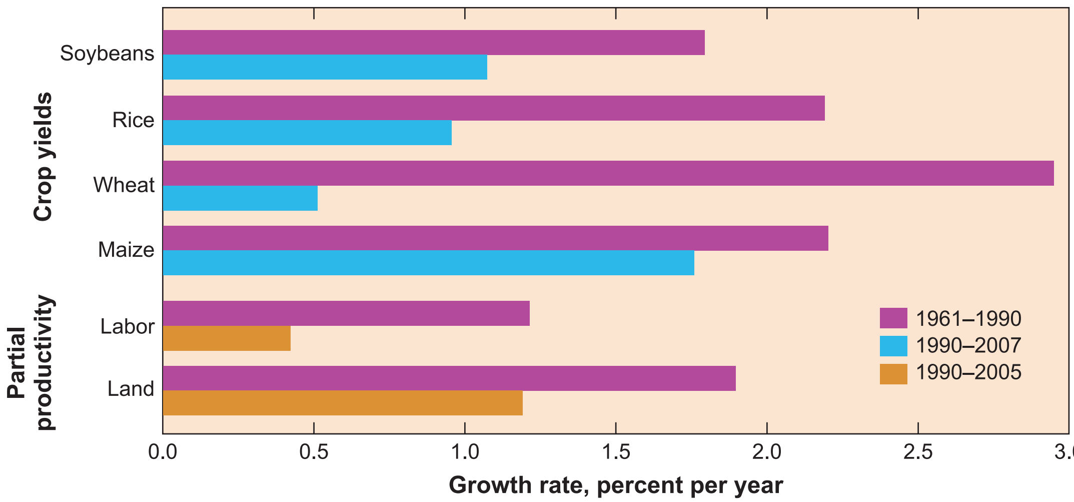


Figure 8.3 Global agricultural yield and productivity growth rates, 1961–2007. *Yield is measured as metric tons per hectare. Labor and land productivity are total agricultural output per agricultural worker and agricultural area, respectively, excluding China. Total agricultural output was derived using 1999–2001 price weights. Source: Alston et al. 2009.*

8.3.3 Technology and Information Assistance

The United States has been a world leader in the development of new technologies that have greatly increased the quantity and quality of food over the past 100 years (Mowery and Rosenberg 1998 p. 6). Organized public and private investment in agricultural research has been a major contributor to the rapid growth in agricultural productivity experienced since the 1950s (Evenson et al. 1979). Wang et al. (2013) find a strong direct relationship between public investment in agricultural R&D and total factor productivity (TFP). Fuglie and Rada (2013) argue that changes in TFP are a robust measure of the effect of new agricultural technologies, an indication of the rate at which basic research is translated into practical applications. TFP has been rising in many developing countries (Ray et al. 2012). In many regions, crop yields and TFP have remained low; it is possible this may be the result of little agricultural research and investment.

Alston et al. (2009) observe that in the past, most countries (especially low-income countries) have relied heavily on knowledge and technology resulting from agricultural research by a small number of developed countries, including the United States. Some such technologies include crop breeding that increased crop tolerance to drought, heat, and salinity, as well as early maturation breeds that shorten the growing season and reduce farmers' exposure to risk of extreme weather events (Lybbert and Sumner 2012). Such technologies are expected to provide critical climate-change adaptation possibilities for developing countries. Looking into the future, technology will need to play a large role in helping farmers everywhere increase the productivity of their operations, especially in the face of challenging climate changes. However, current productivity trends are not promising. Alston et al. (2009) note a global slowdown in the growth rates of wheat, rice, maize, and soybean yields over the period 1990–2007 versus the period 1960–1990. They postulate that declining investment in agricultural research and development globally, but especially in high-income countries like the United States, is a primary driver of lower yield growth. There has been a global commitment to increase investments in agricultural development, hunger, and undernutrition, which may result in an increased

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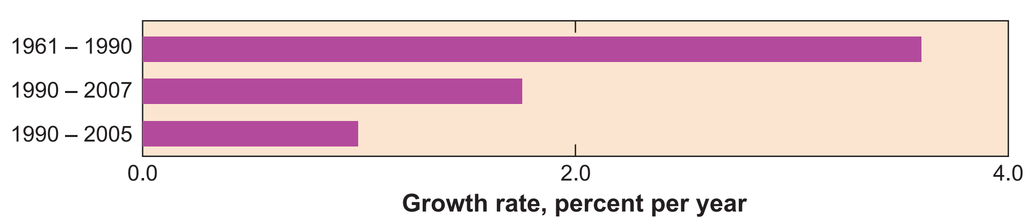

Figure 8.4 Annual growth rate of U.S. public agricultural R&D spending, 1950–2007. *The underlying public agricultural R&D spending data are adjusted to reflect 2000 prices. Public agricultural R&D includes intramural USDA research and research conducted at the state agricultural experiment stations. Source: Alston et al. 2009.*

rate of yield growth (Flora 2010). Figures 8.3 and 8.4 demonstrate a relatively close correspondence in growth rates between U.S. public investment in agricultural research and development and global crop yield and productivity growth over the period of 1950–2007. While increasing private-sector research has compensated for some of the loss of public investment in agricultural research and development to some extent, public divestment comes at a time when concerns about stagnating yields for major crops such as rice, maize, and soybeans have been raised (Cassman et al. 2003).

Conventional breeding approaches to increasing climate resilience in crops will be important in the future (Tester and Langridge 2010). Especially important are the development of new technologies that improve genotyping and phenotyping methods and the expansion of available genetic diversity in breeding germplasm. The biggest opportunity to improve food security with those technologies is to deliver them to developing countries in a form that is economically accessible and readily disseminated (Tester and Langridge 2010). Recent experiences with the development and use of GM crops such as maize and soybeans in the United States illustrate the potential for GM crops to increase yields in other areas (Xu et al. 2013). There is insufficient evidence to assess the degree to which GM crops can potentially contribute to overall global food security in the future, but it does appear that genetic engineering, along with conventional breeding approaches, have the technical potential to play a significant role in expanding global agricultural capacity.

As agriculture becomes increasingly science-based, the role of information in helping farmers deal with risk, particularly weather and climate risk, has increased. Improving climate risk management throughout the food chain will be an important strategy for adapting to climate change. The United States has been a leader in the development and application of Agricultural Decision Support Systems (ADSS) that help farmers manage risk, including climatic changes (Agrios 2005). The ADSS are computer simulation models, sometimes coupled with advanced observational technologies, that can be used by individual producers or distributors to help make decisions under uncertainty. In addition to modeling climatic uncertainty directly, these systems have also been developed to determine optimal responses for pest-management and irrigation considerations. These systems represent another U.S. technology that is easily transferable and helps to improve agricultural efficiency in both the developed and developing world when facing climatic uncertainty.

Once new technologies are developed, whether they are new cultivars or GM crops, new water- and soil-management strategies and other agronomic practices, or changes in crop species planted, such technologies must be proactively managed and directed toward targeted regions and situations in low-income countries (Lybbert and Sumner 2012). For example, new cultivars must be adapted to local conditions and distributed to farmers through a system of poorly connected institutions and markets. Lybbert and Sumner (2012) point out that inefficient input markets in many developing countries, including little private-sector investment and involvement in the seed sector, can severely limit farmers' access to new varieties. The United States, therefore, has an opportunity to proactively engage with regions being targeted for technology transfer aimed at facilitating agricultural adaptation to climate change.

The recent emergence of "Climate-Smart Agriculture" (CSA; FAO 2014a), which intends to simultaneously increase productivity, conserve natural resources, and adapt to changing climate patterns, is one example of an organized movement to engage governments to expedite and focus adaptation to climate change. The FAO (2014a) states that “CSA integrates the three dimensions of sustainable development (economic, social, and environmental) by jointly addressing food security and climate challenges. It is composed of three main pillars: (1) sustainably increasing agricultural productivity and incomes; (2) adapting and building resilience to climate change; and (3) reducing and/or removing GHG emissions, where possible.” Rather than a set of prescribed technologies or policies, CSA is a conceptual framework that encourages governments and other food-related institutions to take an organized approach to preparing food systems to cope with climate change.

CSA has four operational goals (Lipper et al. 2014). First, CSA seeks to build an evidence-based catalog of adaptation options that are shown to be effective in certain situations and locations (Lipper et al. 2014). Second, it focuses on improving institutional efficiency in disseminating adaptive strategies. Four main areas that require public support to complement private efforts in that regard are identified: “(1) extension and information dissemination, particularly on using evidence to adapt practices to local conditions; (2) coordinated efforts where practices generate positive spillover benefits, for instance by reducing flood risks or pest outbreaks, or preserving biodiversity; (3) comprehensive risk-management strategies for managing extreme weather events that affect many farmers simultaneously; and (4) reliable, timely and equitable access to inputs to support resource-use efficiency” (Lipper et al. 2014). Third, CSA aims to improve coordination between national agricultural, climate change/environmental, and food system policies. Fourthly, CSA seeks to improve the targeting of financing to support the transition to CSA. In particular, the linkage of climate-related financing (e.g., Global Environment Fund and others) with traditional sources of agricultural financing is an important part of these efforts.

8.4 Domestic Changes Resulting From Global Changes

Given changes in the expectations of U.S. producers, then, to participate in the world market, changes in transportation infrastructure for moving food from its place of origin to its ultimate consumer can be decisive. For example, given a globally averaged 0.61 m rise in sea level—roughly that which might be expected under RCPs 6.0 or 8.5 (Church et al. 2013)—Kafalenos et al. (2008) predict that 64% of the U.S. Gulf Coast region’s port facilities may be inundated, while an additional 20% of highway arterial miles and 19% of total interstate miles would be at risk by 2100. A 1.22 m sea level rise, which exceeds current RCP 8.5 estimates (Church et al. 2013), would likely inundate nearly three-quarters of Gulf-region port facilities; 28% of highway arterial miles and 24% of interstate miles would also be at risk. The study also found that storm surge could significantly affect rail transport, though sea-level rise alone was a lesser concern for that mode of food shipment. A 5.5 m storm surge would place one-third of the rail lines in the region at risk, while a 7 m storm surge would place 41% of rail lines and 51% of freight facilities in the region at risk by 2100, challenging the transportation system’s capacity for the timely export of food.

Watersheds supplying water to the Great Lakes are likely to experience drier conditions in a changing climate, resulting in lower water levels (Angel and Kunkel 2010, Chao 1999, Easterling and Karl 2001). This projected decline in the Great Lakes water level potentially reduces shipping capacity and increases the cost of shipping agricultural and other commodities via this artery (Millerd 2005, 2011). Using scenarios that were roughly comparable to the RCPs 4.5 and 8.5 discussed in this report, Millerd (2011) projected an increase in the operating costs of U.S. vessels exporting agricultural products of between 4.15% and 22.62%. Using sensitivity analysis of 5%, 10%, and 20% increases in waterborne shipping costs, corresponding to Millerd’s 2011 projections along the Great Lakes, Attavanich et al. (2013) predicted reduced grain shipments to and from Great Lakes ports ranging from 4% to 92% under scenarios comparable to RCPs 4.5 and 8.5, respectively. At the same time, all scenarios reflect higher grain shipments to Lower Mississippi River ports (up to 3%) and to Atlantic ports (up to 49%).

U.S. producers are sensitive to changes in the global market and are likely to respond as the geography of agriculture adjusts to new climatic circumstances.

U.S. agricultural producers respond to changing global market conditions by altering what they grow or other elements of their operations. Changes in climate are one source of change. As consumptive demands expand and ideal production zones shift, alterations to the global food supply and demand equation are likely to occur, making some foods more profitable and others less so. U.S. producers are sensitive to changes in the global market and are likely to respond as the geography of agriculture adjusts to new climatic circumstances.

8.5 Conclusions

The U.S. food system is part of a larger global food system that produces, processes, stores, transports, sells, and consumes food through an international network of markets. One outcome of effective food systems, regardless of scale, is food security (Ingram et al. 2013). Climate change will challenge that outcome in many geographic regions across the Earth. This chapter addressed two major questions: (1) In what ways is the U.S. food system likely to affect food security in other countries, especially those at risk of food insecurity, as climates change? And (2), how might the effects of climate change on global food security affect the U.S. food system? These are daunting questions and the research literature does not contain fully developed answers. But useful insights can be deduced from the foregoing review.

Answers to these questions are conditioned in part by how climate change is likely to affect the U.S. food system. Climate change has been ubiquitous across the United States over the past century. All parts of the country except the Southeast have warmed, and precipitation intensity has increased nearly everywhere in the country. There are important regional variations in precipitation amounts. For the future, all of the United States is projected to warm considerably, regardless of the path of future GHG emissions. Much of the Corn Belt is expected to receive less summer precipitation, although most of the country is projected to receive higher winter precipitation. Such climate changes are likely to have important effects on U.S. agricultural production. While production across most of the United States should be able to accommodate the initial stages of climate change without major yield loss by implementing simple agronomic adjustments such as changes in irrigation timing and amounts and cultivar choices, as climate change continues, crop yields, livestock production, and revenues are expected to decline. Decline estimates are likely to be on the low end because of less-well-known indirect climate effects on factors such as pests and pathogens, which are currently excluded from yield- and livestock-loss modeling and estimates.

The United States has an important role to play in helping less economically advanced regions, many of which are currently food insecure, manage the consequences of climate change for their food security. The United States is the largest food exporter in the world, although its market share is shrinking as other nations increase exports. Import demand in many developing countries is expected to rise, thus creating additional export markets for the United States. Some simulations, such as the AgMIP work cited in this report, estimate that climate change will increase U.S. food imports by up to 5% over 2005 levels by 2030; the same simulations suggest slightly smaller increases in exports.

Many developing countries are becoming food exporters (e.g., Brazil), and high-value crops including coffee and fresh produce are being purchased by the United States. Such purchasing influence over development may help to cope with climate change. An important facet of U.S. trade for climate-change adaptation is the export of virtual water from the United States, which may provide a channel for the trade of water-intensive foods to countries experiencing drier conditions.

U.S. international food- and development-assistance programs are likely to continue to provide strategic assistance for both long-term agricultural development and for emergency conditions in food-insecure regions. Such programs have been reconfigured in recent years to complement multiple development objectives, including promoting climate-adaptation strategies and improving long-term efficacy.

The United States has been influential in developing and disseminating new technologies designed to help farmers worldwide cope with climate change. The United States has been a major source of innovations that have helped increase agricultural productivity, not just for U.S. producers, but for producers in other countries, too. Investment in agricultural research and development is important to improving yields. Many tools exist or may be developed to maintain or improve robust food systems under climate change, including agronomic and conventional crop-breeding adjustments, GM crops, and sophisticated computerized decision-making tools for managing risk. Climate Smart Agriculture is among the first organized efforts to encourage investment in adapting food systems to climate change by integrating sustainable development goals with locally tailored adaptation strategies. CSA is gaining momentum in the research, translational, and popular literature.

As climate-change effects on global food security become more pronounced, there are likely to be important consequences for the United States. food system. The U.S. is expected to see the rate of growth in food exports decline with climate change, while the rate of food imports is expected to grow relative to exports, thus changing the U.S. balance of food trade. An important component of successful international trade is the existence of adequate infrastructure (e.g., roads and ports) to effectively handle exports and imports. Ports, riverine barge systems, and roads in regions experiencing sea-level rise and changing frequency of climate extremes such as heat waves and drought due to climate change may literally impede the movement of food from places that produce food to places that cannot.

In summary, the U.S. food system is likely to experience effects from climate change, including yield loss in important production regions, stress on important agricultural resources such as water and soil, and disruption to transportation infrastructure. However, evidence suggests that the United States will continue to maintain a strong position as a major food exporter and importer. The United States has the opportunity to maintain a leadership position in developing new strategies and technologies for adapting food systems in food-insecure regions in a changing climate.


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Chapter 9

Report Conclusions

Achieving food security—ensuring that an adequate amount of nutritious food is available, accessible, and usable for all people—is a widely shared global objective, most recently codified in the 2030 Agenda for Sustainable Development (UN General Assembly 2015). The quest for universal food security is one of the greatest human development challenges facing the world, despite significant progress in recent decades.

There were about 1.01 billion people who were estimated to be food insecure in 1990–1992, or 19% of the global population at the time. This number has fallen to about 805 million people today, or 11% of the global population (FAO et al. 2014). Hence the number of food-insecure people in the world has been reduced by about 20%, with the proportion almost halved in the last quarter-century, but at least 2 billion live with insufficient nutrients (Pinstrup-Andersen 2009) and about 2.5 billion are overweight or obese (Ng et al. 2014), though not necessarily receiving adequate nutrition. Food insecurity is widely distributed, afflicting urban and rural populations in wealthy and poor nations, and is particularly acute for the very young, because infant and child malnutrition results in damaging lifelong health and economic outcomes.

Can recent progress in reducing hunger be maintained or even accelerated when climate change is added to this set of problems? Global average temperature has already increased by about 0.8 °C since 1900 and further change is projected over the next century (Stocker et al. 2013). Global average temperature is projected to increase by another 1–2 °C by 2050 and 1–4° C by 2100, with accompanying increases in precipitation, precipitation intensity, floods, extreme heat events (day and night), droughts, and sea level, as well as changes in precipitation patterns, and decreased soil moisture (Stocker et al. 2013). This report has examined the potential effects of such changes on food security, with detailed findings presented in the summaries of each chapter. Our main conclusions are presented here.

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. Climate change is projected to result in more-frequent disruption of food production in many regions and increased overall food prices. Climate risks to food security are greatest for poor populations and in tropical regions. Wealthy populations and temperate regions that are not close to limiting thresholds for food availability, access, utilization, or stability are less at risk. Some high-latitude regions may actually experience near-term productivity increases due to high adaptive capacity, CO_2 fertilization, higher temperatures, and precipitation increases. However, damaging outcomes become increasingly likely in all cases from 2050–2100 under higher-emissions scenarios.

The potential of climate change to affect global food security is important for food producers and consumers in the United States. The United States is part of a highly integrated global food system: climate-driven changes in the United States influence

Food insecurity is widely distributed, afflicting urban and rural populations in wealthy and poor nations, and is particularly acute for the very young, because infant and child malnutrition results in damaging lifelong health and economic outcomes.

other nations, and changes elsewhere influence the United States. The United States appears likely to experience changes in the types and cost of foods available for import. The United States is similarly likely to experience increased demand for agricultural exports from regions that experience production difficulties yet have sufficient wealth to purchase imports; the United States is likely to be able to meet increased export demand in the near term. Demand for food and other types of assistance from the United States could increase in nations that lack purchasing power. In the longer term and for higher-emissions scenarios, increased water stress associated with climate change could diminish the export of "virtual water" in agricultural commodities. Climate change is likely to increase demand from developing nations with relatively low per hectare yields for advanced technologies and practices, many of which were developed in the United States.

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Climate change risks extend beyond agricultural production to other elements of global food systems that are critical for food security, including the processing, storage, transportation, and consumption of food. Production is affected by temperature increases; changes in the amount, timing, and intensity of precipitation; and reduced availability of water in dry areas. Processing, packaging, and storage are very likely to be affected by temperature increases that could increase costs and spoilage. Temperature increases could also make utilization more difficult by increasing food-safety risks. Sea-level rise and precipitation changes alter river and lake levels, and extreme heat can impede waterborne, railway, and road transportation. Constraints in one component of food security may often be compensated through another—for example, food insecurity may be avoided when production decreases *(availability)* are substituted with food acquired through purchase *(access)*. Alternatively, constrictions at one point within the food system may be so severe or have no feasible alternative possibilities within a local context such that food security may be compromised—for example, a country with ample food production but inadequate transport conduits has more limited capacity for food purchases by remote populations. As a consequence of these interactions and dependencies, a systems-based approach is needed to understand the implications of climate change.

Climate risks to food security increase as the magnitude and rate of climate change increases. Higher emissions and concentrations of greenhouse gases are much more likely to have damaging effects than lower emissions and concentrations. Worst-case projections based on high GHG concentrations (~850 ppm), high population growth, and low economic growth imply that the number of people at risk of undernourishment would increase by as much as 175 million above today's level by 2080. The same socioeconomic conditions with GHG concentrations of about 550 ppm result in up to 60 million additional people at risk, while concentrations of about 350 ppm—less than today's level—do not increase risk. Scenarios with lower population growth and more-robust economic growth result in large reductions in the number of food-insecure people compared to today, even when climate change is included, but higher emissions still result in more food insecurity than lower emissions.

Effective adaptation can reduce food-system vulnerability to climate change and reduce detrimental climate-change effects on food security, but socioeconomic conditions can impede the adoption of technically feasible adaptation options. The agricultural sector has a strong record of adapting to changing conditions. There are still many opportunities to bring more advanced methods to low-yield agricultural regions, but water and nutrient availability may be limiting in some areas, as is the ability to finance expensive technologies. Other promising adaptations include innovative packaging and expanded cold storage that lengthens shelf life, improvement and expansion of transportation infrastructure to move food more rapidly to markets, and changes in cooking methods, diets, and purchasing practices.

The complexity of the food system within the context of climate change allows for the identification of multiple food-security intervention points that are relevant to decision makers at every level. The future need for, and cost of, adaptation is lower under lower emissions scenarios. Trade decisions could help to avoid large-scale price shocks and maintain food availability in the face of regional production difficulties such as drought. Improved transportation systems help to reduce food waste and enable participation in agricultural markets. Public- and private-sector investments in agricultural research and development, coupled with rapid deployment of new techniques, can help to ensure continued innovation in the agricultural sector. Refined storage and packaging techniques and materials could keep foods safer for longer and allow for longer-term food storage where refrigeration is absent and food availability is transient.

Accurately projecting climate-change risks to food security requires consideration of other large-scale changes. Ecosystem and land degradation, technological development, population growth, and economic growth affect climate risks and food-security outcomes. Population growth, which is projected to add another 2 billion people to Earth's population by 2050, increases the magnitude of the risk, particularly when coupled with economic growth that leads to changes in the types of foods demanded by consumers. Sustained economic growth can help to reduce vulnerability if it reduces the number of poor people and if income growth exceeds increases in food costs in vulnerable populations. Analyses based on hypothetical scenarios of sustained economic growth and moderate population growth without climate change suggest that the number of food-insecure people could be reduced by 50% or more by 2040, with further reductions over the rest of the century. Such analyses should not be misinterpreted as plausible projections, since climate change is already occurring, but they clearly indicate that socioeconomic factors have large effects on food security and that these effects can either offset or amplify the effects of climate change. In the end, climate change and socioeconomic change must be analyzed in an integrated way to provide a full understanding of how food security might change in the future.

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Appendix A

Authors and Contributors

Author	Affiliation
Caspar Ammann	National Center for Atmospheric Research
John Antle	Oregon State University
Witsanu Attavanich	Kasetsart University
Peter Backlund	Colorado State University
Chris Barrett	Cornell University
Marc Bellemare	University of Minnesota
Molly Brown	University of Maryland
Edward R. Carr	Clark University
Violet Dancheck	U.S. Agency for International Development
Bill Easterling	Pennsylvania State University
Chris Funk	U.S. Geological Survey
Kathryn Grace	University of Utah
John Ingram	University of Oxford
Hui Jiang	U.S. Department of Agriculture Foreign Agricultural Service
Hector Maletta	Universidad de Buenos Aires
Tawny Mata	U.S. Department of Agriculture/American Association for the Advancement of Science
Anthony Murray	U.S. Department of Agriculture Economic Research Service
Moffatt Ngugi	U.S. Agency for International Development /U.S. Department of Agriculture Foreign Agricultural Service
Dennis Ojima	Colorado State University
Brian O'Neill	National Center for Atmospheric Research
Claudia Tebaldi	National Center for Atmospheric Research
Margaret Walsh	U.S. Department of Agriculture Climate Change Program Office

Technical Contributors	Affiliation
Mamta Choudhari	George Washington University
Shannon Mesenhowski	U.S. Agency for International Development
Micah Rosenblum	U.S. Department of Agriculture Foreign Agricultural Service
Isabel Walls	U.S. Department of Agriculture National Institute of Food and Agriculture
Keith Wiebe	International Food Policy Research Institute

Project Management	Affiliation
Lawrence Buja	National Center for Atmospheric Research
Joanne Dunnebecke	National Center for Atmospheric Research
Glynis Lough	U.S. Global Change Research Program
Greg Guibert	City of Boulder, Colorado
Linda Gorman	Independent Technical Editor
Karen Griggs	National Center for Atmospheric Research
Michelle McCambridge	University Corporation for Atmospheric Research
Paula Robinson	University of Colorado
Michael Shibao	Smudgeworks

Contributors	Affiliation	Contributed To
Susan Aragon-Long	U.S. Global Change Research Program	Glossary
Tess Carter	U.S. Global Change Research Program	Glossary
Bryce Golden-Chen	U.S. Global Change Research Program	Glossary
Ilya Fischhoff	U.S. Global Change Research Program	Glossary

Appendix B

Commonly Used Abbreviations

AAAS	American Association for the Advancement of Science
AgMIP	Agricultural Model Intercomparison and Improvement Project
AR	Assessment Report
CCGA	Chicago Council on Global Affairs
CGE	Computable General Equilibrium
CMIP5	Coupled Model Intercomparison Project
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DOI	Department of Interior
EE	Environmental Enteropathy
ERS	Economic Research Service (USDA)
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Statistics Division Data Service
FDA	U.S. Food and Drug Administration
GCM	General Circulation Model
GCRA	Global Change Research Act
GDP	Gross Domestic Product
GGCM	Global Gridded Crop Model
GTIS	Global Trade Information Services, Inc.
HadCM3	Hadley Centre Coupled Model version 3
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology
IFAD	International Fund for Agricultural Development
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
KNMI	Royal Netherlands Meteorological Institute
NASA	National Aeronautical and Space Administration
NASS	National Agricultural Statistics Service
NCA	National Climate Assessment
OECD	Organization for Economic Co-Operation and Development
PE	Partial Equilibrium
PPP	Purchasing Power Parity
PSD	Procurement Systems Division (USDA)
RAP	Representative Agricultural Pathway
RCP	Representative Concentration Pathway
SRES	Special Report on Emissions Scenarios
SSP	Shared Socioeconomic Pathway
UN	United Nations
UNISDR	United Nations International Strategy for Disaster Reduction
USAID	United States Agency for International Development
USBLS	United States Bureau of Labor Statistics
USD	United States Dollars
USDA	United States Department of Agriculture
USGCRP	United States Global Change Research Program
WASH	Water, Sanitation, and Hygiene
WFP	World Food Programme
WG	Working Group
WIDER- WIID	World Institute for Development Economics Research/World Income Inequality Database (United Nations University)

Appendix C

Glossary

Abiotic: Nonliving chemical and physical properties of the environment (e.g., soil moisture, nutrient availability, solar radiation).

Access: One has access to food when one has the necessary resources to obtain appropriate foods for a nutritious diet. Achieving food security requires few or no limitations on food access.

Adaptation: The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Adaptive capacity: The ability of systems, institutions, humans, and other organisms to adjust to potential damage, take advantage of opportunities, or respond to consequences.

Aerosol (atmospheric): A collection of airborne solid or liquid particles, with a typical size of between 0.01 and 10 µm, that reside in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin.

Aflatoxin: Toxic metabolite produced by fungal species in the genus *Aspergillus*. Toxin production is dependent on environmental factors during preharvest, storage, and processing.

Agricultural inputs: Resources used to sustain or increase agricultural production, including but not limited to crop chemicals, crop seed and biotech traits, fertilizers, farm machinery, animal health/nutrition products, and animal genetics products.

Availability: The existence of food in a particular time and place. Food availability addresses the "supply side" of food security and is determined by levels of food production, stocks, and net trade. The availability of food does not guarantee that it is accessible or that it may be utilized.

Biodiversity: The variability among living organisms from terrestrial, marine, and other ecosystems. Biodiversity includes variability at the genetic, species, and ecosystems levels.

Bioenergy: Energy derived from any form of biomass, such as recently living organisms or their metabolic by-products.

Biofuel: A fuel, generally in liquid form, developed from organic matter or combustible oils produced by living or recently living plants. Examples of biofuel include alcohol (bioethanol), black liquor from the paper manufacturing process, and soybean oil.

Biophysical: Describes biotic and abiotic factors in biological systems.

Biotic: The living properties of the environment (e.g., populations of prey, predators, and pests).

Carbohydrate: Any member of a group of organic compounds made up of carbon, hydrogen, and oxygen. Carbohydrates produced by plants are an important component of the animal diet.

Carbon sequestration: The uptake (i.e., the addition of a substance of concern to a reservoir) of carbon-containing substances, in particular carbon dioxide (CO_2), in terrestrial or marine reservoirs. Biological sequestration includes direct removal of CO_2 from the atmosphere through land-use change, afforestation, reforestation, revegetation, carbon storage in landfills, and practices that enhance soil carbon in agriculture (e.g., cropland management, grazing land management).

Cereal: Any species in the grass (*Poaceae*) family yielding edible grain.

Climate: In a narrow sense, the average weather of the entire Earth, or a particular region or location, over a time period of months to decades, or longer. Climate is usually described statistically in terms of the mean and variability of atmospheric properties such as temperature and precipitation. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. Climate in a wider sense is the state (including a statistical description) of the climate system.

Climate change: A long-term change, or trend, in the state of the climate generally driven by an external factor, persisting for decades to centuries, or longer. Climate change is usually described statistically by changes in the mean and/or the variability of atmospheric properties such as temperature and precipitation.

- **Natural climate change** is caused by internal climate system processes, such as cyclical changes in atmospheric and ocean circulation, or natural forces external to the climate system, such as volcanic eruptions or a decrease or increase in solar energy entering the atmosphere.
- **Anthropogenic climate change** is caused by human activities, such as land-use change or industrial processes that result in GHG emissions that change the composition of the atmosphere, and is in addition to natural climate variability observed over comparable time periods.
- **Climate change impact assessment**—the practice of identifying and evaluating, in monetary and/or nonmonetary terms, the effects of climate change on natural and human systems.

Climate model: A numerical representation of the climate system based on the physical, chemical, and biological properties of its components and their interactions and feedback processes, and accounting for some of its known properties.

Climate prediction: A climate prediction or climate forecast is the result of an attempt to produce (starting from a particular state of the climate system) an estimate of the actual evolution of the climate in the future, for example, at seasonal, interannual, or decadal time scales.

Because the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature.

Climate projection: The simulated response of the climate system to a scenario of future emissions or concentrations of GHG and aerosols generally derived using climate models.

Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.

Climate scenario: A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.

Climate system: The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere, and the biosphere, and the interactions among them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations, and anthropogenic forcings such as the changing composition of the atmosphere and land-use change.

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability) or to variations in natural or anthropogenic external forcings (external variability).

Crop yield: The measurement of the amount of cereal, grain, or legume produced per unit area, normally measured in metric tons per hectare. Yield multiplied by area harvested equals total agricultural production for a crop in a region.

Demography: The statistical study of human population size, trends, density, distribution, and other vital data.

Distributing: Transporting unprocessed and processed food to a market, between markets, and from a market to communities for retail.

Domestic supply: The amount available for food consumption once other uses (e.g., animal feed, biofuels) and food exported and either put in or taken out of stock are calculated at the national level. When divided by the total population, it estimates the per-capita food available for consumption.

Downscaling: A method that derives local- to regional-scale (generally one to a few tens of kilometers) information from larger scale models or data analyses. There are two main methods: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the

output of regional climate models, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical method employs observed statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the driving model remains an important limitation on the quality of the downscaled information.

Drought: A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term; therefore, any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity that is under discussion. For example, shortage of precipitation during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought, also termed agricultural drought) and during the runoff and percolation season primarily affects water supplies (hydrological drought). Soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in precipitation. A period with an abnormal precipitation deficit is defined as a meteorological drought. A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.

Dry spell: A period of time without precipitation. Typically this is a number of consecutive dry days without agriculturally meaningful rainfall (generally <1 mm/day) during a growing season, resulting in a measurable decline in crop yield.

Ecosystem: A biological community of interacting organisms and their physical environment.

Ecosystem services: The benefits people obtain from functioning natural ecosystems, such as provisioning of high quality soil, regulation of waste, and production of oxygen.

Edema (nutritional): A form of acute malnutrition that results in bilateral fluid retention, typically starting in the feet. It is measured by applying thumb pressure to the top of both feet for 3 seconds and checking whether this leaves a pit. If pits are not seen on both feet it is not nutritional edema.

Emissions scenarios: A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., GHG, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships.

Environmental enteropathy: A subclinical condition caused by contamination of the food and/or water supply, resulting in blunting of intestinal villi and intestinal inflammation, and diminishing a body's ability to assimilate nutrients from food.

Extensification: Using more land to grow more food, typically using traditional management strategies, as opposed to sustainable intensification on land already in use through improved farm management.

Extreme event: An event that causes large fluctuations in the behavior of an element of the food system, such as a large reduction in agricultural yield or abrupt changes in the price of oil. By definition, the characteristics of what is called an extreme event may vary from place to place.

Famine: An extreme food shortage during which at least 20% of households in an area have a limited ability to cope, the acute malnutrition rate exceeds 30%, and the crude death rate exceeds either 2 per 10,000 per day or the under-5 mortality rate exceeds 4 per 10,000 per day.

Food energy: Energy (calories) that animals and people derive from their food by consuming and digesting it; needed to maintain energy for living.

Food safety: Assurance that a food or beverage product does not pose a health risk when consumed orally either by a human or an animal.

Food security: A state or condition when all people at all times have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life.

Food sovereignty: The right of countries and peoples to define agricultural, pastoral, fishery, and food policies that are ecologically, socially, economically, and culturally appropriate for them.

Food supply chain: A network of food-related business enterprises through which food products move from production through consumption, including preproduction and postconsumption activities.

Food system: Encompasses activities whose ultimate goal is individual food consumption: that is, producing, processing, packaging, distributing, transporting, refrigerating, retailing, preparing, and consuming food.

Food value chains: Food value chains are distinguished from traditional food supply chains by the combination of how they operate as strategic partnerships (business relationships) and how they differentiate their products (by focusing on food quality and functionality, and environmental and social attributes).

Forcing (radiative): Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W m^{-2}) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun.

Genetically modified organisms: Organisms (i.e., plants, animals, or microorganisms) in which the genetic material (DNA) has been altered in a way that does not occur naturally by mating and/or natural recombination.

Global climate models: Formally known as "general circulation models" in the climate science literature. A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties.

Green revolution: A series of research, development, and technology transfer initiatives, occurring between the 1940s and the late 1960s, that greatly increased agricultural productivity.

Greenhouse gases (GHG): Those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and by clouds.

Gross domestic product: The sum of gross value added, at purchasers' prices, by all resident and nonresident producers in the economy, plus any taxes and minus any subsidies not included in the value of the products in a country or a geographic region for a given period, normally 1 year. GDP is calculated without deducting for depreciation of fabricated assets or depletion and degradation of natural resources.

Heat stress: Physiological stress caused by elevated temperatures that results in the failure of the body's means of controlling its internal temperature; in livestock, heat stress can make animals more susceptible to illness.

Heavy precipitation events: Rainfall that exceeds the highest 10th percentile of 24-hour rainfall events based on the historical distribution of precipitation events at a given location.

Horticultural: Having to do with the practice of growing fruits, vegetables, and ornamentals.

Hunger: Not having enough to eat to meet energy requirements. Hunger can lead to malnutrition, but absence of hunger does not imply absence of malnutrition.

Impact assessment: The practice of identifying and evaluating, in monetary and/or nonmonetary terms, the effects of climate change on natural and human systems.

Integrated assessment model: A quantitative model used to combine, interpret, and communicate knowledge from diverse scientific disciplines so that all relevant aspects of a complex societal issue can be evaluated and considered for the benefit of decision making.

Intensification: Intensification in conventional agriculture is understood primarily as using a higher input of nutrient elements and of pesticides per land unit. It also means more energy (direct for machinery and indirect for inputs).

Just-in-time: An inventory strategy companies employ to increase efficiency and decrease waste by receiving goods only as they are needed in the production process, thereby reducing inventory costs.

Land use: The social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation).

Macronutrients: Nutrients required in relatively large quantities; includes proteins, simple and complex carbohydrates, and fats and fatty acids.

Malnutrition: A broad term that encompasses both undernutrition and overnutrition. People are malnourished if their diet does not provide adequate calories, protein, and other nutrients for growth and maintenance or they are unable to fully utilize the food they eat due to illness (undernutrition). They are also malnourished if they consume too many calories and/or other nutrients (overnutrition).

Micronutrients: Nutrients essential to body processes and required in relatively small quantities; includes vitamins and minerals.

Mitigation: A human intervention to reduce the sources or enhance the sinks of greenhouse gases.

Mycotoxins: Poisonous chemical compounds produced by certain fungi. They can have great significance in the health of humans and livestock. The effects of some food-borne mycotoxins are acute, symptoms of severe illness appearing very quickly. Other mycotoxins occurring in food have longer term chronic or cumulative effects on health, including the induction of cancers and immune deficiency.

Overnutrition: When nutrients are consumed beyond the amounts required for normal body functioning, leading to deleterious health effects.

Packaging: The process of packaging food involves providing containment, security, tampering resistance, and physical, chemical, or biological protection. It may bear a nutrition facts label and other information about food being offered for sale.

Pathogen: Infectious agent that causes disease in virtually any susceptible host.

Photosynthesis: The process by which plants take carbon dioxide from the air (or bicarbonate in water) to build carbohydrates, releasing oxygen in the process. There are several photosynthetic pathways, each with different responses to atmospheric carbon dioxide concentrations.

Post–farm gate: Post–farm gate activities are all food system activities that occur after a raw material has left the farm, fishery, or forest and typically include processing, packaging, trading, retailing, and consuming.

Processing: Processing is the transformation of raw ingredients into food or of food into other forms. Food processing typically takes harvested crops or animal products and adds value to these to produce attractive, marketable, and often long shelf-life food products that can be purchased in a store.

Producing: Producing food describes on-farm activities to raise crops and livestock, as well as off-farm natural resource extraction, such as hunting and fishing, that results in the raw materials of food products.

Projection: A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.

Purchasing power parity: Purchasing power parity conversion factor is the number of units of a country's currency required to buy the same amounts of goods and services in the domestic market as a U.S. dollar would buy in the United States.

Representative agricultural pathway: A consistent narrative together with quantitative information about the economic, technological, social, and institutional context in which agricultural development occurs that can be used for agricultural model intercomparison, improvement, and impact assessment in a manner consistent with the new global pathways and scenarios.

Representative concentration pathway: A scenario that includes time series of emissions and concentrations of the full suite of greenhouse gases, aerosols, and chemically active gases, as well as land use/land cover. The word "representative" signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term "pathway" emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome.

Resilience: The capacity of a social-ecological system to cope with a hazardous event or disturbance, responding or reorganizing in ways that maintain its essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.

Risk: The potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the consequences if these events occur. This report assesses climate-related risks.

Risk assessment: The qualitative and/or quantitative scientific estimation of risks.

Risk management: The plans, actions, or policies implemented to reduce the likelihood and/or consequences of a given risk.

Scenario: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Scenarios are neither predictions nor forecasts but are useful to provide a view of the implications of developments and actions.

Senescence: The process by which plants age, leading to organ or plant death while metabolites are recycled.

Shared socioeconomic pathways (SSPs): SSPs describe plausible alternative trends in the evolution of society and natural systems over the 21st century at the level of the world and large world regions. They consist of two elements: a narrative storyline and a set of quantified measures of development. SSPs are "reference" pathways in that they assume no climate change or climate impacts, and no new climate policies.

Shock: A sudden upsetting or surprising incident that causes a system or process to react abruptly.

Smallholders: Smallholders are small-scale farmers, pastoralists, forest keepers, and fishers who manage areas varying from less than 1 ha to 10 ha in size. Smallholders are characterized by family-focused motives, such as maintaining the stability of the farm household system, using mainly family labor for production and using part of the produce for family consumption.

Socioeconomic: Relating to or concerned with social and/or economic factors.

Special Report on Emissions Scenarios (SRES): The storylines and associated population, GDP, and emissions scenarios associated with the Special Report on Emissions Scenarios (SRES), and the resulting climate change and sea level rise scenarios. Four families of socioeconomic scenario (A1, A2, B1, and B2) represent different world futures in two distinct dimensions: a focus on economic versus environmental concerns, and global versus regional development patterns.

Stability: The consistency of the three other components of food security (availability, access, and utilization) over time and space. The stability of food availability, access, or utilization might vary due to seasonal or annual weather cycles, or due to sudden shocks (e.g., an economic or climatic disruption).

Stakeholder: An entity, such as a person, business, or organization, with an interest or concern in something.

Stressor: Something that has an effect on people and on natural, managed, and socioeconomic systems. Multiple stressors can have compounded effects, such as when economic or market stress combines with drought to negatively impact farmers.

Stunting: Chronic malnutrition that reflects chronic exposure to food insecurity. Stunting is measured by calculating a child's height for age and comparing that to the median of a reference population. If the child's height-for-age falls below two standard deviations of the median, the child is considered stunted.

Threshold: The level of magnitude of a system process at which sudden or rapid change occurs. A point or level at which new properties emerge in an ecological, economic, or other system, invalidating predictions based on mathematical relationships that apply at lower levels.

Total Factor Productivity (TFP): The portion of output not explained by the amount of measured inputs used in production.

Uncertainty: An expression of the degree to which future climate is unknown. Uncertainty about the future climate arises from the complexity of the climate system and the ability of models to represent it, as well as the inability to predict the decisions that society will make. There is also uncertainty about how climate change, in combination with other stressors, will affect people and natural systems.

Undernourishment: A measure for hunger compiled by FAO, it refers to the proportion of the population whose dietary energy consumption is less than a predetermined threshold. This threshold is country specific and is measured in terms of the number of kilocalories required to conduct sedentary or light activities but not active physical labor, such as farming. The undernourished are also referred to as suffering from food deprivation.

Undernutrition: The outcome of insufficient food intake and repeated infectious diseases. It includes being underweight for one's age, too short for one's age (stunted), dangerously thin for one's height (wasted), and deficient in vitamins and minerals (micronutrient malnutrition).

Utilization: Nutritional value of food and how the body assimilates a food's nutrients. Sufficient energy and nutrient intake is also the result of biophysical and sociocultural factors related to food safety and food preparation, dietary diversity, religious practices, and distribution of food.

Value chain: The full range of value-adding activities required to bring a product or service through the different phases of production, including the procurement of raw materials and other inputs.

Vector: In epidemiological terms, a person, animal, or microorganism that carries and transmits an infectious pathogen to another organism.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Wasting: Acute malnutrition, or "wasting," results from a rapid decrease in food consumption over a short period of time and from illness. It is measured by calculating a child's weight for age and comparing that to the median of a reference

population. If the child's weight-for-height falls below two standard deviations of the median, the child is considered wasted. Wasting can also be measured through checking a child's or adult's mid-upper arm circumference.

Weather: The state of the atmosphere, mainly with respect to its effects upon life and human activities. As distinguished from climate, weather consists of the short-term (minutes to months) variations of the atmosphere. Popularly, weather is thought of in terms of temperature, humidity, precipitation, cloudiness, brightness, visibility, and wind.

Yield gap: The difference between the realized crop productivity of a place and what is attainable using the best genetic material, technology, and management practices.

Appendix D

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U.S. GLOBAL CHANGE RESEARCH PROGRAM
1800 G Street, NW, Suite 9100 Washington, D.C. 20006 USA
http://www.globalchange.gov Tel: +1 202 223 6262 Fax: +1 202 223 3065