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

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

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REPORT-IN-BRIEF

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Universal food security is among the most elusive challenges facing the world, despite real progress in recent decades, and is an important policy focus. 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 exists 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 involves 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 twenty-one federal, academic, nongovernmental,

1 intergovernmental, and private organizations in four countries, identifying climate change effects
2 on global food security through 2100, and analyzing the United States' likely connections with that
3 world.

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

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

14 Adaptation across the food system has great potential to manage climate change effects on food
15 security, and the complexity of the food system offers multiple potential points of intervention for
16 decision makers at every level, from a household to nations and international governance
17 structures. However, effective adaptation is subject to highly localized conditions and
18 socioeconomic factors, and the technical feasibility of an adaptive intervention is not necessarily a
19 guarantee of its application if it is unaffordable or does not provide benefits within a relatively
20 short time frame. The accurate identification of needs and vulnerabilities, and the effective
21 targeting of adaptive practices and technologies across the full scope of the food system, are central
22 to improving global food security in a changing climate.

23

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 international objective, most recently codified in the 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.

Table ES-1: The Components of Food Security.

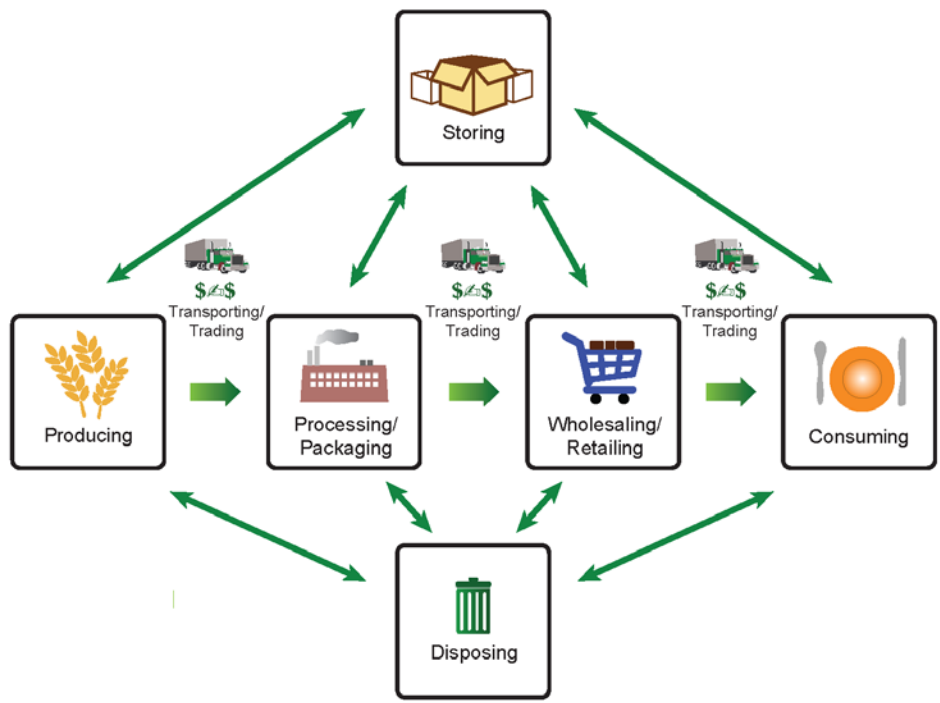
For food security to be achieved, all four components must be attained and maintained, simultaneously. Each is sensitive to climate change.

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.

Food security challenges are widely distributed, afflicting urban and rural populations in wealthy and poor nations. They 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 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

1 security. There are currently about 805 million people, or 11% of the global population, who are
 2 undernourished according to the Food and Agriculture Organization of the United Nations, down
 3 from about 1.01 billion, or 19%, in 1990-92. At least two billion currently receive insufficient
 4 nutrition. The fundamental issue addressed by the *Climate Change, Global Food Security, and the*
 5 *U.S. Food System* assessment is whether progress can be maintained in the face of changing climate.
 6 Relationships between climate and agriculture are well documented. Agricultural production is
 7 governed in large part by climate conditions, and is a central consideration for food availability. It
 8 is less widely appreciated that climate conditions also affect access to food, its utilization, and the
 9 overall stability of each. These effects occur through climate's influence on global food system
 10 activities, including processing, packaging, transportation, storage, waste, and consumption (Figure
 11 ES-1).



12
 13 **Figure ES- 1. Food system activities and feedbacks.**
 14 *Food system activities include the production of raw food materials, transforming the raw material*
 15 *into retail products, marketing those products to buyers and through to consumption. Transportation,*
 16 *storage and disposal of waste play a role in each of these activities.*

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

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

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

20 **Report Findings**

21 **Climate change is very likely to affect global, regional, and local food security by disrupting**
22 **food availability, decreasing access to food, and making utilization more difficult.** Climate
23 change is projected to result in more frequent disruption of food production in many regions and in
24 increased overall food prices. Climate risks to food security are greatest for poor populations and in
25 tropical regions. Wealthy populations and temperate regions that are not close to limiting

1 thresholds for food availability, access, utilization, or stability are less at risk. Some high-latitude
2 regions may actually experience near-term productivity increases due to high adaptive capacity,
3 CO₂ fertilization, higher temperatures, and precipitation increases. However, damaging outcomes
4 become increasingly likely in all cases from 2050-2100 under higher emissions scenarios.

5 **Climate change's potential to affect global food security is important for food producers and**
6 **consumers in the United States.** The U.S. is part of a highly integrated global food system:

7 Climate-driven changes in the U.S. influence other nations, and changes elsewhere influence the U.S.

8 The U.S. appears likely to experience changes in the types and cost of foods available for import.

9 The U.S. is similarly likely to experience increased demand for agricultural exports from regions
10 that experience production difficulties yet have sufficient wealth to purchase imports; the U.S. is

11 likely to be able to meet increased export demand in the near-term. Demand for food and other

12 types of assistance from the U.S. could increase in nations that lack purchasing power. In the

13 longer-term and for higher emissions scenarios, increased water stress associated with climate

14 change could diminish the export of "virtual water" (the water that is embodied throughout the

15 entire production process of a traded commodity) in agricultural commodities. Climate change is

16 likely to increase demand from developing nations with relatively low per hectare yields for

17 advanced technologies and practices, many of which are developed in the U.S.

18 **Climate change risks extend beyond agricultural production to other elements of global food**

19 **systems that are critical for food security, including processing, storage, transportation, and**

20 **consumption of food.** Production is affected by temperature increases, changes in the amount,

21 timing, and intensity of precipitation, and by reduced availability of water in dry areas. Processing,

22 packaging, and storage, are very likely to be affected by temperature increases that could increase

23 costs and spoilage. Temperature increases could also make utilization more difficult by increasing

24 food safety risks. Sea-level rise and precipitation changes alter river and lake levels, and extreme

25 heat can impede waterborne, railway, and road transportation. Constraints in one component of

1 food security may sometimes be compensated through another—e.g., food insecurity may be
2 avoided when production decreases (*availability*) are substituted with food acquired through
3 purchase (*access*). Alternatively, constrictions at one point within the food system may be so
4 severe, or have no feasible alternative possibilities within a local context, that food security may be
5 compromised. As a consequence of these interactions and dependencies, a systems-based
6 approach is needed to understand the implications of climate change on food security.

7 **Climate risks to food security increase as the magnitude and rate of climate change**
8 **increases. High emissions and concentrations of greenhouse gases are much more likely to**
9 **have damaging effects than lower emissions and concentrations.** Worst case projections based
10 on high GHG concentrations, high population growth, and low economic growth imply that the
11 number of people at risk of undernourishment would increase by as much as 175 million above
12 today's level by 2080. The same socioeconomic conditions with GHG concentrations of about 550
13 parts per million result in up to 60 million additional people at risk, while concentrations of about
14 350 ppm – less than today's level – do not increase risk. Scenarios with lower population growth
15 and more robust economic growth result in large reductions in the number of food insecure people
16 compared to today, even when climate change is included, but higher emissions still result in more
17 food insecurity than lower emissions.

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

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

12 **Accurately projecting climate change risks to food security requires consideration of other**
13 **large-scale changes.** Ecosystem and land degradation, technological development, population
14 growth, and economic growth affect climate risks and food security outcomes. Population growth,
15 which is projected to add another two billion people to Earth's population by 2050, increases the
16 magnitude of the risk, particularly when coupled with economic growth that leads to changes in the
17 types of foods demanded by consumers. Sustained economic growth can help to reduce
18 vulnerability if it reduces the number of poor people and if income growth exceeds increases in
19 food costs in vulnerable populations. Analyses based on scenarios of sustained economic growth
20 and moderate population growth without climate change suggest that the number of food insecure
21 people could be reduced by 50% or more by 2040, with further reductions over the rest of the
22 century. Such analyses should not be misinterpreted as projections, since climate change is already
23 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 by a team of technical experts 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 21 federal, academic, nongovernmental, intergovernmental, and private organizations in four countries, identifying climate change effects on global food security through 2100, and analyzing the U.S.'s likely connections with that world.

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 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 fuel 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

1 climate conditions. The most recent set of inputs, called Representative Concentration Pathways,
2 were developed through the Coupled Model Intercomparison Project (CMIP) for use in climate
3 modeling experiments and assessment efforts, such as those conducted by the Intergovernmental
4 Panel on Climate Change (IPCC). The RCPs are the basis for the climate projections in the recent 5th
5 assessment report of the IPCC and are used in this document, where we focus on the climate
6 implications of two possible emissions futures.

- 7 • Representative Concentration Pathway (RCP) 2.6 is a low-emissions scenario with
8 extensive mitigation and a CO₂ concentration of about 421 ppm by 2100. This results in a
9 global average temperature increase of about 1 °C by 2050, with no further change by 2100,
10 and global average sea level rise of about 0.17-0.32 m by mid-century and 0.26-0.55 m by
11 late century
- 12 • RCP 8.5 is a high emissions scenario, where emissions continue to increase rapidly,
13 producing a CO₂ concentration of 936 ppm by 2100. This results in global average
14 temperature increase of about 2 °C by 2050 and 4 °C by 2100, and global average sea-level
15 rise of about 0.22-0.38 m by mid-century (2046–2064) and 0.45-0.82 m by late century.
16

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

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

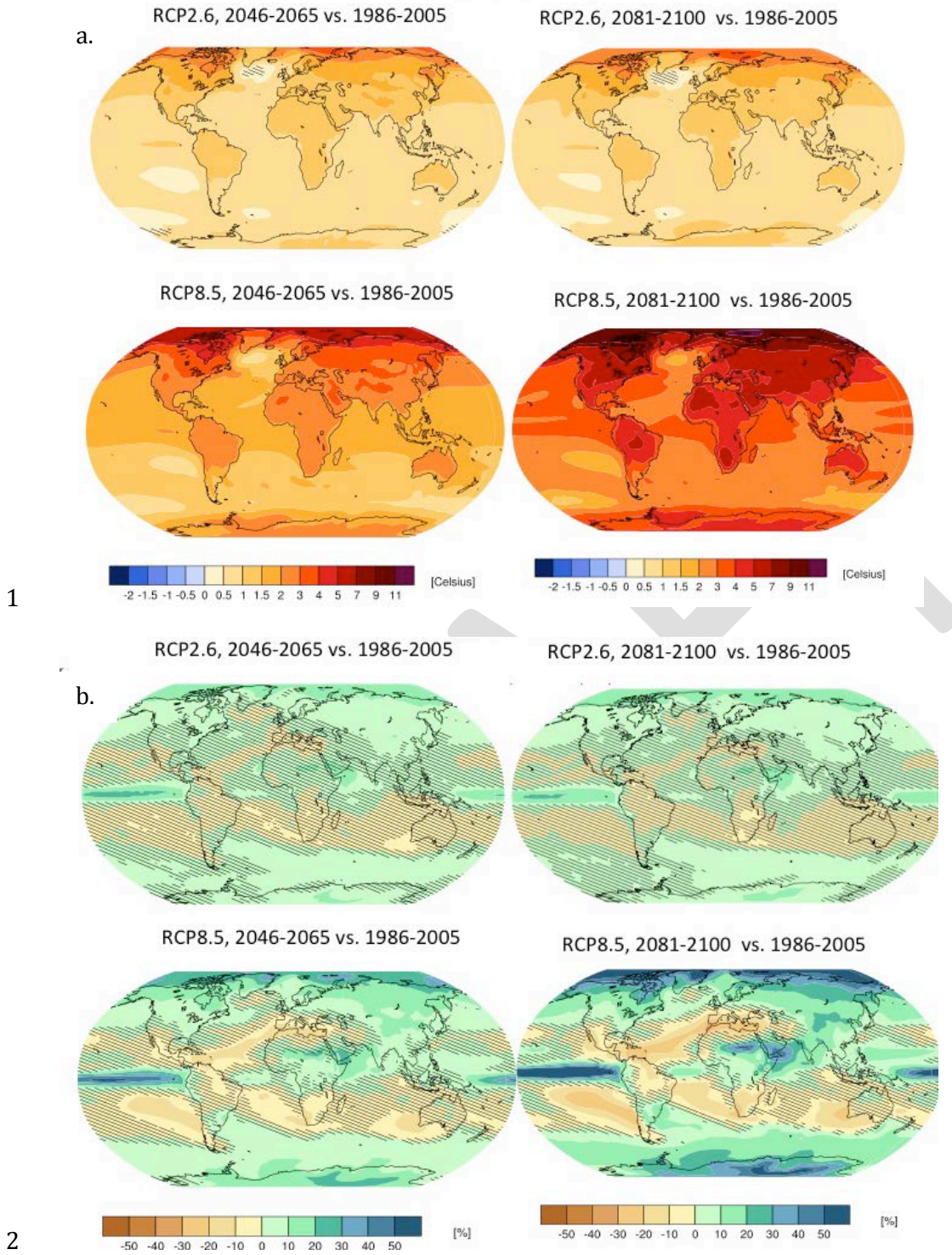


Figure ES- 2. Projected changes in global surface temperature (a) and precipitation (b). Mid (left) and late (right) 21st century changes are compared with the period 1986 to 2005 for low emissions (RCP 2.6 – top) and high emissions (RCP 8.5 – bottom) scenarios. Multimodel ensemble-mean changes are shown where gray dashes indicate areas where 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/>.

1 ***Scenarios of Socioeconomic Change***

2 One of the challenges of projecting societal impacts is the complexity and rapid rate of change; from
3 1950 to today, global population increased from about 2.5 billion to over 7 billion and global gross
4 domestic product (GDP) from about \$5.3 trillion to \$77.6 trillion. We know future society and
5 adaptive capacity will differ in many respects from today, but it is not yet possible to determine the
6 relative likelihood of many possible societal changes. It is, however, possible to identify alternative
7 sets of internally consistent future changes that could occur together. Scientists can then compare
8 plausible future climates to plausible future societies and determine likely effects of different
9 combinations.

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

19 Taken together, the set of RCPs and SSPs provides a basis for the scientific community to conduct
20 systematic and comparable analyses of future vulnerability, risks, and effects of climate change in
21 the context of other environmental and socioeconomic changes. Most of the integrated modeling
22 results examined in this assessment used combinations of SSP 1, SSP 2, and SSP 3 with RCP 2.6 and
23 RCP 8.5. In some cases, SSPs are also used as a frame for qualitative assessment of likely future
24 risks to food security.

25

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 produce direct calculations of food security outcomes, i.e., numbers of undernourished people, but do provide insights about possible changes in prices, consumption, and trade, in addition to yield, cultivated area, and production.

Most use a structure like that outlined in Figure ES-3, which links climate models, biophysical models of agricultural systems, and economic models. They help explain food system changes that affect food security. Outputs are too aggregated to assess all of the important food security concerns related to 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 inter-comparisons are needed to fully assess climate change effects on all dimensions of food security at subnational, local, and household levels.

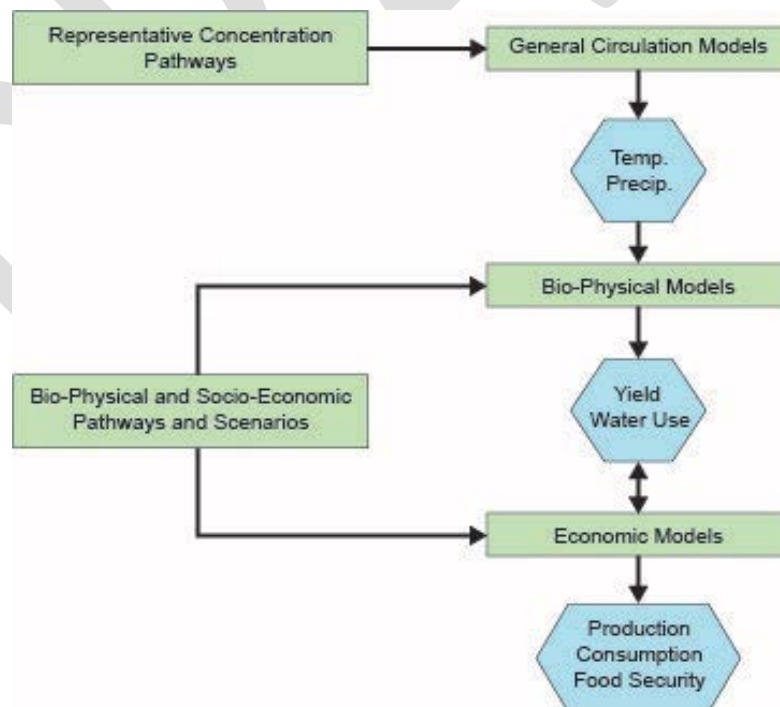
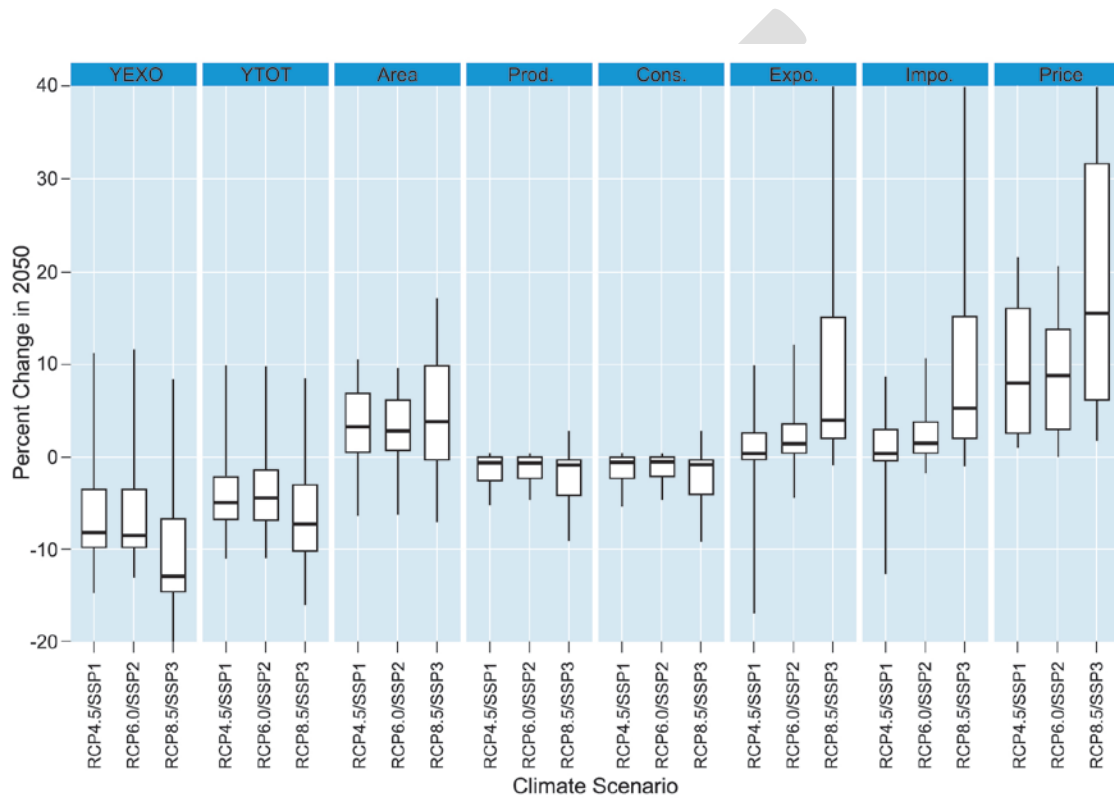


Figure ES-3. Framework for integrated agricultural and food system impact assessments.

1 *Models of global economic and biophysical system, driven by climate model outputs for different RCPs,*
2 *are linked to assess outcomes under different future scenarios.*

3 Results reviewed in this assessment show that climate change effects on overall global food
4 production are likely to be detrimental, particularly later in the century. Figure ES-4 shows recent
5 global modeling results across three different scenarios for 2050. Yields are down, area in
6 production increased, prices rise, and production and consumption are slightly reduced.



7 **Figure ES-4. Climate change effects on agricultural commodities in 2050 under different**
8 **SSPs and RCPs.**

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

18
19
20 But it is important to recognize that effects vary substantially by region due to differing biophysical
21 and socioeconomic conditions that determine both the effects of climate change and the potential

1 for adaptation. The most adverse effects are likely to be in the tropics and sub-tropics, and some
2 near-term benefits are possible at higher latitudes, due to the combined effects of CO₂ fertilization,
3 higher temperatures, precipitation increases, and stronger adaptive capacity.

4 Integrated assessment studies clearly show that technological, economic, and policy decisions each
5 play a major role in the global food system and future global food security, demonstrating that
6 climate assessments need to be made in the context of plausible future socioeconomic scenarios.
7 Many studies indicate that these technological and socioeconomic factors are likely to be more
8 important to food security than climate change under low to medium emissions and concentration
9 scenarios in the near term to mid-century. Under less optimistic socioeconomic scenarios, higher
10 emissions scenarios, and longer time frames, climate effects are projected to be equal to or greater
11 than the effects of socioeconomic change.

12 **Food Availability and Stability**

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

19 Climate change influences food availability and its stability through each food system activity.

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

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

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

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

20 Processing, packaging, storing, trading, and transporting food are frequently prerequisites for food
21 to reach its ultimate consumers. Climate change's influence on which crops are grown where in the
22 world affects the location of storage, processing, and packaging facilities, as well as that of the
23 underlying transportation infrastructure for moving food from producer to consumers or to trade
24 hubs. Higher temperatures require more post-harvest cooling for fresh fruits and vegetables, which
25 is likely to result in additional energy expenditure and costs. Temperature and precipitation, along

1 with extreme events, directly influence transportation systems (e.g., flooding of roads, storm surge
 2 in ports) and can impair just-in-time food distribution networks. One-sixth of global agricultural
 3 production is traded internationally, which can act to stabilize food supplies when local or regional
 4 production fails due to climate or other factors.

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

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

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

19 Future climate change effects on food availability and its stability are considered using the
 20 socioeconomic pathway (SSP) and emissions futures frameworks, and reflect the informed
 21 judgement of the authors. The risks posed by climate change to food production are greatest under

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

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

18 **Food Access and Stability**

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

23 Global real food prices generally decreased over the last half of the 20th Century; they have been
24 increasing since 2000. Price affects food affordability, which integrates food prices with income for
25 purchasing food and can originate outside of the food system.

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

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

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

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

23
24
25

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

(P: poorer nations, W: wealthier nations)

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

1 **Figure ES- 3. Relative risks to food access for different SSPs.**

2 *The risks to food access would be lowest under the economic conditions described in SSP 1 and SSP 5*
3 *for a given scenario of climate change, with poorer nations being at higher risk across almost all food*
4 *affordability and allocation categories for all SSPs. Shading represents higher or lower risks for each*
5 *SSP from climate change. Risks are based upon this report's authors' consideration of the available*
6 *literature.*

7 Using the socio-economic pathways and emissions futures, we can examine how climate change is
8 likely to affect food access in the future. This discussion reflects the informed judgement of the
9 authors. Under SSPs 1 and 5, highly integrated and well-functioning world markets suggest that
10 climate change alone would be unlikely to generate the exceptional price shocks that compromise
11 widespread food availability. SSPs 2, 3, and 4 each present various futures under somewhat
12 constrained global trade. SSP2 would likely experience many stresses and shocks in availability,
13 and issues of price increases and affordability are prevalent in poorer countries. Under SSPs 3 and
14 4, this pattern and outcome are accentuated.

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

21

Food Utilization and Stability

1
2 Food *utilization* is the ability of individuals to make use of the food otherwise available and
3 accessible to them. Nutritional outcomes are frequently measured in terms of malnutrition, which
4 manifests as undernutrition or overnutrition. The prevalence of child stunting in the developing
5 world decreased from approximately 47% in 1980 to 29.2% in 2000, and is expected to further
6 decrease to 23.7% by 2020. The prevalence of obesity since 1970 has increased for all developed
7 countries and for a number of developing countries, with the largest increases seen in urban
8 populations and in the lowest income groups.

9 Climate has a number of potential and observed effects on food utilization, which include
10 contamination of the food supply, the nutritional composition of food, and a body's ability to
11 assimilate the available nutrients. Climate change affects food safety by influencing vectors of food
12 contamination and levels of toxins in food. Elongated supply chains expose food products to
13 greater risk of potential contamination and make it harder to verify the quality of food at various
14 stages. Temperature increases are associated with bacteria-caused illness related to poor food
15 storage and handling practices in the supply chain. Fungal contamination resulting in the increase
16 of mycotoxins in the food supply occurs due to high temperature and moisture levels during pre-
17 and post-harvest and during storage, transportation, and processing, as well as pre-harvest
18 practices and timing, the handling of agricultural products, and insect damage. Aquatic and fishery
19 food sources are affected by climate influences on algal blooms that lead to high toxin levels and
20 uptake rates within the food supply.

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

24 Food waste that occurs as a result of climate-sensitive activities during food storage, processing,
25 packaging, trade affects utilization rates. Estimates suggest that 30% to 50% of total global food

1 production is lost globally as waste. Food waste in retail, food service, and at home accounts for
 2 most food waste in developed regions; in developing nations, the absence of adequate food-system
 3 infrastructure is a primary cause.

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

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

(P: poorer nations, W: wealthier nations)

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

9 **Figure ES- 4. Relative risks to food utilization for different SSPs.**

10 *The risks to food utilization would be lowest under the economic conditions described in SSP 1 and SSP*
 11 *5, with poorer nations being at higher risk across all food utilization categories for all SSPs. Shading*
 12 *represents higher or lower risks for each SSP from climate change. Risks are based upon this report's*
 13 *authors' consideration of the available literature.*

14 The influence of climate change upon food utilization depends on how the food system responds
 15 under differing socioeconomic and climate futures; this section reflects the informed judgement of
 16 the authors. Rates of economic growth and environmental quality are expected to be high or
 17 improve in poor countries under SSPs 1 and 5, expanding their capacity to manage changes in
 18 climate and respond quickly to climate-related disasters. Under SSP 2, technology transfer and
 19 economic growth would be somewhat lower than under SSP 1, but globalized trade might compel
 20 investment in, or transfer of, food safety technologies to meet international certification
 21 requirements, limiting significant challenges to food safety. Environmental quality is expected to

1 deteriorate under SSPs 2, 3, and 4, leading to more illness-based diseases that affect a body's
2 capacity for absorbing nutrients from food. In SSPs 3 and 4, poor countries will experience low
3 rates of economic growth and technology transfer, limiting adaptive capacity in these cases. Under
4 SSP 4, high levels of intra-country inequality could produce highly variable outcomes within a
5 country, with the wealthy largely insulated and the poor experiencing increasing exposure to food
6 utilization and stability challenges posed by climate change.

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

14 **The U.S. as a Global Food System Actor**

15 The U.S. makes significant contributions to global food security through trade, assistance programs,
16 technology transfer, and export of environmental management systems used in agriculture. The
17 U.S. agriculture sector is responsive to the main drivers of global food demand, including
18 population and income growth. The trend of rapidly rising global incomes is expected to be a
19 significant source of increasing demand for food, though this may be tempered somewhat as the
20 growth in global population is expected to slow in the coming decades, bringing with it a lowering
21 of the growth rate of food consumption. Three major challenges to meeting this demand and
22 achieving broader global food security that are likely to involve the U.S. food system include closing
23 yield gaps, increasing food production, and reducing food waste.

24 Increasing food production is a key to providing continued upward growth in food supplies, and is
25 particularly important for producers for whom agriculture represents both a food and an income

1 source. Yield gaps are the difference between the actual crop productivity of a place, and what
2 might otherwise be attained using the best genetic material, technology, and management practices.
3 Yield gaps are typically caused by lack of access to contemporary technology and management
4 knowledge. Genetically modified crop varieties and the technological advances that produce them
5 could play a significant role to increase food production in nations with large yield gaps, if they are
6 suited to the local cultural, ecological, and economic situation. Other technologies, such as high
7 efficiency irrigation systems, advanced mechanization and fertilization methods can also contribute
8 to reducing the yield gap.

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

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

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

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

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

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

25

CHAPTER 1: INTRODUCTION AND REPORT BACKGROUND

The connections between 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 by the Food and Agriculture Organization of the United Nations 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 1990-92, 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), with the stability of each over time as the fourth component. 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 processing, packaging,

1 transporting, storing, trading, wholesaling, retailing, consuming, and disposing of food waste. It is
2 not possible to understand and characterize the potential effects of climate change on food security
3 without this broad food systems perspective. A systems perspective is needed to address the effects
4 of climate change on global food security and feedbacks to the United States. The U.S. is tightly
5 connected to the global food system through its role as a major exporter and importer of food, a
6 provider of assistance for many food-insecure nations, and a developer of relevant food
7 technologies and research outputs.

8 Questions this report will address include

- 9 ▪ How are climate and society projected to change in the next 20-30 years, and the next 70-
10 100 years? (Chapter 3)
- 11 ▪ How might plausible changes in climate and socioeconomic conditions influence the
12 production, consumption, trade, and prices of food? (Chapter 4)
- 13 ▪ What are the components of food security and how might climate change affect them?
14 (Chapters 5, 6, and 7)
- 15 ▪ How might climate change affect global food security and influence the U.S. food system?
16 (Chapter 8)

17 **1.1 Report Background**

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

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

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

11 **1.2 Report Scope**

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

22 This report addresses the spectrum of food security components: availability, access, utilization,
23 and stability. While food production (including livestock, fisheries, and wild harvesting, in addition
24 to crops) is clearly related to food availability, post-farm gate activities (processing, packaging,
25 transporting, storing, trading, wholesaling, retailing, consuming, and disposing of food waste)

1 matter a great deal to comprehensive food security outcomes. Each is considered within economic,
2 social, and biophysical contexts.

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

9 **1.3 Report Organization**

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

- 15 ▪ The **Executive Summary** affords an overview of the report's full content.
- 16 ▪ The **Introduction** (this chapter) provides background and an orientation to the report's
17 layout.
- 18 ▪ **Key Concepts** (Chapter 2) includes a general description of key concepts that are prevalent
19 throughout the volume and definitions of important terms.
- 20 ▪ Chapter 3, **Climate and Socioeconomic Projections** summarizes recent projections and
21 scenarios that describe how overall global climate and climate variables relevant to food
22 security are likely to change under different levels of greenhouse gas emissions and
23 concentrations. It also describes alternative pathways of future socioeconomic change that
24 could affect vulnerability and response capabilities. These scenarios reflect a range of

1 plausible future conditions against which risks, vulnerabilities, and opportunities may be
2 assessed in an integrated fashion.

- 3 ▪ Chapter 4, **Integrated Assessment Modeling of Agricultural and Food Systems**,
4 describes global and regional modeling of climate change effects on food production,
5 agricultural land use, prices, and numbers of food-insecure people.
- 6 ▪ Chapter 5, **Food Availability and Stability**, documents the relationships between climate
7 change and the parts of the food system relevant to availability of food supplies.
- 8 ▪ Chapter 6, **Food Access and Stability**, documents the relationships between climate change
9 and the parts of the food system relevant to people’s access to food.
- 10 ▪ Chapter 7, **Food Utilization and Stability**, documents the relationships between climate
11 change and the parts of the food system relevant to people’s utilization of food.
- 12 ▪ Chapter 8, **Implications for the U.S. of Changing Food Security**, describes how climate
13 change affects global food systems and global food security could affect the food system of
14 the United States.
- 15 ▪ Chapter 9, **Report Conclusions**, describes the high-level findings that the authors have
16 drawn from this assessment.
- 17 ▪ Finally, a series of **appendices** lists author and technical contributors and their affiliations
18 (Appendix A), commonly used abbreviations (Appendix B), a glossary (Appendix C), and the
19 report’s references (Appendix D).

20 **1.4 Report Development Process**

21 USDA engaged USGCRP Agencies with an initial “scoping session,” identifying specific interests in
22 the report. Additional stakeholders were engaged at an initiation workshop with the report authors
23 in June 2013 to help scope the report and provide the most useful possible information to those

1 communities most likely to make use of it.¹ A second stakeholder meeting was held during a
2 session of the National Council for Science and the Environment in January 2014.² Overall, more
3 than 50 stakeholder groups representing production groups, food assistance organizations,
4 financiers, private industry, nongovernmental representatives, the federal service, and others were
5 engaged in the initial scoping and development stages of the report. Participation by an additional
6 26 organizations was solicited.

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

18 Peer-reviewed documents and specific types of government or intergovernmental data sources
19 (e.g., FAOSTAT) have been included in this evaluation. Trade journals, URLs that document the
20 existence of a particular program, and other types of publications, may contain information both
21 useful and important to the subject matter of this report that is not generally available in the peer-
22 reviewed technical literature. However, because those sources are not subject to peer-review

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/>

1 standards, their quality and veracity can vary greatly. As a consequence, those sources are included
2 here only in cases where a specific opinion or perspective is being represented as such, and is
3 consequently not in need of review verification.

4 The report was primarily drafted between October 2013 and October 2014. Expert peer reviewers
5 were solicited via Federal Register in July and August 2014. Six hundred and fifty-two comments
6 were responded to through peer-review and interagency comment, followed by a public comment
7 period in September 2015, and a revised draft was submitted to federal clearance in the autumn of
8 2015.

DRAFT

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, 2012). Globally, about 805 million people are food insecure (FAO et al. 2014) and at least two 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 (United Nations Food and Agriculture Organization) definition above holds “sufficient, safe and nutritious” as the goal; overweight or obesity can themselves lead to damaging health effects (Ng et al. 2014).

Many factors determine food security, including economic conditions from the global to the micro levels, the conditions of trade, food safety, land use, demographics, and disease, in addition to food production (Ericksen et al. 2009, Misselhorn et al. 2012), which is an important prerequisite for food security to be achieved, but is alone insufficient to do so. 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).

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

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

20
21

1 **Table 2.1: The Components of Food Security.**

2 *For food security to be achieved, all four components must be attained simultaneously. Adapted from*
3 *UN FAO 2008d.*

Component	Definition
Availability	The existence of food in a particular place at a particular time. Addresses the “supply side” of food security, 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 intra-nation and intra-household 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 socio-cultural 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.

4 .
5 Food security is determined by each of these components acting and interacting across multiple
6 spatial and temporal scales (Carr 2006, Davis et al. 2001, Kotzé 2003, Maxwell 1996, Maxwell and
7 Smith 1992). Changes in one region may affect food security in other countries at great distances
8 (Dronin and Kirilenko 2008). While some changes may directly diminish food security, they may be
9 compensated for through alternative pathways (e.g., as when supply disruptions are addressed
10 through trade (Parry et al. 2004). A globalized food system can in this way buffer the local effects of
11 weather events, but may also increase vulnerability by transmitting price shocks globally (Godfray
12 et al. 2010). As a major food importer and exporter (USDA ERS 2013a), the U.S. can be significantly
13 influenced by climate events and changes in other parts of the world.

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

1 **2.2 Food Insecurity**

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

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

14 Just as food security is determined through interactions occurring across multiple spatial and
15 temporal scales, the consequences of food insecurity are also observable across those ranges. For
16 an individual, chronic food insecurity may manifest as a reduced capacity to perform physically,
17 diminished mental health and development, and an increased risk of chronic disease (Jyoti et al.
18 2005, Seligman et al. 2007, Seligman et al. 2009, Slack and Yoo 2005, Whitaker et al. 2006).

19 Undernourishment, including inadequate caloric and/or nutrient intake (WFP 2012), is a
20 consequence of food insecurity and leads to outcomes such as stunting (short for one’s age),
21 wasting (thin for one’s age), and micronutrient malnutrition.

22 Collectively, these changes diminish global economic productivity by 2%–3% annually (USD 1.4–2.1
23 trillion; FAO 2013b), with individual country costs estimated at up to 10% of national GDP (WFP
24 2013a, Martínez and Fernández 2008).

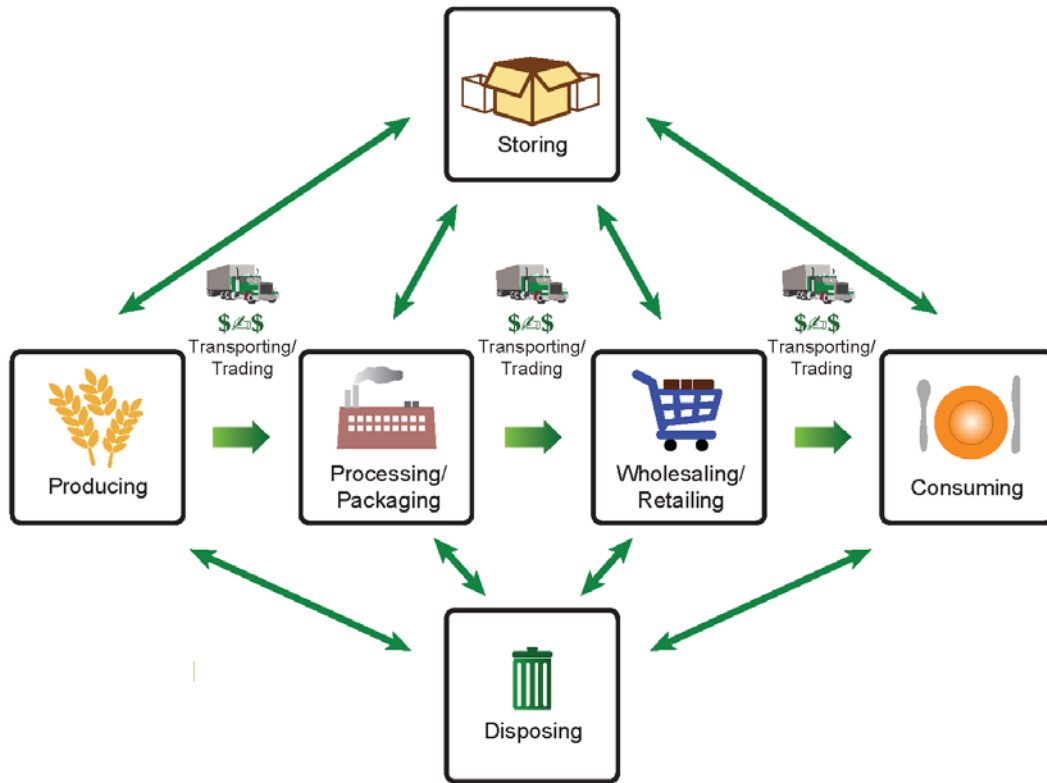
1 2.3 Food Systems

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

- 7 ▪ **Producing** food relies on agricultural production, including crops, livestock, and
8 fisheries and their relationships with climate and environmental change (Crane et al.
9 2011, Ericksen et al. 2011, IPCC 2007c, Schlenker and Lobell 2010, Vermeulen and
10 Aggarwal et al. 2012).
- 11 ▪ **Processing** of primary agricultural commodities transforms them into more easily
12 edible and digestible food (Boughton and Reardon 1997).
- 13 ▪ **Packaging** food protects it during transportation, extends its shelf life, and reduces the
14 chance of contamination.
- 15 ▪ **Storing** food items keeps them in one location for a period of time and may occur at
16 each step of the food system.
- 17 ▪ **Wholesaling** refers to the purchase and resale of agricultural commodities and food in
18 bulk, to be retailed by others.
- 19 ▪ **Retailing** describes economic agents, from roadside vendors and open markets to
20 supermarkets and restaurants, selling a range of unprocessed to processed and
21 prepared foods to consumers.
- 22 ▪ **Trading** refers to economic exchanges of food or other materials for payments or
23 export revenue; it can occur across all of the food system activities
- 24 ▪ **Transporting** describes the movement of food to markets and between markets, and
25 from markets to communities and homes.

- 1 ▪ **Consuming** is eating food by individuals and families to sustain themselves in their day-
- 2 to-day lives.
- 3 ▪ **Disposing** of spoiled, inedible, or surplus food by feeding it to animals, harvesting it for
- 4 nutrients through composting, or discarding into a landfill or centralized waste facility.

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



10

11 **Figure 2.1 Food system activities and feedbacks.**

12 *Food system activities include the production of raw food materials, transforming the raw material*
 13 *into retail products, marketing those products to buyers and through to consumption. Transportation,*
 14 *storage and disposal of waste play a role in each of these activities.*

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

10 **2.4 Climate Change**

11 Climate change is identified by changes over an extended period in the average and/or variability of
12 properties such as temperature and precipitation. This report also considers elevated atmospheric
13 carbon dioxide (CO₂) concentrations, which are a driver of climate change. Human activities have
14 resulted in large changes in Earth's climate over the last few centuries (Stocker et al. 2013). Much
15 larger changes are projected for the next century if greenhouse gas emissions and concentrations
16 continue to increase (Stocker et al. 2013).

17 Human activities have changed and will continue to change the Earth's climate (Stocker et al. 2013).
18 Since 1750, atmospheric concentrations of CO₂ have increased by about 40%, nitrous oxide by
19 20%, and methane by about 150%, leading to increasing temperatures and changes in the timing
20 and amount of precipitation in many areas. CO₂ concentrations have reached 400 parts per million,
21 and global average temperatures increased by 0.85 °C (about 1.6 °F) between 1880 and 2012
22 (Stocker et al. 2013). Precipitation has observably increased over the mid-latitude terrestrial areas
23 of the Northern Hemisphere (estimates range from 1.44 to 3.82 mm per year per decade), while
24 precipitation trends over other areas have been less significant. Increased ocean temperatures

1 along with the melting of glaciers and ice caps have contributed to an observed rise in global sea
2 level of approximately 0.2 m between 1901 and 2010 (Stocker et al. 2013).

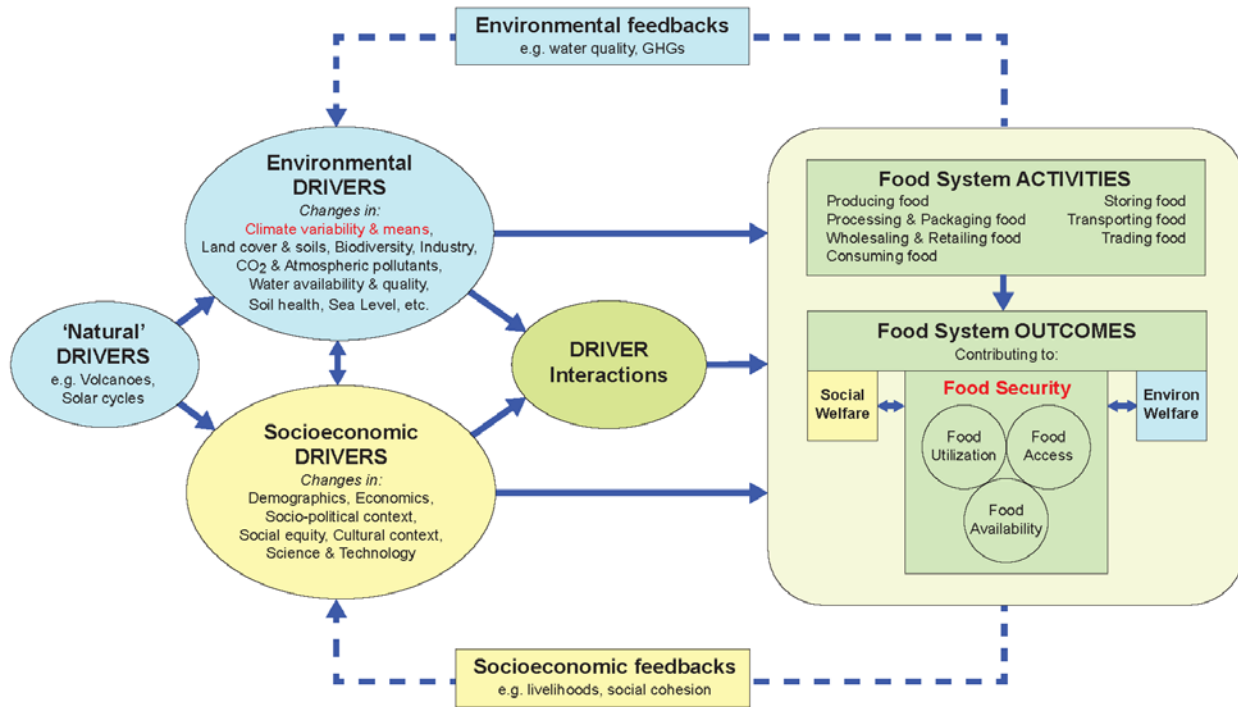
3 This report investigates how past climate has influenced food system activities and food security,
4 using those historical relationships as a basis for understanding possible future near-term (~2040
5 – 2060) and longer-term (~2080 – 2100) food security outcomes. It focuses on two different
6 scenarios of climate change: (1) relatively low emissions and atmospheric concentrations of GHG,
7 and (2) high emissions and concentrations of GHG, both derived from the recent climate
8 assessments of the IPCC (IPCC 2013). The low scenario discussed in this report is Representative
9 Concentration Pathway 2.6 (RCP 2.6), in which CO₂ concentrations increase to about 421 parts per
10 million and then stay at about that level (current concentrations are about 400 ppm). The high
11 scenario is RCP 8.5, in which concentrations increase steadily throughout the 21st century, reaching
12 a level of about 936 parts per million by 2100. It also outlines five broad scenarios, or pathways, of
13 socioeconomic change that could affect the structure of society over time and future capabilities
14 and willingness of society to adapt to and mitigate climate change and its effects.

15 Effects of changes in climate on agriculture tend to be gradual until a threshold is reached (IPCC
16 2013). For example, at increasingly high temperatures, plants may continue to grow at a reduced
17 pace, until a particular temperature is reached (the precise temperature specific to the crop type
18 and variety). At the point that the plant ceases to grow, it has reached a threshold temperature
19 (Walthall et al. 2012). Thresholds may influence food security in a number of ways – a bridge is
20 either passable, or it is not, with consequences for market access or for a community awaiting a
21 shipment. Instances of thresholds are discussed in this report.

22 **2.5 Non-Climate Drivers of Food Systems and Food Security**

23 Food security and food systems are driven by many factors. Although this report focuses on
24 changes caused by climate change, this is only one among a set of interconnected trends and drivers
25 facing agriculture, food systems, and hence, food security (FAO 2008d). Some of the most relevant

1 technological and socioeconomic factors driving changes in food systems include technological and
 2 structural changes in the food system, including food production, food processing, distribution, and
 3 markets; increasing population; changes in wealth; demographic changes; urbanization; disaster
 4 response; and changes in energy availability and use (Figure 2.2).



5
 6 **Figure 2. 2 Food system drivers, interactions, and feedbacks.**
 7 *Changes and interactions in environmental and socioeconomic conditions can affect food security*
 8 *outcomes in distant locations. The primary foci of this report are highlighted in red but occur within a*
 9 *broader context, with many feedbacks. Source: Adapted from Ingram 2011.*

10 **Technological and Structural Changes in the Food System.** Technology has been historically
 11 important to allowing the food supply to keep pace with increased demands caused by population
 12 and income growth in the 20th century (Pingali 2012). Those technological advances included, for
 13 example, better fertilization, crop improvements through breeding and hybridization, and
 14 improved mechanization, all of which increased individual farm outputs. These technological
 15 changes went hand-in-hand with major structural changes in agricultural production, for example,
 16 with a continuing concentration of commercial production at larger farms in the U.S. and some
 17 other industrialized countries (MacDonald et al. 2013). Also, the food processing, distribution, and

1 market systems have moved increasingly to larger scale, integrated firms (Ericksen 2008, Ingram
2 2011, Reardon et al. 2012).

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

14 **Population and Demographic Change:** Population is a strong driver of the demand for food.
15 Population expansion over the next century is expected to occur primarily in less-developed, food-
16 insecure nations, placing more pressure on stressed systems with limited adaptive capacity for
17 climate change. By 2050, the world population is projected to be 9.6 billion, rising to 10.9 billion by
18 2100 (UN 2012). Globally, family size is expected to decline in the latter half of the 21st century
19 from a changing age and educational structure (Lutz and Samir 2010, UN 2012). These changes in
20 overall population size may be expected to lead to overall changes in food demand.

21 **Urbanization:** As of 2011, half of the global population is classified as urban (UN 2012). This is
22 projected to increase to about 67% by 2100 (UN 2012). The growth in urban populations and
23 reduction in rural populations leads to fewer agricultural producers overall, shifting dietary
24 demands, larger and more centralized food distribution structures, and a greater role for

1 transportation and trade (Lee et al. 2012, Neven et al. 2009, Reardon et al. 2012, Satterthwaite et al.
2 2010).

3 In coastal cities, in particular, imported food that is affordable and accommodates changing dietary
4 preferences will increasingly compete with food produced by domestic inland producers (Pingali
5 2007). As urban centers expand to accommodate the growing urban populations, neighboring
6 arable land will be removed from production and remaining cultivated lands will be subject to
7 greater pollution (Chen 2007). It is important to note that the overall loss of arable land from
8 urbanization is not large in a global context. Recent estimates of current urban land extent vary
9 depending on methodological and classification decisions, but most range from about 0.25% to
10 0.57% of global land area, excluding Greenland and Antarctica (Schneider et al. 2007). This is
11 projected to triple by 2030 (Seto et al. 2012), but would still amount to less than 2% of global
12 arable land.

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

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

20 Communication and food security analyses have improved the knowledge of and past response to
21 food security shocks (Hillbruner and Moloney 2012). Management of environmental disruption
22 often improves in a given location over the long term, though climate-related shocks – that is, an
23 abrupt change that causes a sudden change in food security – tend to have a detrimental effect on
24 the adaptive capacities of affected households, particularly when such shocks are repetitive (USAID
25 2011).

1 The actual effects of natural disasters and food security shocks are mediated by socioeconomic
2 conditions and the effectiveness of disaster response (Coughlin de Perez et al. 2014). A more
3 sensitive individual, household, or community has lower resilience to a given shock from any
4 source. Chronic vulnerability anywhere in the world may be due to poverty, degraded ecosystems,
5 inadequate physical infrastructure, conflict, and ineffective governance (FAO 2008a, Schreiner
6 2012), meaning that vulnerable people are more at risk to weather extremes (Coughlan de Perez et
7 al. 2014) and other stresses. In such settings, a relatively mild stress on chronically vulnerable
8 households can lead to serious consequences due to the households' inability to effectively respond
9 (Frankenberger et al. 2012).

10 **Energy:** Energy is a major driver of economies, societies, and food production. Agricultural
11 production, food storage, and other elements of the food system are energy intensive. Therefore,
12 energy costs are reflected at multiple stages of the food system (Vermeulen and Campbell et al.
13 2012), affecting access for income-limited consumers. Higher energy prices can also affect
14 commodity markets, incentivizing biofuel production and land-use conversions away from food
15 production (Difflenbaugh et al. 2012, Hazell 2013).

16 **2.6 Conclusions**

17 Food security, food systems, and climate change are multifaceted topics. Their interactions are
18 likewise complex, and affected by a wide range of environmental and socioeconomic factors. It is
19 nevertheless clear that there are multiple connections between climate conditions and many
20 different elements of food systems, and that climate change can affect food systems in ways that
21 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, including increases in temperature, number of very hot days, precipitation intensity, length of very dry periods, and rising sea levels.
- The greater the increase in 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. Our intent is 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. The first section focuses on description of climate models and how they are used to project future climate change. It includes an overview of the most recent projections of near term (the next 20–30 years) and the longer-term (the next 80–90 years) climate change, emphasizing possible changes in variables relevant to agriculture and food security. The second section 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 non-linear interactions of the Earth's climate system in a quantitative way because controlled large-scale experiments are not possible in the

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

19 Coupled climate models have been developed by many large institutions worldwide. More than 40
20 such models contributed their output to the latest (fifth) phase of the Coupled Model
21 Intercomparison Project (CMIP5; Taylor et al. 2012), which provides a coordinated suite of
22 experiments that form the basis for the results described in the 5th Assessment Report of the
23 Intergovernmental Panel on Climate Change (IPCC) (Stocker et al. 2013) and are also the basis of
24 the climate projections included in this report. The output of CMIP experiments includes
25 simulations of past and current conditions so that model fidelity can be evaluated through
26 comparison to actual observations. Additionally, modeling groups perform common “control”

1 experiments and compare results across models to help further diagnose and evaluate model
2 performance. The full collection of models and experiments in CMIP, often including multiple
3 experiments with the same model but different initial conditions, creates a very large database to
4 support statistical analysis and enables better characterization of uncertainty in projections. The
5 CMIP effort has been underway since 1995 and helps to assure that high-quality, well-documented,
6 and comparable estimates of future climate change are available for use in research and scientific
7 assessments, including those of the IPCC.

8 **3.1.1 *Uncertainty in Climate Models***

9 Climate models work by representing the fundamental physical laws that govern our climate
10 system. But they also need to approximate small-scale processes and their interaction with the
11 larger scales that are directly simulated. There are no unique solutions to these approximations,
12 and different models choose different approaches, all scientifically defensible, that result in
13 different outcomes. This is the main source of model-to-model uncertainty in climate projections.
14 For example, when the different models in CMIP 5 used the same scenario of high GHG
15 concentrations to project increases in global average temperature by 2100, the results ranged from
16 about 3 °C to almost 6 °C (Figure 4.1), with a mean value of about 4° C relative to average
17 temperatures between 1986 and 2005 (Stocker et al. 2013).

18 It is also important to recognize that the scenario-based inputs, or “forcings” used to drive climate
19 model projections, such as levels of GHG emissions and concentrations, are themselves uncertain.
20 High concentrations lead to larger climate changes and lower concentrations to lower changes, but
21 it is not possible to determine which concentration future is most likely.

22 Analysis of modeling results, and comparison of model results to observations, shows that climate
23 models differ in their strengths and weaknesses. All are affected by some common errors, but it is
24 not yet clear which aspects of model errors and model performance in simulating the past and
25 present are also most critical to the reliability of future projections. The process of selecting models

1 or weighting their results is thus somewhat arbitrary. Section 3.3 provides mean results from all
2 models contributing simulations to the CMIP process under a given scenario.

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

16 **3.1.2 Downscaling Climate Model Results**

17 Planning and decision processes in the agricultural sector happen at all spatial scales and generally
18 involve a wide range of time horizons. However, global-scale modeling results at spatial resolutions
19 of roughly 100x100 km, such as discussed in this chapter, are generally seen as too coarse to be
20 usable in regional or local-scale analyses and management decisions. Thus, one of the most
21 common complications when trying to integrate climate projections into these workflows is to
22 bridge the gaps and mismatches in scales. This step of bringing the information from general
23 circulation models to the decision level is called *downscaling*.

24 There is a long and deep history in downscaling climate model output to various user needs
25 (Benestad et al. 2008, Wilby et al. 1998). Approaches fall into two basic categories. The empirical-

1 statistical methods exploit relationships between observed data (e.g., a weather station or grid
2 points in a gridded observational product) and model output over a period when both are
3 available—called the calibration period—and then estimate the higher resolution field from the
4 model projection, assuming a constant relationship (Benestad et al. 2008, Maurer and Hidalgo
5 2008, Stoner et al. 2013, Wood et al. 2002). In this category are also methods that determine the
6 closest analog situations from the observed record, which are used to construct spatially more
7 coherent conditions.

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

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

21 Each downscaling method has strengths and weaknesses. Users should be aware that downscaled
22 climate information that is optimized for a particular purpose may not be ideal for different uses.
23 For example, hydrologic and ecologic applications often require unbiased cumulative sums of
24 precipitation over a basin or accumulated heat during the growing season while disaggregating and
25 even reshuffling daily sequences (Maurer et al. 2002, Wood et al. 2002). Others focus specifically on

1 the preservation of sequences, and particularly the occurrence of extremes (Yates et al. 2003, Clark
2 et al. 2004, Bürger et al. 2012), with their specific multi-variate and spatially coherent context to
3 better represent feedback processes (Benestad et al. 2012). Similarly, direct analog-based methods
4 (Abatzoglou and Brown 2012) also preserve the full context and are very useful to provide multi-
5 variate inputs into process models. Finally, the exploitation of dynamical methods, as is done
6 through the use of high-resolution regional models driven by lower-resolution global results, often
7 provides the most flexible, and ultimately the only geophysically consistent framework to study
8 Earth system change (Kharin and Zwiers 2000, Giorgi and Mearns 2003, Racherla et al. 2012).
9 However, such methods involve substantial computational costs and may introduce additional
10 uncertainties through hand off of results across multiple modeling systems.

11 In the end, users need to be aware of the strength and weaknesses of different products, which
12 were often designed for one particular application. Just because the data are offered at spatial and
13 temporal resolutions resembling observations doesn't necessarily mean that they also contain all
14 the characteristics of the real world data. Careful evaluation of data towards the key characteristics
15 for the application remains critical before data should be applied.

16 **3.2 GREENHOUSE GAS (GHG) EMISSIONS AND CONCENTRATION SCENARIOS**

17 To investigate human-induced climate change, researchers use projections of future GHG
18 concentrations and other anthropogenic drivers of change, such as the emission of aerosol
19 precursors and land-use change, as input to climate model calculations. The most recent set of
20 inputs developed by the scientific community, used in the CMIP5 process and many other
21 experiments, are called *representative concentration pathways* (RCPs). The RCPs replace the
22 scenarios described in the IPCC Special Report on Emissions Scenarios (SRES; Nakicenovic et al.
23 2000) that were used in the CMIP3 simulations (Meehl et al. 2007) that informed the IPCC 4th
24 Assessment Report.

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

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

17 For the purposes of this report, we concentrate our description on the differences between a low-
18 emissions case and a high-emissions case. This approach spans a broad range of possible future
19 climate conditions and enables us to address the potential effects of actions to reduce GHG
20 emissions versus allowing continued rapid emissions growth. RCP 2.6 is a low-emissions scenario
21 that assumes extensive mitigation efforts to reduce emissions, resulting in a CO₂ concentration of
22 about 421 ppm (parts per million) by 2100 (van Vuuren et al. 2011). RCP 8.5 is a high-emissions
23 scenario that produces a CO₂ concentration of 936 ppm by the end of the century (Riahi et al.
24 2011). In some instances, we also discuss results from studies that used other low and high-
25 emissions scenarios, such as SRES, or studies that used more intermediate scenarios, such as RCP

1 4.5 and RCP 6.0. For reference, current CO₂ concentrations in the atmosphere are around 400 ppm,
2 and pre-industrial levels were approximately 280 ppm.

3 **3.3 CLIMATE PROJECTIONS**

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

12 The new set of climate projections confirm and extend the findings of previous studies described in
13 the scientific literature and earlier IPCC reports such as the 4th Assessment Report (Solomon et al.
14 2007). As expected, the range of results is somewhat wider because of the wider range of forcing
15 levels spanned by the RCPs compared to previous emissions scenarios. But the geographical
16 patterns and magnitude of change (conditional on the scenario used) are consistent with previous
17 work.

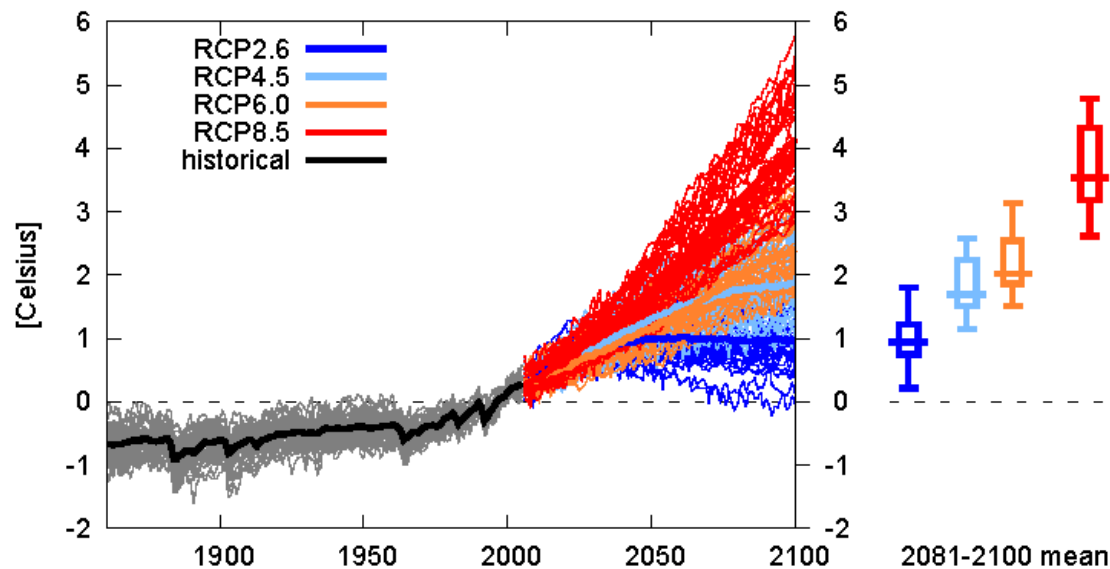
18 If GHG emissions and concentrations continue to increase rapidly throughout the 21st century (as
19 represented in RCP8.5), global average temperature is projected to increase by about 2 °C by 2050
20 and about 4 °C by 2100 (Stocker et al. 2013), relative to global average temperature during the
21 period from 1986-2005. Global average sea level is projected to rise by about 0.3 m by mid-century
22 (2046–2064) and 0.74 m by the end of the century (Stocker et al. 2013) relative to 1986-2005.
23 Global average sea level is projected to rise by about 0.22-0.38 m by mid-century (2046–2064) and
24 0.45-0.82 m by late century (2081-2100) relative to 1986-2005 (Stocker et al. 2013).

1 If aggressive mitigation actions are taken to slow the increase of GHG emissions and concentrations,
2 global average temperature is projected to increase by about 1 °C by 2050 and remain at about that
3 level through 2100 (Stocker et al. 2013), relative to the 1986-2005 average. Global average sea level
4 is projected to rise by approximately 0.24 m by mid-century and 0.44 m by the end of the century
5 (Stocker et al. 2013), again relative to 1986-2005. Global average sea level is projected to rise by
6 approximately 0.17-0.32 m by mid-century and 0.26-0.55 m by late century (Stocker et al. 2013),
7 again relative to 1986-2005. The likely range of about 0.26-0.82 m for late century (2081-2100)
8 sea level rise listed here is slightly less than the 0.3-1.2 m projected by the Third U.S. National
9 Climate Assessment for late century (Melillo et al. 2014).

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

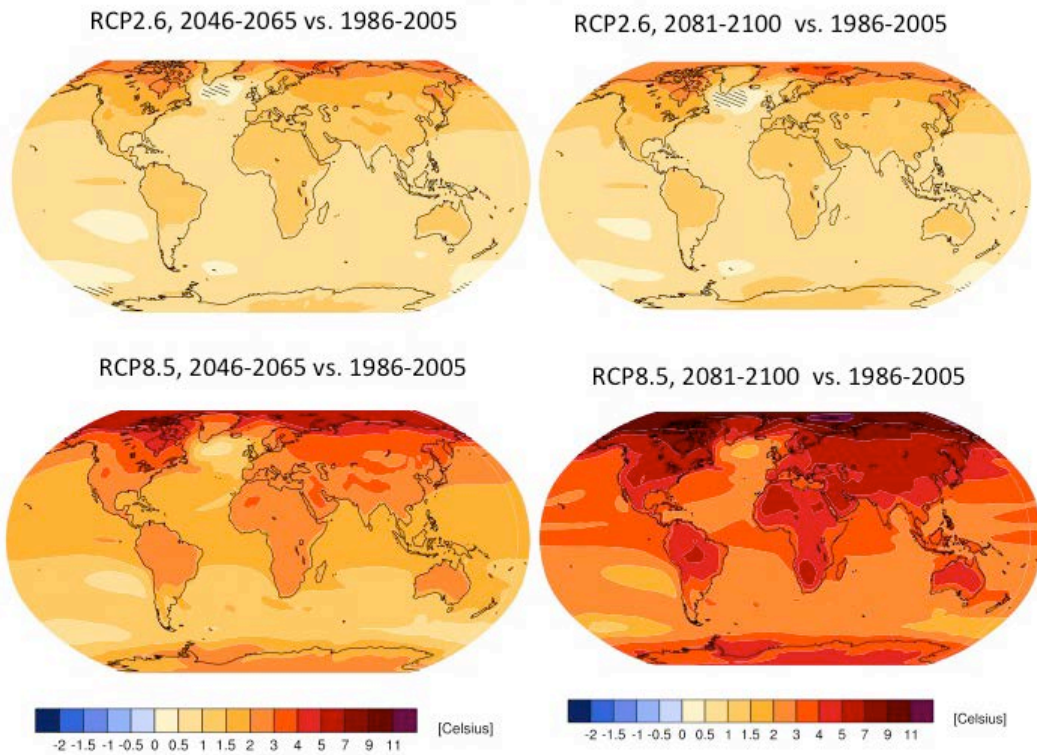
16 Projected changes from today's global average temperature by 2100 range from an ensemble mean
17 value of about 1°C for RCP 2.6 to an ensemble mean value of about 4°C for the highest scenario, RCP
18 8.5. A 2 °C warming threshold with respect to preindustrial levels would not likely be exceeded
19 under a RCP 2.6 scenario (Stocker et al. 2013). Under RCP 4.5 it is more likely than not to be
20 exceeded, and under RCPs 6.0 and 8.5 it is likely be exceeded (Stocker et al. 2013).

Temperature change World Jan-Dec wrt 1986-2005 full CMIP5 ensemble



1
2 **Figure 3.1 Global Average Temperature Change Relative to 1986–2005 Baseline.**
3 *Time series of surface temperature under historical forcings (gray) and future RCPs 2.6 (low-emissions*
4 *scenario, in blue), 4.5 (aqua), 6.0 (orange), and 8.5 (high-emissions scenario, in red) are shown out to*
5 *2100. Thin lines show individual model trajectories; thick lines show the multimodel ensemble mean.*
6 *Boxplots in margin show the distribution (mean, interquartile range, and 90% range) derived from*
7 *the model ensemble for the average changes over the 20-year period at the end of the century. Source:*
8 *This figure was produced using CMIP5 model output through the web application “Climate Explorer”,*
9 *available at <http://climexp.knmi.nl/>.*

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



1

2 **Figure 3.2 Projected changes in global surface temperature.**

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

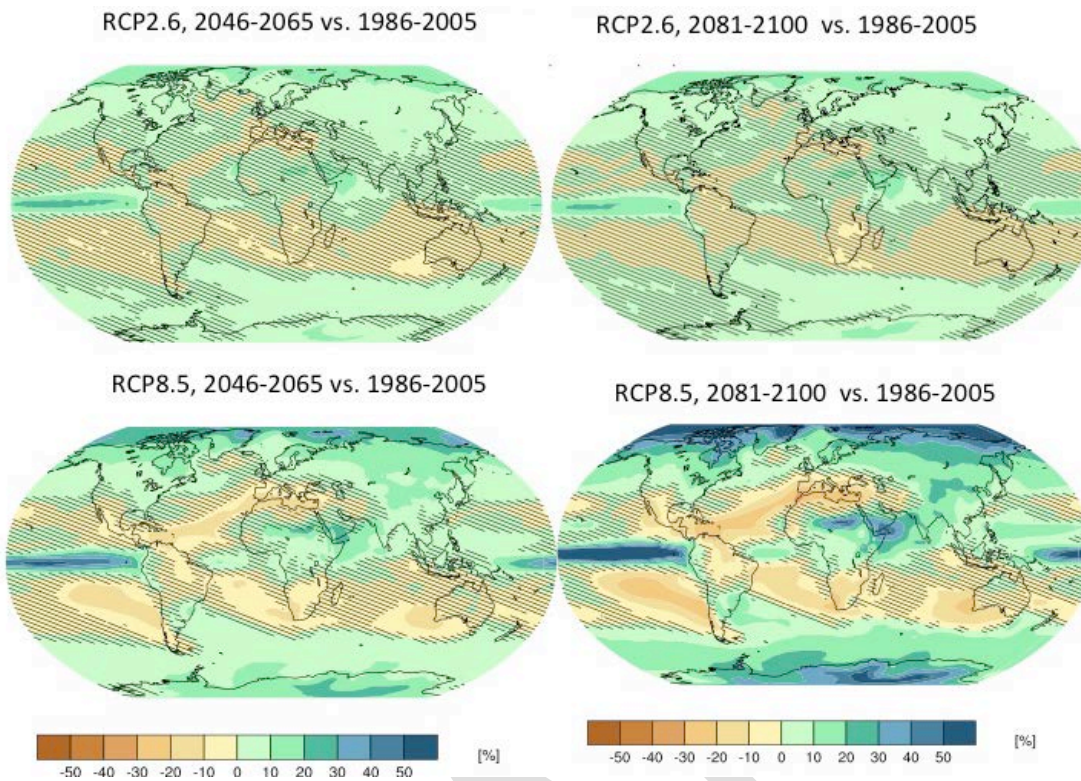
9 Well-known features of temperature change can be seen in the figure: high latitudes warm more
 10 than low latitudes, continents more than oceans, and the Northern Hemisphere more than the
 11 Southern. The RCP 2.6 low-emissions scenario results in warming of about 1–2 °C for much of
 12 North and South America, Europe, Africa, Australia, and Asia by mid-century, and this level of
 13 warming persists through the end of the century. Warming in some northern areas exceeds 2 °C.
 14 The RCP 8.5 high-emissions scenario results in warming of 2–3 °C for North and South America,
 15 Europe, Africa, Australia, and Asia by mid-century. By late century, this scenario results in 4–5 °C
 16 warming in these same areas, with some high-latitude northern regions experiencing warming of 7
 17 °C or more. The North Atlantic experiences less warming than surrounding areas due to the Atlantic
 18 Meridional Overturning Circulation in the ocean slowing down because of warmer temperatures

1 and increased freshwater. Similarly, changes in the southern oceans also result in somewhat
2 reduced warming in some locations due to better and deeper mixing of the ocean layers there.

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

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

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



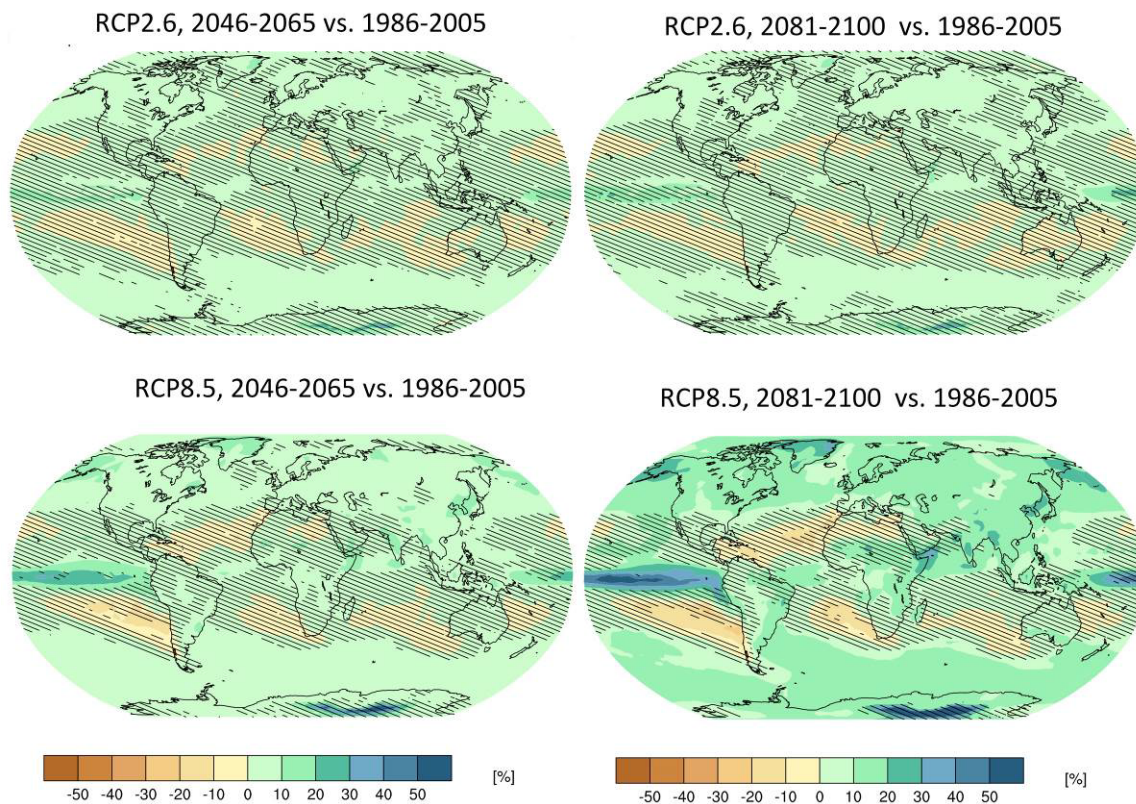
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2 **Figure 3.3 Projected changes in global precipitation.**

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

9

10

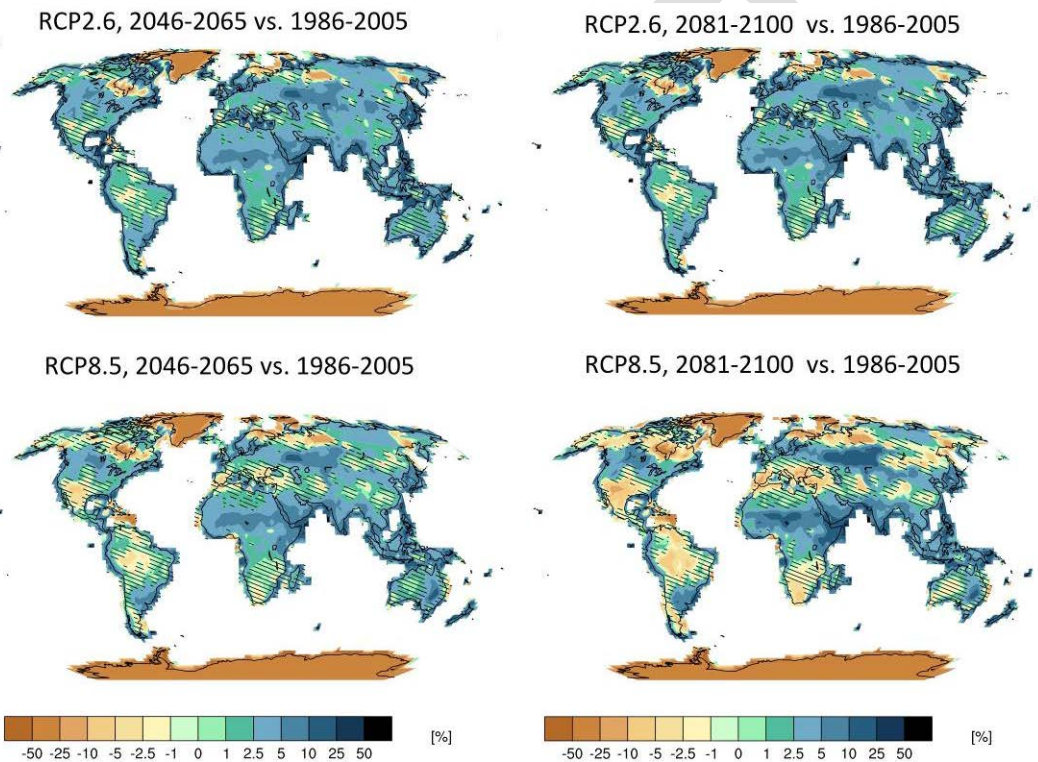


1
 2 **Figure 3.4 Projected changes in precipitation intensity.**
 3 *Mid (left) and late (right) 21st century changes are compared to the 1986–2005 baseline under the*
 4 *low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-*
 5 *mean changes are shown where gray dashes indicate areas where changes are small (less than one*
 6 *standard deviation) compared to natural variability. Precipitation intensity is defined as the total*
 7 *amount of annual precipitation divided by the number of wet days. Source: This figure was produced*
 8 *using CMIP5 model output through the web application “Climate Explorer,” available*
 9 *at <http://climexp.knmi.nl/>.*

10 These broad regional patterns of change in temperature and precipitation are common across all
 11 scenarios and are driven for the most part by increasing long-lived, well-mixed GHG. They are also
 12 common across time (for example, they can be seen in average changes around the middle of the
 13 century as well as those at the end of the century) and, in first approximation, across models. The
 14 regions of largest discrepancies among models are the very high latitudes for temperature and,
 15 conversely, the low latitudes for precipitation.

16 Soil moisture is another important variable for agriculture that integrates the history of
 17 temperature and precipitation to some extent. Projected changes in soil moisture are shown in
 18 Figure 3.5. There are notable differences between changes under high versus low scenarios of GHG

1 emissions and concentrations. Results for RCP 2.6 show some drying in high-latitude regions and
2 central South America, with increased moisture in many other areas, while RCP 8.5 results in much
3 more extensive drying in mid-latitude regions as well as high latitudes. This is seen in both the
4 near-term and long-term projections, with the most extensive reductions found in the high-
5 emissions results for the end of the century. This is a reflection of the fact that temperature plays an
6 important role in depleting the soil of moisture through evaporation, and warming is significantly
7 higher under the high-emissions scenario by the end of the century.



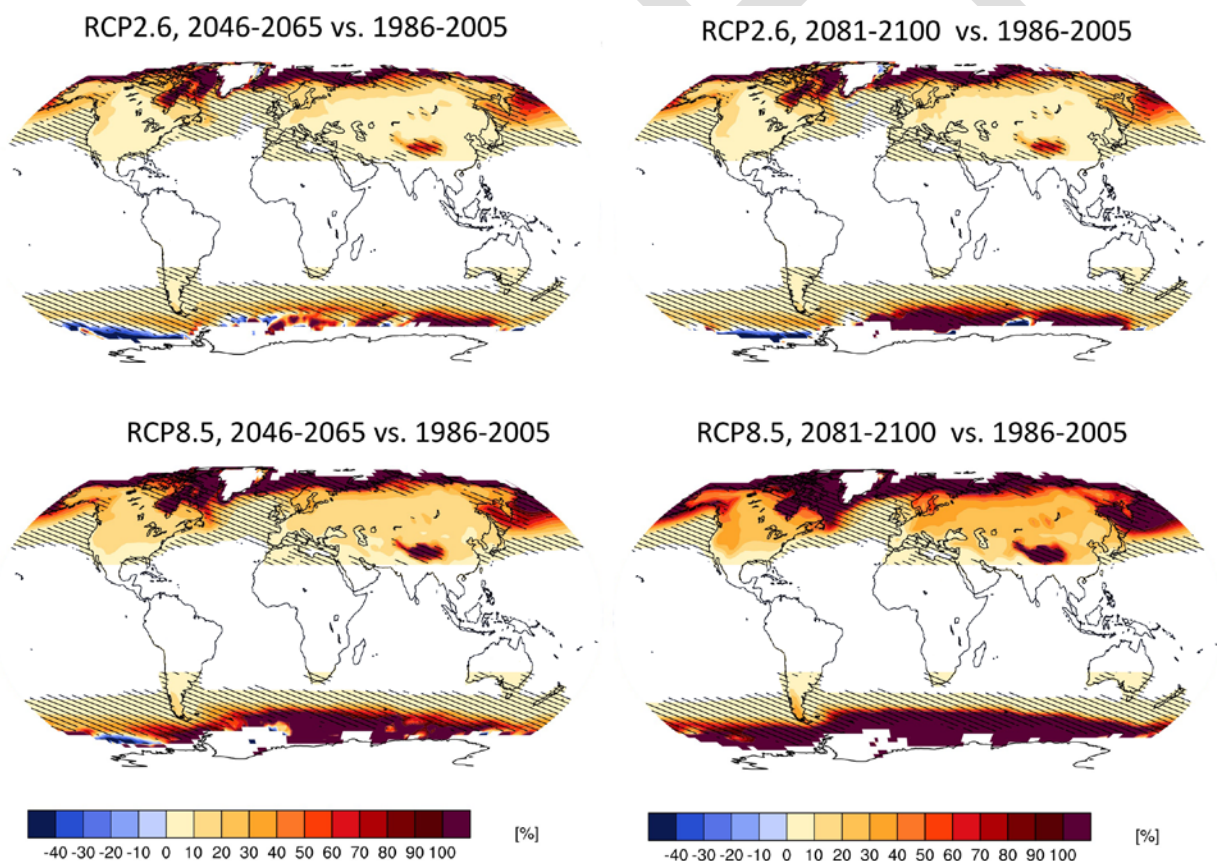
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9 **Figure 3.5 Projected changes in soil moisture.**

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

17 Another important agricultural quantity that can be derived from climate model simulations is
18 length of the growing season. Figure 3.6 shows projected changes in an index that adopts a
19 simplified and uniform definition, where growing season length is represented by the number of

1 consecutive days during the year with an average temperature above 5 °C. This index does not
2 capture changes in tropical and subtropical areas that do not experience temperatures below 5 °C,
3 where exceedance of physiological thresholds with higher temperatures can reduce growing season
4 length. The RCP 2.6 low-emissions scenario results in growing seasons that are up to about 10%
5 longer than currently throughout much of the mid-latitudes in the Northern Hemisphere by mid-
6 century, without much further change by the end of the century. Some higher latitude areas of the
7 Northern Hemisphere could see increases of 20%–30% and very high latitudes increases of 80%–
8 100%. For the RCP 8.5 high-emissions scenario, many of the northern mid-latitude areas see
9 increases of 20%–30% by mid-century, with a more extensive area at very high latitudes increasing
10 by 70%–100%.



11

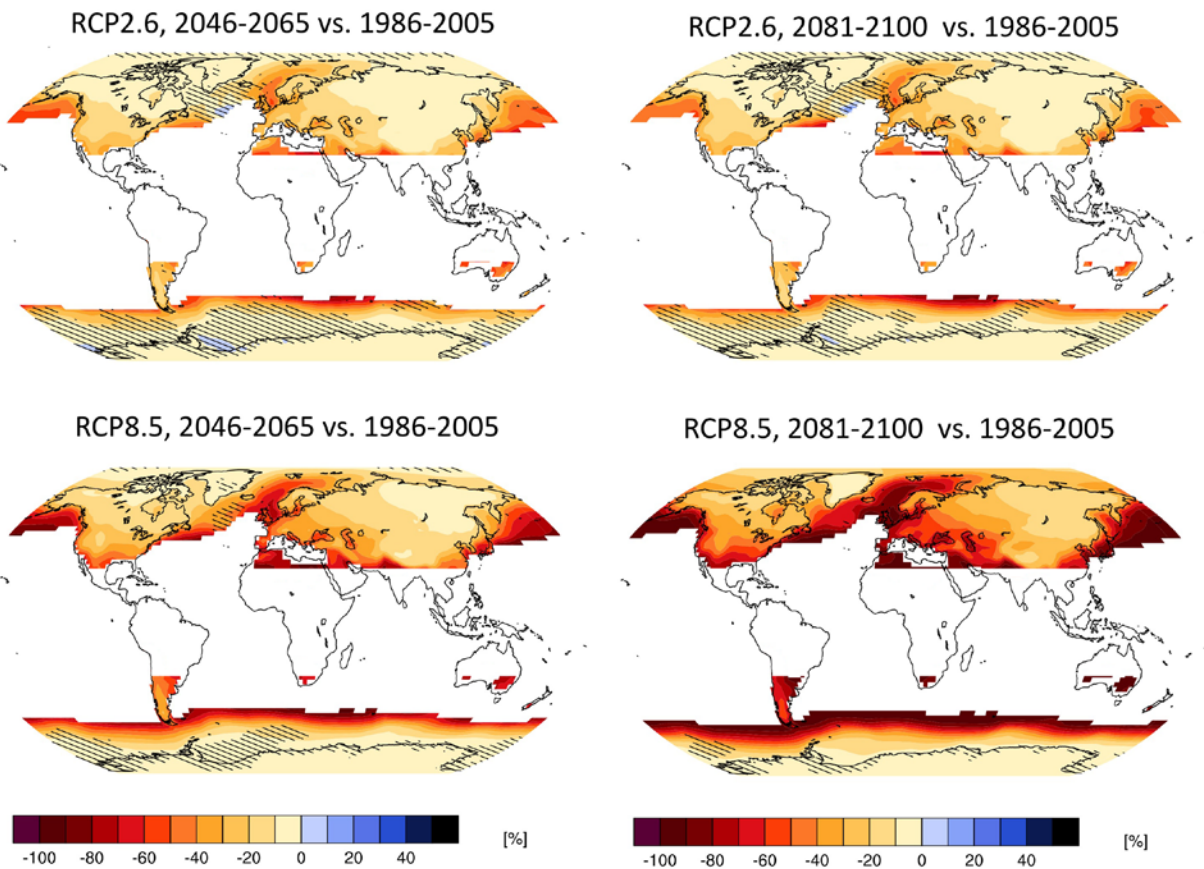
12 **Figure 3.6 Projected changes in growing season length.**

13 *Mid (left) and late (right) 21st century changes are compared to the 1986–2005 baseline under the*
14 *low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-*
15 *mean changes are shown where gray dashes indicate areas where changes are small (less than one*

1 *standard deviation) compared to natural variability. Source: This figure was produced using CMIP5*
2 *model output through the web application "Climate Explorer," available at <http://climexp.knmi.nl/>.*

3 The index displayed in Figure 3.6 does not capture change in tropical and subtropical areas, which
4 are expected to experience shorter growing seasons due to lack of sufficient moisture and
5 temperature increases that exceed physiological tolerances for many crops. In semi-arid regions of
6 the tropics, the length of the growing season is not determined by the number of days with
7 temperatures greater than 5 °C, but by the balance between water supply (precipitation) and
8 atmospheric water demand (potential evapotranspiration). In many areas, the latter will increase
9 with increasing air temperatures. In some regions, these effects are expected to lead to substantial
10 reductions in the length of the viable growing seasons by mid-century (Thornton et al. 2011, Cook
11 and Vizzy 2012).

12 Changes in average climate conditions are important, but agricultural production and other food
13 system elements are also affected by changes in extreme conditions. Figures 3.7 through 3.9 show
14 changes in the tails (i.e., extremes) of the distribution of values derived from daily output of
15 temperature or precipitation (Sillmann et al. 2013). The Frost Days index (Figure 3.7) counts the
16 number of days in the year with minimum temperatures below freezing. The Consecutive Dry Days
17 index (Figure 3.8) measures the longest stretch of days without agriculturally meaningful
18 (>0.1mm/day) precipitation every year. Finally, Figure 3.9 shows projected changes in the number
19 of very hot days, defined as days with maximum temperatures in the upper 10% of observed daily
20 highs in 1986–2005.

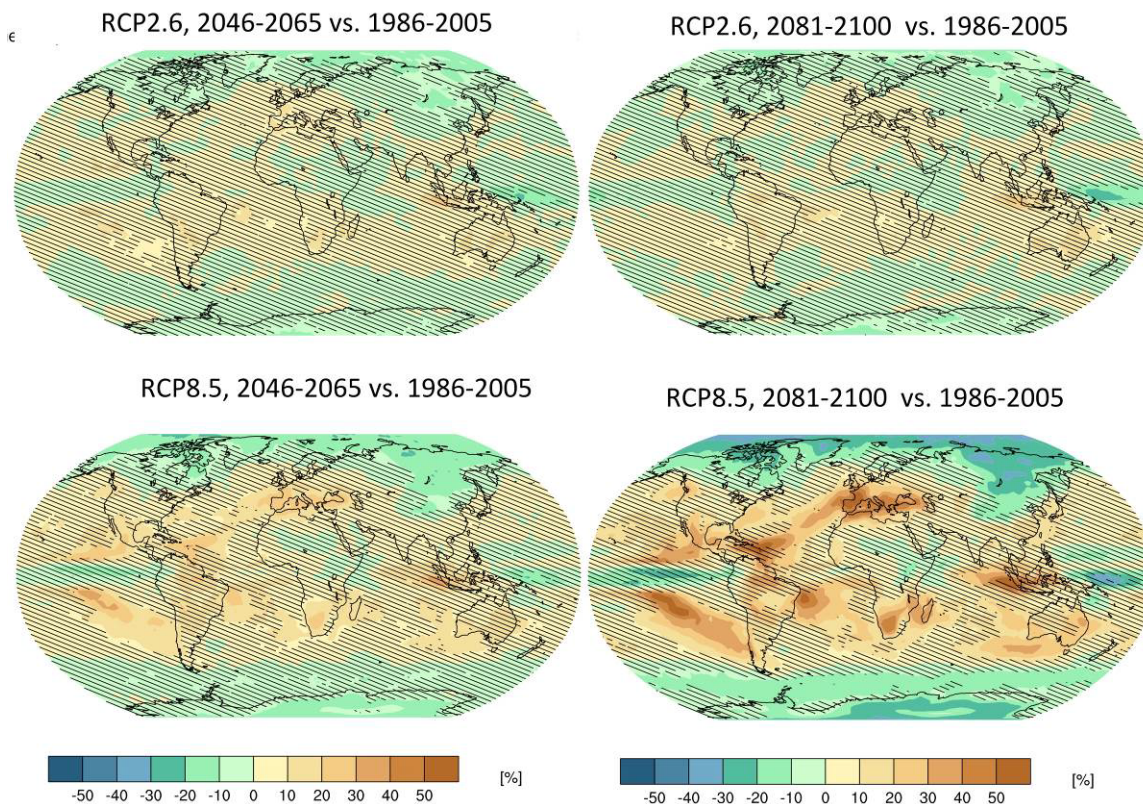


1

2 **Figure 3.7 Projected changes in frost days.**

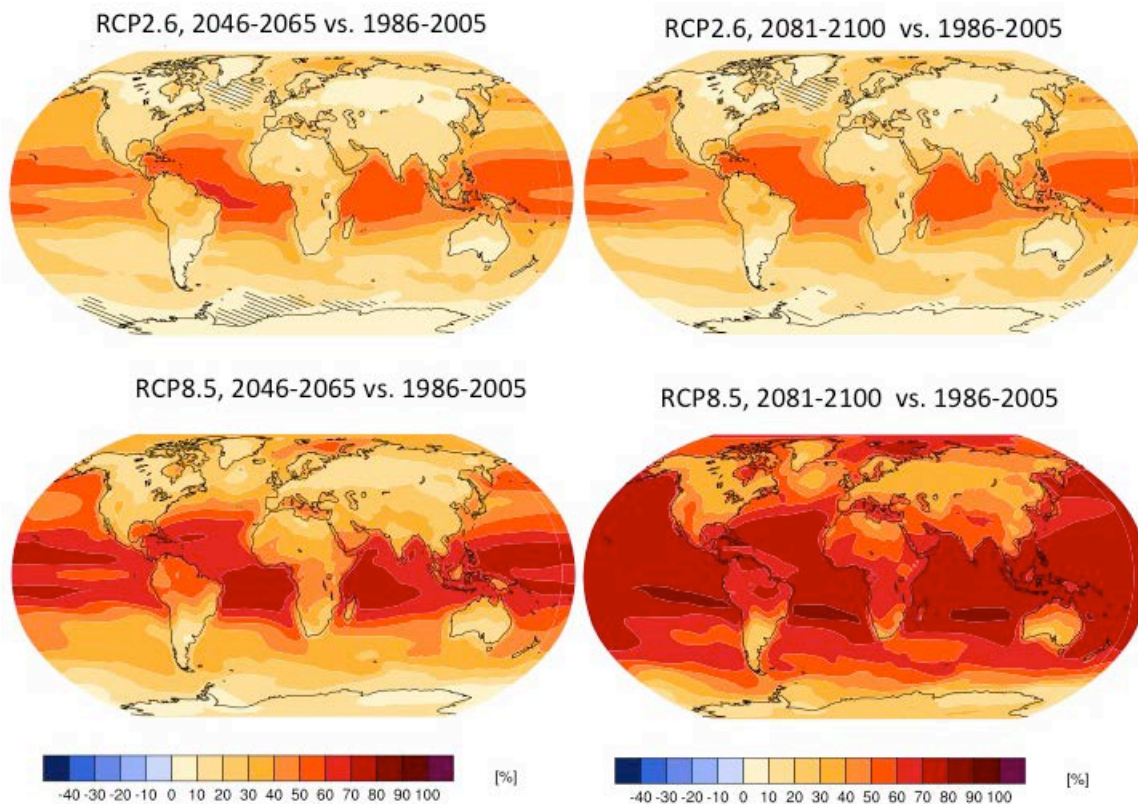
3 *Mid (left) and late (right) 21st century changes are compared to the 1986–2005 baseline under the*
 4 *low-emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-*
 5 *mean changes are shown where gray dashes indicate areas where changes are small (less than one*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

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



1
 2 **Figure 3.8 Projected changes in annual maximum number of consecutive dry days.**
 3 *Mid (left) and late (right) 21st century changes are compared to the 1986–2005 baseline under the*
 4 *low emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-*
 5 *mean changes are shown where gray dashes indicate areas where changes are small (less than one*
 6 *standard deviation) compared to natural variability. Source: This figure was produced using CMIP5*
 7 *model output through the web application “Climate Explorer,” available at <http://climexp.knmi.nl/>.*

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



1
 2 **Figure 3.9 Projected changes in annual number of very hot days.**
 3 *Mid (left) and late (right) 21st century changes are compared to the 1986–2005 baseline under the*
 4 *low emissions (RCP 2.6, top) and high-emissions (RCP 8.5, bottom) scenarios. Multimodel ensemble-*
 5 *mean changes are shown where gray dashes indicate areas where changes are small (less than one*
 6 *standard deviation) compared to natural variability. Very hot days are when maximum daily*
 7 *temperatures are above the 90th percentile of current climatology. Source: This figure was produced*
 8 *using CMIP5 model output through the web application “Climate Explorer,” available*
 9 *at <http://climexp.knmi.nl/>.*

10 When we look at very hot days (Figure 3.9) in the low-emissions scenario (RCP 2.6), we see
 11 increases of 10%–20% in such days across large areas of continental interiors in the mid-latitudes
 12 and tropics, with smaller areas seeing increases of 30%–40%. This change then persists in the long
 13 term, with late-century conditions quite similar to those seen in mid-century. The high-emissions
 14 scenario results in a greater number of very hot days. In the near term, large areas of the mid-
 15 latitude continental interiors are projected to see increases of 30%–40%, and some parts of South
 16 America and Africa may see increases over 50%. In contrast to the low-emissions scenario, changes
 17 continue to occur and grow in magnitude. These increases may reduce the length of the effective
 18 growing season in some places in Africa, for example, by the middle of the 21st Century (Cook and

1 Vizzy 2012). By the end of the 21st century, large parts of South America and Africa are projected to
2 see increases of 60%–70% in the number of very hot days compared with today.

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

11 **3.4 Socioeconomic Change**

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

19 The rate and magnitude of recent technological and socioeconomic change is very large. Global
20 population increased from about 2.5 billion in 1950 to over 7 billion today. Global GDP changed
21 from about \$5.3 trillion to about \$77.6 trillion over this same period. This rapid evolution must be
22 considered in assessment of potential future effects of climate change. Examining the way that
23 different climate conditions would affect today's world can offer insights into some aspects of
24 vulnerability but is unlikely to provide an accurate picture of future risks. In order to construct
25 meaningful assessments of the potential future impacts of climate change, as well as possibilities for

1 mitigation and adaptation, projections of future climate change need to be combined with
2 projections of future biophysical and socio-economic conditions, including demographic, economic,
3 technological, social, and governance outcomes and the couplings and feedbacks between human
4 and ecological systems (Ostrom 2009).

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

10 **Shared Socioeconomic Pathways**

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

22 Five SSPs have been developed. SSP1 assumes low challenges to mitigation and adaptation; SSP2
23 assumes medium challenges to both; SSP3 assumes high challenges to both; SSP4 assumes that
24 adaptation challenges dominate; and SSP5 assumes that mitigation challenges dominate. Each SSP
25 consists of a qualitative narrative, summarized below, describing general trends in the various

1 elements of societal conditions and the logic for how and why these trends unfold together over
2 time. In addition, each SSP will include quantitative projections, global, and country-by-country, of
3 key elements: population projections by age, sex, and education level; urbanization; and changes in
4 gross domestic product (GDP). Some of these have been published or submitted for publication;
5 others are still under development. None is considered more or less likely than another.

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

18 **SSP2: Moderate challenges to mitigation and adaptation.** The world follows historical social,
19 economic, and technological trends. Development and income growth proceed unevenly, but most
20 economies are politically stable. Globally connected markets function imperfectly. Global and
21 national institutions make slow progress improving living conditions and access to education, safe
22 water, and health care. Technological development proceeds but without fundamental
23 breakthroughs. Environmental systems mainly degrade, although there are some improvements.
24 Overall intensity of resource and energy use declines. Fossil fuel dependency decreases slowly, but
25 there is no reluctance to use unconventional fossil resources. Global population growth is moderate

1 and levels off in the second half of the century, but the transition to low fertility rates in low-income
2 countries is not accelerated. Persistent income inequality, continued societal stratification, and
3 limited social cohesion result in continued vulnerability to societal and environmental changes and
4 constrain sustainable development.

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

17 **SSP4: Low challenges to mitigation, high challenges to adaptation.** Highly unequal investment
18 in human capital, and increasing disparities in economic opportunities and political power, lead to
19 increasing inequalities and stratification across and within countries. Over time, a gap widens
20 between an internationally connected, well-educated society that contributes to and benefits from
21 the global economy and a fragmented collection of lower income, poorly educated societies that
22 work in a labor-intensive, low-tech economy. Vulnerable groups have little representation in
23 national and global institutions. Economic growth is moderate in developed and middle-income
24 countries, while low-income countries struggle to provide adequate access to water, sanitation, and
25 health care for the poor. Social cohesion degrades, and conflict and unrest are increasingly

1 common. Technology development is high in the high-tech economy and sectors. Uncertainty in the
2 fossil fuel markets leads to underinvestment in new resources in many regions. Oil and gas prices
3 rise, volatility increases, and energy companies invest in both low-carbon energy sources and
4 carbon-intensive fuels such as coal and unconventional oil. Environmental policies focus on local
5 issues around middle- and high-income areas.

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

20 Taken together, the set of RCPs and SSPs provides a basis for the scientific community to conduct
21 systematic and comparable analyses of future vulnerability, risks, and effects of climate change in
22 the context of other environmental and socioeconomic changes. Most of the integrated modeling
23 results examined in this assessment used combinations of SSP 1, SSP 2, and SSP 3 with RCP 2.6 and
24 RCP 8.5. In some cases, SSPs are also used as a frame for qualitative assessment of likely future
25 risks to food security, as they occur alongside other environmental and socioeconomic changes.

1 3.5 Conclusions

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

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

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

24 In summary, the Earth's climate is projected to continue changing over the coming decades and this
25 century. Some degree of change will occur in response to past emissions even if aggressive action is

1 taken to limit GHG increases in the future. Many projected changes are directly relevant to
2 agriculture and food security, including increased temperatures, increased incidence of very hot
3 days, decreased incidence of very cold days, increased precipitation, increased precipitation
4 intensity, longer dry periods, decreased soil moisture in many regions, and rising sea levels.

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

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

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

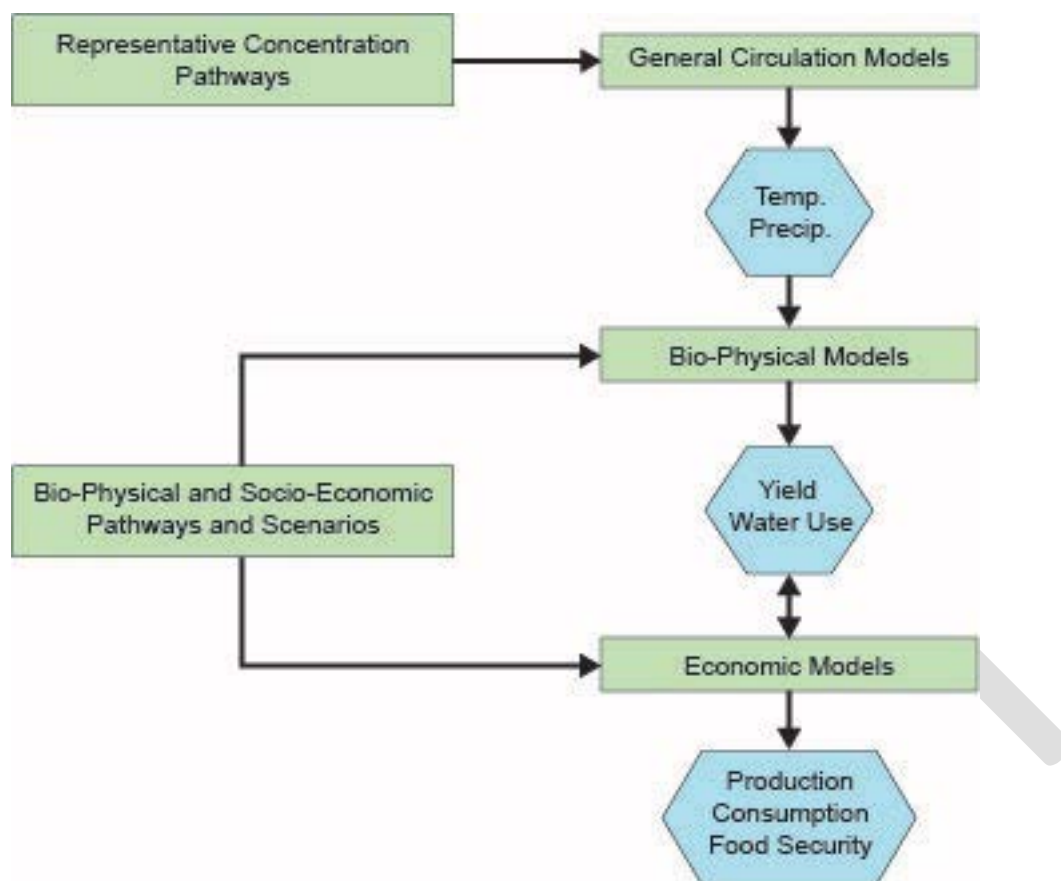
Previous chapters have described projections of climate and societal change and interactions of climate change and various elements of food security. Those chapters show that the global food system links farm production systems to consumers globally through a web of interconnected food systems. In this 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. Next we 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 “questions” about climate change: (1) What effects would a change in climate today have on the current food system? (2) What effects could 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

1 system perform in the future with climate change *and* adaptation? How would adaptation reduce
2 vulnerabilities and help exploit any benefits of climate change? As previously discussed, studies
3 addressing the first question can help to characterize current sensitivity and vulnerability, but are
4 of limited use in assessing future climate change effects. We therefore focus most of the following
5 discussion on studies addressing the later questions.

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



1

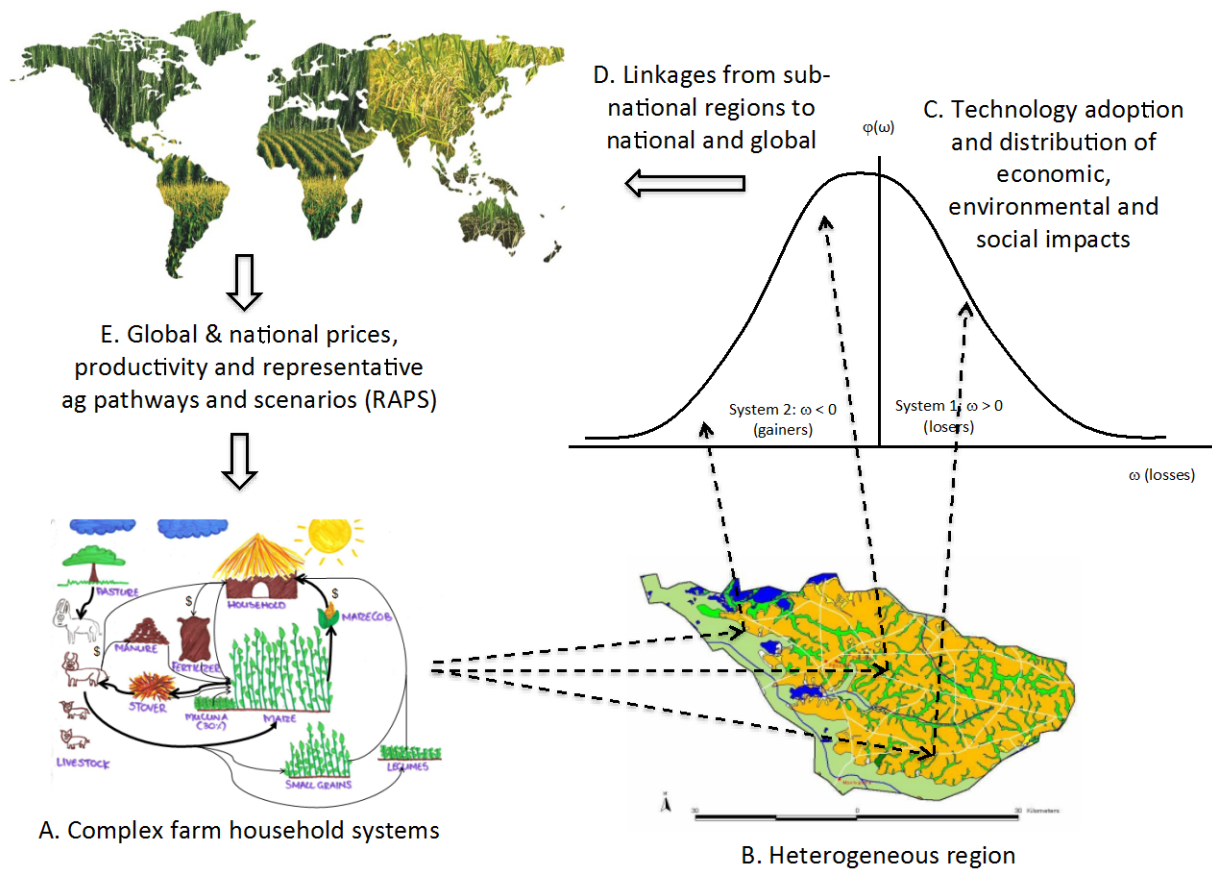
2 **Figure 4.1 Framework for integrated agricultural and food system impact assessments.**

3 *Models of global economic and biophysical system, driven by climate model outputs for different RCPs,*
 4 *are linked to assess outcomes under different future scenario. Source: Wallach et al. 2015.*

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

13 Global modeling systems generate outcomes such as food production and consumption at the
 14 national level or in multi-country regions and are thus relevant to food availability at those scales.

1 To achieve higher analytical resolution for outcomes such as poverty and food security, several
2 approaches have been developed. One approach is to link a global model to nationally
3 disaggregated data (Hertel et al. 2010). Alternatively, the Agricultural Model Intercomparison and
4 Improvement Project (AgMIP) has developed a coordinated global and regional approach to
5 integrated assessment of agricultural effects and adaptation to address the three questions
6 identified earlier (Antle et al. 2015). In this approach (Figure 4.2), climate projections of
7 temperature and precipitation from GCMs are downscaled and linked to globally gridded
8 biophysical models that simulate crop and livestock productivity effects. In addition, global
9 socioeconomic pathways and scenarios are used to construct projections of other inputs needed for
10 global agricultural economic models, such as productivity growth and trade policy. These global
11 models simulate production, consumption, trade, and land use for multinational or national regions
12 as well as market equilibrium prices. To obtain estimates of effects that are less highly aggregated,
13 for example, specific to geographic regions or socioeconomic groups, the prices and yields from the
14 global economic models are used as inputs into regional economic models. These regional models
15 can simulate outcomes such as the regional distribution of production, income, and poverty rates
16 and can be used to construct food security indicators (see section 4.6.2).



1

2 **Figure 4.2 The AgMIP Regional Integrated Assessment Framework.**

3 *Climate change impacts, adaptation, and vulnerability assessments are linked across scales, from the*
 4 *field and farm scale (A) to the landscape/subcountry scale (B), leading to analysis of technology*
 5 *adoption and impact assessment in heterogeneous farm household populations (C). This regional*
 6 *analysis may feed back to the country and global scales (D). The entire analysis uses consistent inputs*
 7 *and assumptions from global and national price and productivity projections and Representative*
 8 *Agricultural Pathways (E). Source: Antle et al. 2015.*

9 **4.2 BIOPHYSICAL MODELS**

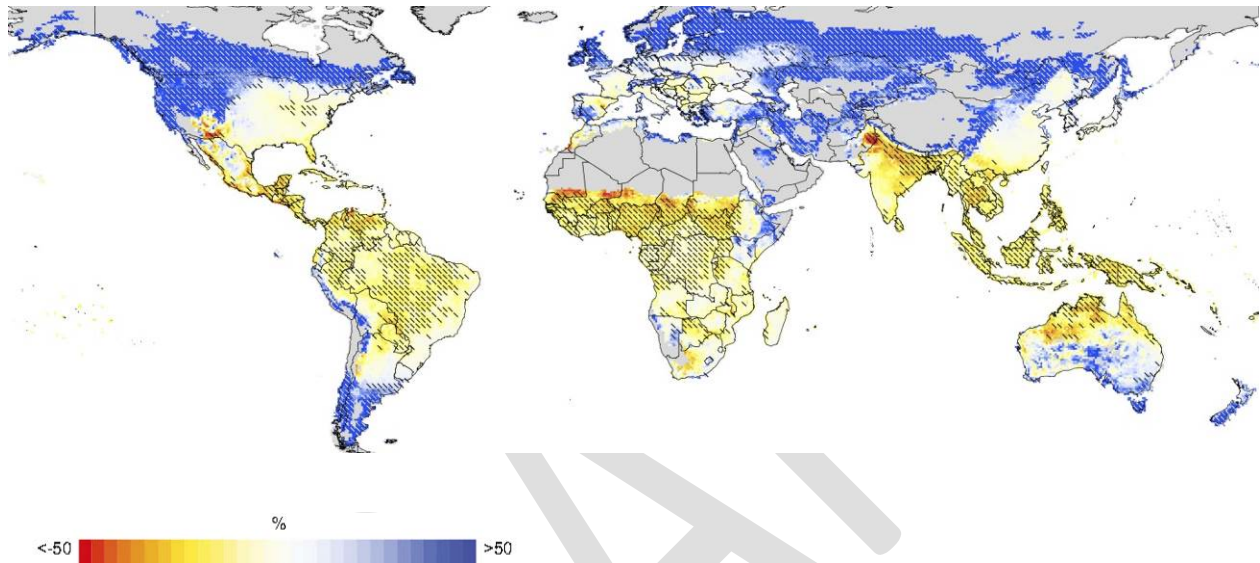
10 The biophysical component of the assessment framework shown in Figure 4.1 can involve several
 11 parts. First, regional climate models or downscaling of gridded GCM outputs to higher spatial and
 12 temporal resolutions are needed to serve as inputs to global gridded production-system models
 13 and regional gridded or point-based models. These biophysical models should, in principle,
 14 represent the major agricultural products, including crops and livestock, although thus far, most
 15 models have represented only major grain commodities, such as maize, soybeans, wheat, and rice,
 16 and some kinds of livestock. In addition, other components may represent water quantity, for

1 example, by linking an economic model such as IMPACT to a watershed model (Rosegrant et al.
2 2012). Similar model linkages may be done with a national or subnational model.

3 Biophysical crop and livestock models are an important tool in translating the biophysical
4 consequences of climate change (i.e., changes in temperature and precipitation) into yield changes
5 that give rise to economic impacts. The findings of a large number of such crop model simulation
6 studies is summarized in a recent meta-analysis that utilized over 1,700 studies of climate impacts
7 on crop yields (Challinor et al. 2014) and in the latest assessment report of the IPCC (Porter et al.
8 2014). Challinor et al. found that without adaptation, losses in aggregate production of about 2-10%
9 are expected for wheat, rice, and maize in both temperate and tropical regions relative to late 20th
10 century temperatures. Crop-level adaptations increase simulated yields by an average of 7%–15%
11 compared to yields modeled without adaptation, with adaptations more effective for wheat and rice
12 than maize. Yield losses were found to be greater in magnitude for the second half of the century
13 than for the first. Consensus on yield decreases in the second half of the century is stronger for
14 tropical than temperate regions, yet even moderate warming may reduce temperate crop yields in
15 many locations.

16 When set up to operate on a spatial grid corresponding to climate data, crop and livestock models
17 provide the expected changes in yield associated with downscaled future climate data generated
18 from the general circulation models (Jones and Thornton 2013). In recent model comparisons
19 (Rosenzweig et al. 2014, Warszawski et al. 2014), three broad types of crop models were identified:
20 site-based crop models, agro-ecological models, and agro-ecological zone models. While differences
21 in model types stem from the original purpose, scale, and parameterization of the models, the suite
22 of models analyzed showed similarities in how they respond to changes in climate. These recent
23 studies also indicate detrimental effects of climate change, especially at higher levels of warming
24 and at low latitudes. Models that include explicit nitrogen stress project more severe impacts (see
25 Figure 4.3 for the case of maize). Across seven global gridded crop models (GGCMs), five GCMs, and

1 four representative concentration pathways, model agreement on the direction of yield changes is
2 found in many major agricultural regions at both low and high latitudes. However, better
3 understanding of yield response to factors such as atmospheric carbon dioxide (CO₂ fertilization),
4 nitrogen applications, and high temperatures is needed to improve confidence in impact
5 assessments and to evaluate adaptation strategies.



6
7
8 **Figure 4.3 Median yield changes for RCP 8.5 (2070–2099) relative to 1980–2010.**
9 *Analysis includes CO₂ effects over five GCMs × seven GGCMs for rain-fed maize. Hatching indicates*
10 *areas where more than 70% of the ensemble members agree on the directionality of the yield change.*
11 *Gray areas indicate historical areas with little to no yield capacity. Source: Rosenzweig et al. 2014.*

12 There are also important limitations to these models that are the subject of ongoing research and
13 model improvements (Bryan et al. 2009, Mertz et al. 2010). For example, crop simulation models
14 can represent only some aspects of adaptation, such as changes in cultivars, planting dates, and the
15 use of irrigation. Another important limitation is that most models do not explicitly account for
16 pests and diseases. Crop models also have difficulty predicting response of yields to the timing of
17 rainfall and dry spells within a growing season (Baigorria et al. 2007, Lobell 2013, Ramirez-Villegas
18 and Challinor 2012). Despite these issues, biophysical models are providing useful insights into
19 potential effects of climate change on crop growth and yield.

1 **4.3 GLOBAL ECONOMIC MODELS**

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

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

17 **4.4 REGIONAL ECONOMIC IMPACT ASSESSMENT MODELS**

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

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

14 **4.5 Global Climate Impact Assessments for Agricultural Systems**

15 Most global agricultural assessments carried out over the past decade have utilized scenarios from
16 the IPCC Special Report on Emissions Scenarios together with corresponding data from the CMIP.
17 Some studies utilized “business as usual” trends, whereas others used scenarios with a range of
18 alternate plausible futures. The latter studies include the recently updated FAO World Agriculture
19 Towards 2030/2050 projections (Alexandratos and Bruinsma 2012), the reference world scenario
20 of the International Assessment of Agricultural Science and Technology for Development (IAASTD
21 2009), the baseline scenarios of the IFPRI Food Security, Farming, and Climate Change to 2050
22 report (Nelson et al. 2010).

23 ***4.5.1 Global Assessment Pathways and Scenarios for Agriculture***

24 In collaboration with AgMIP and the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP)
25 (Warszawski et al. 2014), a group of 10 major modeling teams completed the first global

1 agricultural economic model intercomparison of climate change impacts, in which all of the models
2 used a standard set of scenarios that combined RCP 8.5 with the population and economic growth
3 assumptions from two SSPs, two crop simulation models to project the impacts of climate change
4 on crop productivity, two bio-fuel policy assumptions, and one scenario with a lower price of oil
5 (Nelson and van der Mensbrugge et al. 2014, von Lampe et al. 2014). The goal of the model
6 comparison exercise was to understand the differences in model projections and behavior and to
7 identify their sources, rather than to choose scenarios for their plausibility. But they did use a
8 consistent set of assumptions for key driver variables, including productivity assumptions for crop
9 yields, energy price assumptions (based on crude oil price), and the production of biomass-based
10 energy. Importantly, these scenarios did not embody the effects of increasing CO₂ fertilization or
11 other effects of increasing CO₂ concentrations on crop yields and used climate projections based on
12 RCP 8.5, so in these dimensions they can be viewed as relatively pessimistic scenarios. However,
13 they did incorporate a relatively optimistic set of projected crop yield growth rates to represent the
14 impacts of ongoing productivity improvements, ranging from 1% to 2.5% for major crops (wheat,
15 coarse grains, rice, sugar, and oilseed) across the major regions of the world (von Lampe et al.
16 2014), so in this regard the scenarios can be viewed as somewhat optimistic.

17 To increase the relevance of socioeconomic pathways to agriculture, AgMIP has developed the
18 concept of *representative agricultural pathways* (RAPs) for both global and regional impact
19 assessment. RAPs are designed to be an internally consistent set of narratives and drivers for
20 integrated assessment of climate impact, adaptation, and vulnerability that can be linked to SSPs
21 (Valdivia et al. 2015). As an extension of the AgMIP/ISI-MIP global model intercomparison
22 (described previously) that was carried out with nine models, five of those global modeling teams
23 developed a set of RAPs corresponding to SSPs 1, 2, and 3 (refer to Chapter 3 for SSP definitions). In
24 addition to the economic growth, population growth, urbanization, and land-use assumptions
25 associated with the three SSPs, these RAPs involved a set of distinct agricultural assumptions for
26 yield growth and agricultural trade policy. The first RAP was thus associated with SSP1, RCP 4.5,

1 and a liberalized agricultural trade scenario; the second RAP was associated with SSP2, RCP 6.0,
2 and a neutral (business as usual) agricultural trade scenario; and the third RAP was associated with
3 SSP3, RCP 8.5, and a restrictive agricultural trade scenario (Wiebe et al. 2015). Results from these
4 RAPs are reported in section 4.5.3.

5 **4.5.2 Global Economic Model Projections and Implications**

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

10 Early interdisciplinary studies combined partial and general equilibrium economic models, crop
11 models, and climate models to make projections about future food supplies (Rosenzweig and Parry
12 1994, Rosenzweig and Iglesias 1994, Sonka and Lamb 1987). These studies projected that climate
13 change would cause an increase in the total number of people at risk of hunger relative to a world
14 absent climate change, though that number would represent a lower proportion of the total
15 population due to population growth over that time period (Chen and Kates 1994, Fischer et al.
16 1994, Fischer et al. 1996, Rosenzweig and Parry 1994). Subsequent studies refined projections but
17 did not substantially alter the implications of the earlier studies; however, they did emphasize more
18 adverse effects on developing countries in the tropics (Fischer et al. 2005, Parry et al. 2005). These
19 and more recent studies also demonstrated the differences that technological improvements and
20 overall income growth could play in reducing food insecurity and showed that those effects could
21 be much more important than climate change up to mid-century (Nelson et al. 2009 and 2010,
22 Porter et al. 2014). Thus, recent studies have shown that socioeconomic conditions play a major
23 role in determining vulnerability to climate change.

24 Global modeling studies simulate global and regional food production, prices, consumption, and
25 trade. To translate these effects into changes in food security, additional assumptions and analyses

1 are required. One approach used by global modeling studies is to develop statistical links between
2 projected changes in production or consumption to food security indicators. For example, Fischer et
3 al. (2005) utilized the correlation between the share of undernourished in the population (as
4 defined by the Food and Agriculture Organization) and the ratio of average national food supply
5 (including imports), relative to aggregate national food requirements, to assess the impacts of
6 climate change on food security. Based on this relationship (Figure 4.4), and using a set of
7 socioeconomic scenarios and GHG concentrations based on the SRES, Fischer et al. find that the
8 percentage of undernourished population approached zero in countries where food production
9 exceeds 160% of national requirements.

10 They also projected that a scenario of high GHG concentrations, high population growth, and
11 constrained economic development (the SRES A2 scenario, roughly similar to SSP3) would increase
12 in the number of people “at risk of hunger” finding that an additional 175 million people could be
13 undernourished in 2080 because of climate change (2.6% of the projected overall population of
14 food-insecure countries in 2080). The same socioeconomic conditions with CO₂ concentrations of
15 about 550 parts per million resulted in an estimate of up to 60 million additional people at risk;
16 concentrations of about 350 ppm did not result in an increased number of people at risk In the less
17 pessimistic SRES scenarios, declines in the risk of hunger over time due to socioeconomic change
18 outweigh increase in hunger risk due to climate change. Analyses based on hypothetical scenarios
19 of sustained economic growth and moderate population growth without climate change suggest
20 that the number of food insecure people could be reduced by 50% or more by 2040, with further
21 reductions over the rest of the century. Such analyses should not be interpreted as projections,
22 since climate change is already occurring, but they clearly indicate that socioeconomic factors have
23 large effects on food insecurity.

24



1 **Figure 4. 4 Estimates of undernourished population relative to food supply.**

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

6 Another example of an indicator used for economic outcomes on health and nutrition is the study
 7 by Nelson et al. (2010), which used per capita calorie availability from cereals and meat and an
 8 index of child malnutrition. This study used the IMPACT model, which estimates per capita calorie
 9 availability by country. The percentage of malnourished children under the age of five was
 10 estimated using average per capita calorie consumption, assuming that other factors (life
 11 expectancy, maternal education, and clean water access) are constant in all future scenarios.
 12 Investments in agricultural research, roads, and irrigation were used to alter calorie availability and
 13 child undernutrition estimates. The approach was to estimate the agricultural productivity growth
 14 needed to meet a nutrition or calorie availability target and then estimate the investment
 15 expenditures needed in research, irrigation, and roads to generate that productivity growth. As
 16 with the Fischer et al. (2005) study, a major limitation of this methodology is that it relies on data
 17 aggregated to the national level (in this case, calorie availability) and thus cannot represent changes
 18 in access, utilization, or stability among the population within countries.

19 Based on this methodology, Nelson et al. (2010) found that climate change and ongoing global
 20 development could contribute to price increases for the most important agricultural crops—rice,
 21 wheat, maize, and soybeans—and that higher feed prices result in higher meat prices. These price

1 increases are projected to reduce the growth in meat consumption slightly and cause a more
2 substantial fall in cereal consumption. Projections that combine climate change and pessimistic
3 socioeconomic conditions result in a decline in calorie availability in 2050 relative to 2000 levels
4 throughout the developing world. By 2050, this decline in calorie availability could increase child
5 under-nutrition in low-income developing countries by 20% relative to a world with no climate
6 change. More positive socioeconomic conditions result in less negative effects, but still produce less
7 improvement than cases with no climate change. In conclusion, this study shows that climate
8 change could reduce much of the improvement in child malnourishment levels that could occur
9 without climate change.

10 **4.5.3 AgMIP Global Results**

11 Some key findings of the AgMIP global agricultural model intercomparisons and related climate
12 impact assessments, based on nine global economic models, are discussed below and summarized
13 in Figures 4.5, 4.6, and 4.7 (Nelson and Valin et al. 2014, Nelson and van der Mensbrugghe et al.
14 2014, von Lampe et al. 2014, Wiebe et al. 2015). Figure 4.5 presents price projections for five
15 agricultural commodity groups (wheat, coarse grains, rice, oilseeds, and ruminant meat) for 2050
16 without climate change but includes other factors such as income growth, population growth, and
17 trends in agricultural productivity. This figure is useful because it shows how differently the nine
18 models perform in terms of projecting future economic outcomes such as prices. The figure shows
19 that some models project substantially higher agricultural commodity prices in the future relative
20 to those observed today; whereas other models show prices falling. Therefore, even without
21 imposing climate change on the agricultural economic models, a wide range of plausible future
22 price trends are possible, suggesting a high degree of uncertainty in these model projections,
23 distinct from climate change effects.

24 Figure 4.6 summarizes the projected results for the impacts of climate change, using the nine global
25 economic models in the AgMIP study. This figure shows results from seven different socio-

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

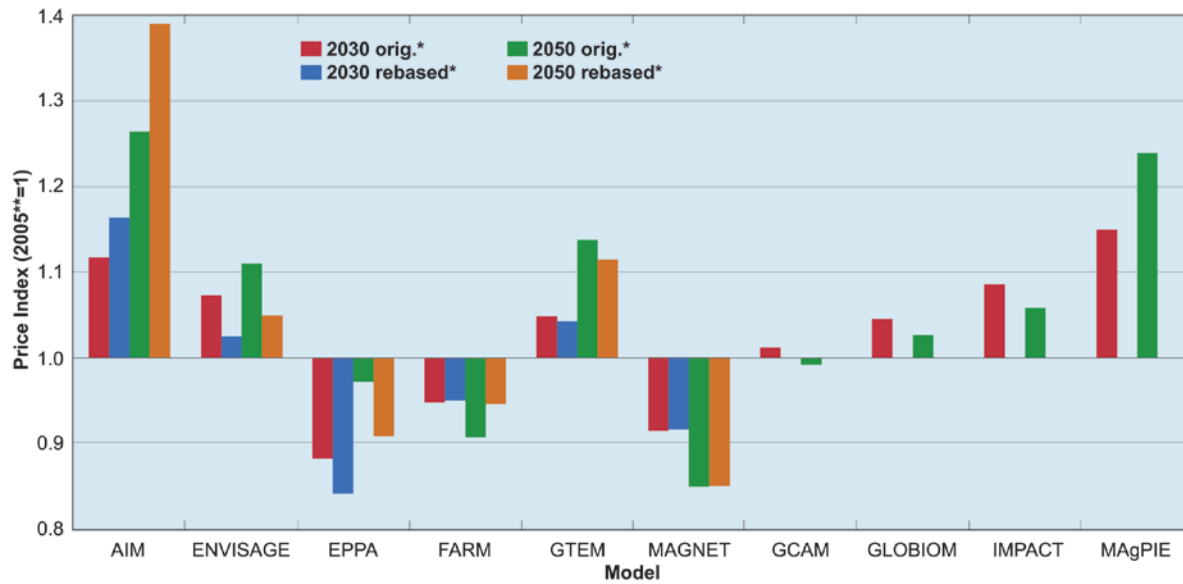
10 An important question for the U.S. food system is how these global projections for production,
11 consumption, trade, and prices compare to impacts on the U.S. When the results of the global
12 models are disaggregated by major regions of the world, the results show substantially the same
13 patterns as Figure 4.6, even though the impacts of climate change on crop and livestock
14 productivity is projected to be larger for regions such as Africa and South Asia. These findings
15 suggest that with largely integrated global markets and relatively free trade, the impacts of climate
16 change are likely to be distributed around the world through the offsetting effects of the market and
17 other economic adjustments.

18 As noted previously, the AgMIP global model intercomparison using nine models was extended to
19 an analysis of RAPs that were designed to be consistent with three SSPs, each combined with a
20 different assumed climate outcome (Wiebe et al. 2015): SSP1 with a medium level of climate change
21 (RCP4.5), SSP2 with somewhat more climate change (RCP6.0), and SSP3 with high climate change
22 (RCP8.5). Figure 4.7 summarizes the results of these projections for aggregate yield, area,
23 production, consumption, trade and prices from five economic models. The results show that there
24 are substantial differences between the “high concentration, high population growth, restrained
25 economic growth” scenario (SSP3/RCP 8.5) on the one hand and the “low concentration, low

1 population growth, high economic growth” and “medium concentration, medium population
2 growth, high economic growth” scenarios (SSP1/RCP4.5 and SSP2/RCP6.0) on the other. The high-
3 concentration, high population, lower economic growth scenario shows much larger climate change
4 effects than the lower-concentration scenarios, and also much larger differences across the models.

5 Yields are projected to decline by an average (median) of 7.2% in the high-concentration scenario,
6 while area increases by 3.8%, production and consumption decline by 0.9%, exports and imports
7 increase by 4.0% and 5.3% respectively, and prices increase on average by 15.5%. The price effects
8 vary more widely across the different crops and models than was the case for the other two
9 scenarios. Further analysis of the baseline scenarios suggests that the climate effects in 2050 of a
10 high-emissions scenario are stronger than the differences between the underlying socio-economic
11 trends, at least at the global level.

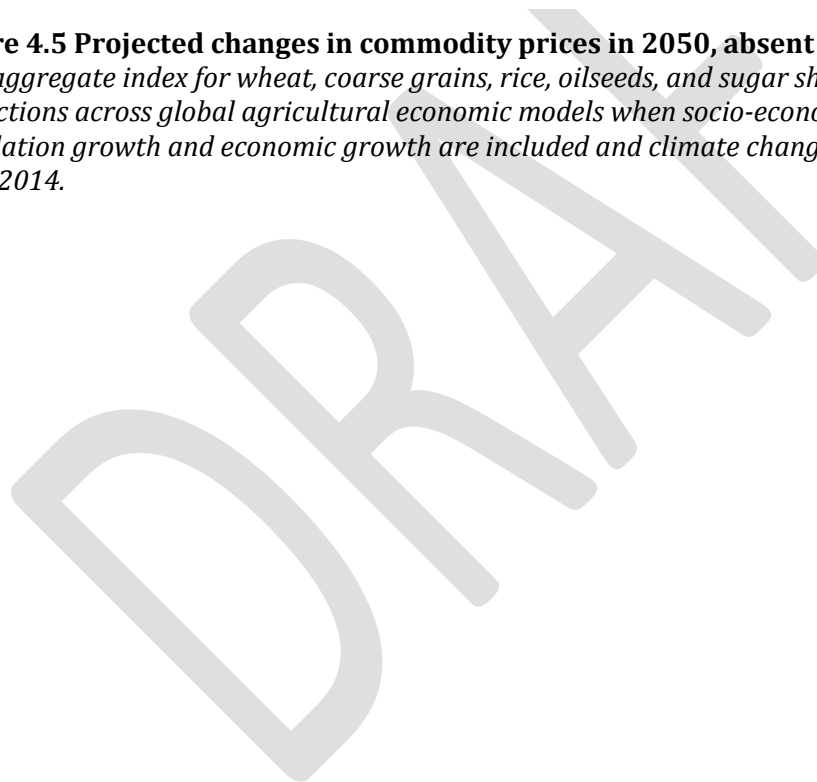
12 Wiebe et al. (2015) also show that in the case of low international cooperation and high
13 concentrations (SSP3/RCP8.5), restricting trade results in higher prices, and thus more adverse
14 consequences of climate change, and a larger spread across models. This result is what economists
15 would expect and shows that trade policy and other aspects of economic and political coordination
16 are likely to play a role in determining the impacts of climate change on global and regional food
17 security. However, it is important to note that the differences across scenarios cannot be attributed
18 to any single factor, as both climate and socioeconomic conditions change.

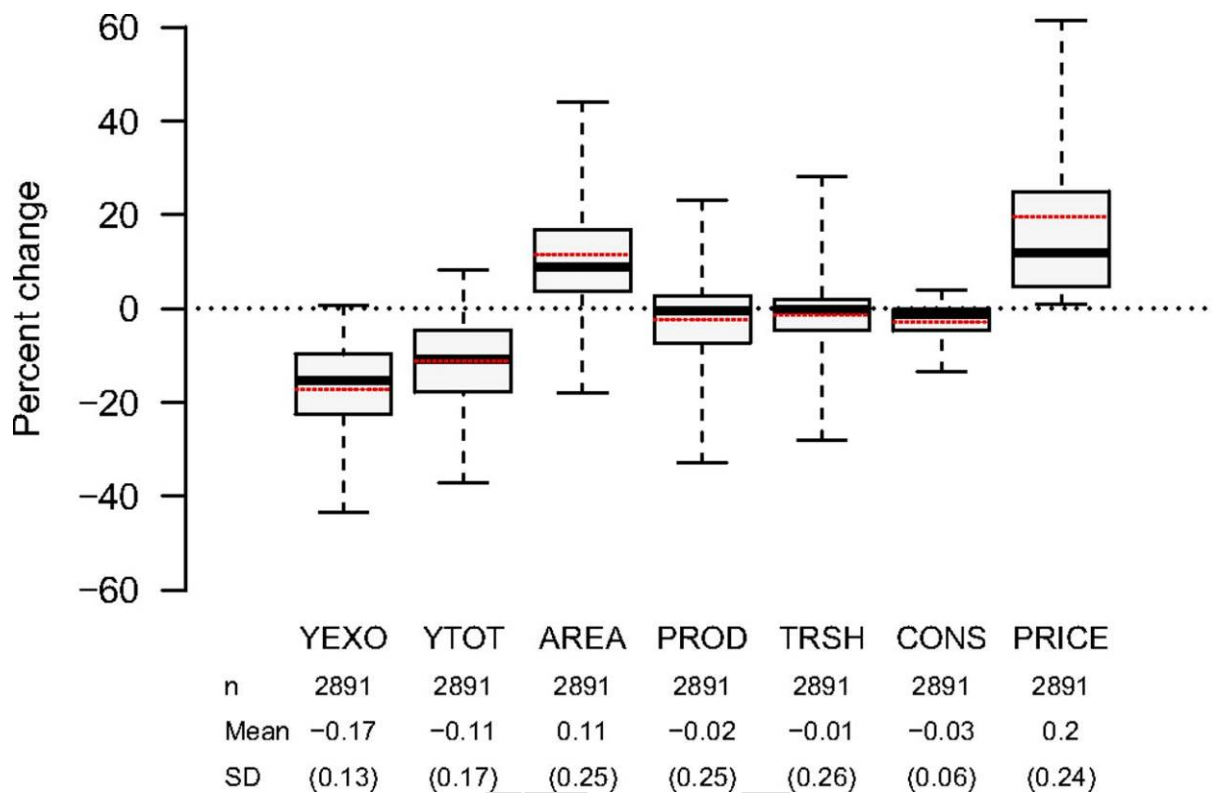


* original: relative to model-standard numeraire; rebased: relative to the price index for the global GDP
 ** trended 2005, i.e. hypothetical in the absence of short-term shocks

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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 socio-economic changes such as population growth and economic growth are included and climate change is not. Source: Von Lampe et al. 2014.



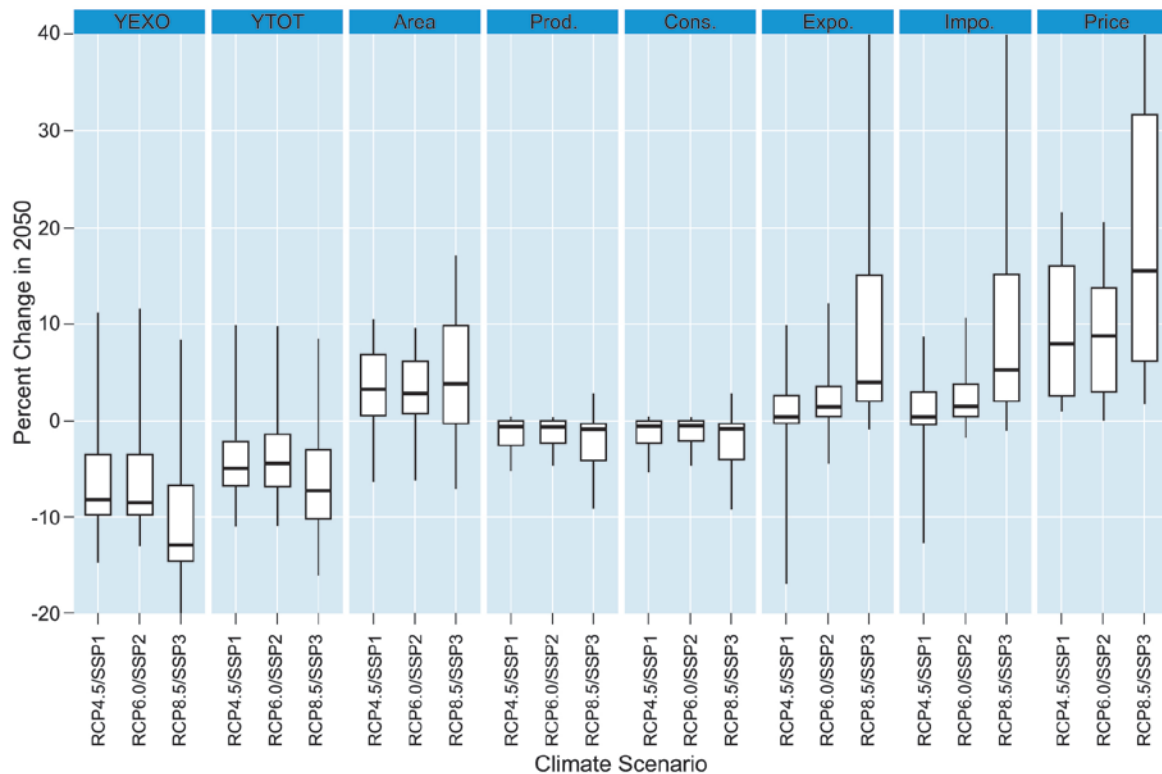


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2 **Figure 4.6 Change and variability of crop and economic model projections for 2050.**

3 *In 2050, lower average yields under climate change, either with (YTOT) or without (YEXO) climate*
 4 *adaptation management measures, result in higher prices (PRICE) for most agricultural commodities,*
 5 *in spite of increased land area under production (AREA). Adaptation measures reduce climate*
 6 *impacts on yields (YEXO vs. YTOT), while global production (PROD), consumption (CONS) and trade*
 7 *(TRSH) are not projected to dramatically change. Significant variability results from the study*
 8 *spanning 9 models, 4 crop aggregates, 7 crop models and socio-economic scenarios, and 13 regions.*
 9 *Source: Nelson and van der Mensbrugge et al. 2014.*

10



1
2 **Figure 4. 7 Climate change effects under different SSPs and RCPs.**
3 *The “high concentration / low international cooperation” scenario (RCP8.5/SSP3) shows much larger*
4 *and more variable climate change effects for the five commodities (coarse grains, rice, wheat, oilseeds*
5 *and sugar), with a more pessimistic development pathway, than the “medium concentration / middle-*
6 *of-the-road” (RCP6.0/SSP2) and “low concentration / sustainable development” (RCP4.5/SSP1)*
7 *scenarios. Results are from three GCMs and five economic models, aggregated across thirteen regions*
8 *(n = 75). YEXO = yield effect of climate change without technical or economic adaptation, YTOT =*
9 *realized yields after adaptation, AREA = agricultural area in production, PROD = total production,*
10 *CONS = consumption, Expo = exports, IMPO = imports, PRICE = prices. Source: Adapted from Wiebe et*
11 *al. 2015.*

12 **4.6 Regional Modeling Studies**

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

1 **4.6.1 Statistical, Econometric, and Integrated Assessment Studies**

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

10 Econometric models have also been used to assess the impacts on economic outcomes such as
11 farmland values and revenues. The findings of a study by Mendelsohn and Dinar (2009) on a
12 number of regions of the world suggest that agriculture in developing countries is more sensitive to
13 climate than agriculture in developed countries. This is consistent with the generally more adverse
14 effects of climate change on crop and livestock productivity in the tropics found in crop and
15 livestock modeling studies. Rain-fed cropland is generally more sensitive to warming than irrigated
16 cropland (Mendelsohn and Dinar (2009). The analysis of adaptation to climate change shows that
17 farmers are likely to make many adjustments, including switching crops and livestock species,
18 adopting irrigation, and moving between livestock and crops. The results also reveal that effects
19 and adaptations vary across landscapes, suggesting that adaptation policies must be location
20 specific. However, the focus of these studies on outcomes such as crop yields and farm revenues
21 limit their ability to provide direct information and assessment of food security outcomes.

22 The recent studies by Valdivia et al. (2012) and Claessens et al. (2012) illustrate the use of a
23 disaggregated regional integrated assessment approach and were the first regional studies to
24 utilize RAPs to project impacts under future socioeconomic conditions. These studies assessed
25 effects and possible adaptation strategies on the incomes and poverty of farm households in two

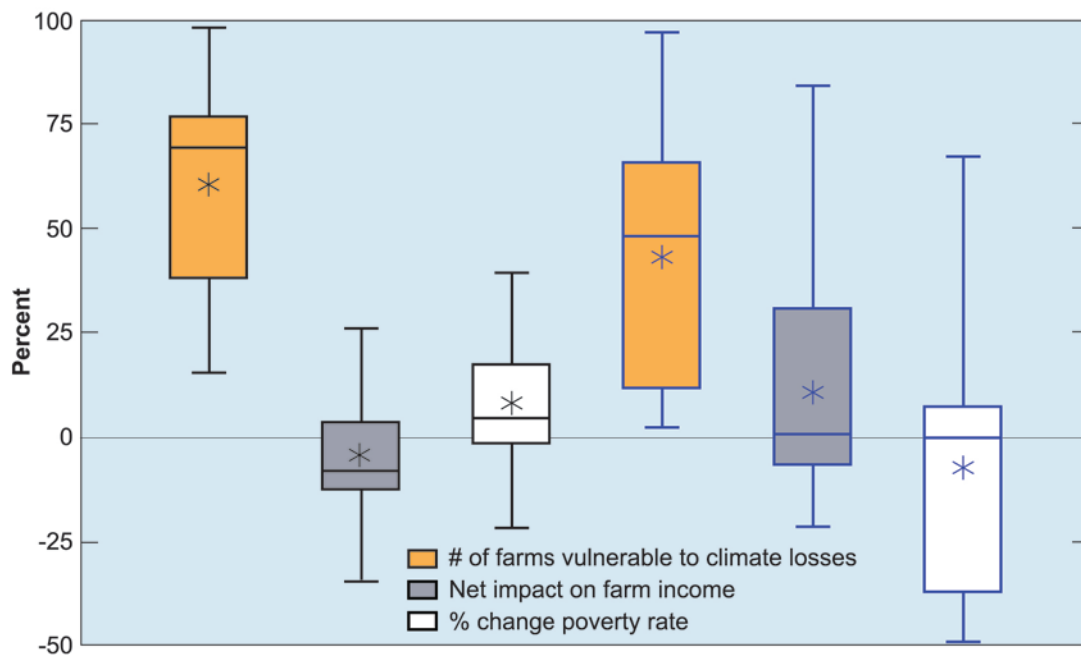
1 regions of Kenya. The studies showed that the adverse impacts of climate change could be largely
2 offset by feasible adaptations involving new crops and intensification of livestock production. Like
3 some of the global studies, these studies also demonstrated the important role that future
4 socioeconomic conditions are likely to play in determining vulnerability to climate change and the
5 value of adaptation. While these studies did assess the distributional effects of climate change on
6 income and poverty, they did not directly incorporate all of the factors, such as regional food
7 availability, utilization, and stability that would be needed to assess climate change effects and
8 adaptations for food security.

9 ***4.6.2 Regional AgMIP Studies of Africa and South Asia***

10 Regional assessments of climate change effects in Africa and South Asia, currently two of the
11 world's most food-insecure regions, have been conducted according to the methodology provided
12 in Figure 4.2, and are summarized in Figure 4.8 (Rosenzweig and Hillel 2015, Valdivia et al. 2015).
13 These assessments were carried out by regional teams that devised a RAP for each of the regions
14 corresponding to the middle-of-the-road global socio-economic scenario SSP2 (Valdivia et al. 2015).
15 Climate change was represented by five general circulation models selected to span the range of
16 climate uncertainty in the IPCC CMIP5 data with RCP 8.5. The RAPs were generally optimistic, being
17 based on the positive trends in productivity growth that were assumed in the AgMIP global model
18 inter-comparison study, as well as positive trends in agricultural prices projected by the IFPRI
19 IMPACT model due to increasing global food demand. The variation in each indicator shown in
20 these figures is due to the variation in climate projections as well as regional differences in bio-
21 physical and socio-economic conditions across the various study sites. Preliminary analysis of
22 adaptation strategies is reported in Rosenzweig and Hillel (2015), but is not included in Figure 4.8.
23 The AgMIP regional studies produced indicators of (a) vulnerability, defined as the number of farm
24 households that lose income due to climate change, (b) impacts on average (or net) per capita
25 income, and (c) changes in poverty, but did not include food security indicators. Figure 4.8

1 demonstrates that there is a wide range of vulnerability to climate change under current socio-
2 economic conditions, averaging about 70% across study sites. The figure also shows that under the
3 generally more favorable future socio-economic conditions defined by the regional RAPs,
4 vulnerability to climate change averages less than 50%, demonstrating that positive socioeconomic
5 developments could increase farm incomes and, in some cases, help to reduce vulnerability to
6 climate change and reduce poverty.

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



1

2 **Figure 4. 8 Summary of Regional Studies of Climate Change Impacts in West, East and**
 3 **Southern Africa and South Asia Under Current and Future Socio-Economic Conditions.**

4 *Adaptation is not considered in this figure. Bars show the range of outcomes from five climate*
 5 *scenarios, two crop models, and one socio-economic scenario (current and future) for various study*
 6 *areas in Africa and South Asia, boxes indicate quartiles, asterisks are averages. Boxes outlined in black*
 7 *(left side) outline indicate current socio-economic conditions, boxes outlined in blue (right side)*
 8 *indicate socio-economic conditions in mid-century based on “middle-of-the-road” SSP2 and*
 9 *corresponding regional RAPs. Source: Adapted from Rozenzweig and Hillel 2015.*

10 **4.7 Conclusions**

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

17 Global-scale food system models can be used to assess climate change effects on global and national
 18 food availability, but data are too aggregated to assess all of the important food security concerns
 19 related to access, utilization, and stability. More detailed data and models and additional model

1 inter-comparisons are needed to assess climate change effects on all dimensions of food security at
2 subnational, local, and household levels.

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

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

16

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 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 – a

1 producer who consumes the eggs from chickens that s/he has raised themselves. Or it may be quite
2 long and involve many intermediaries, such as the case of produce imported from the Southern
3 hemisphere during the Northern winter. Both cases illustrate food availability.

4 **5.1 Influences on Food Availability and Stability**

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

9 **5.1.1 Producing Food**

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

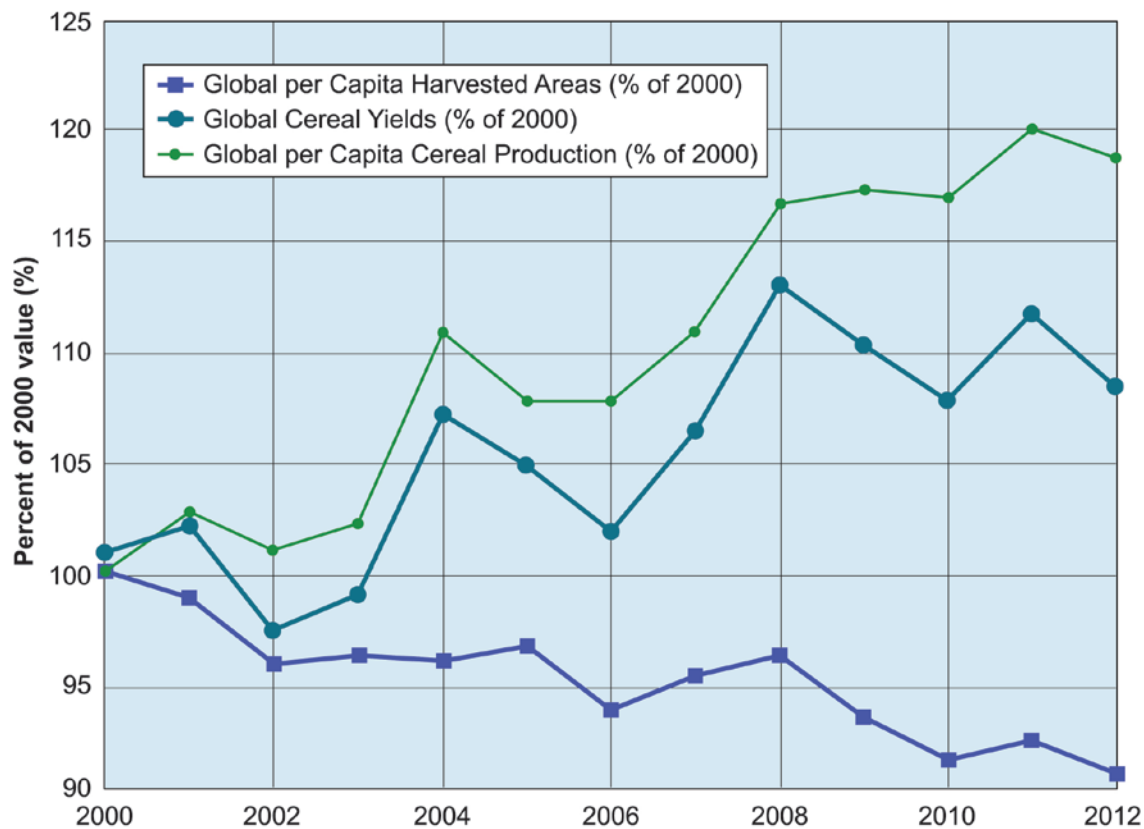
13 **5.1.1.1 Crop Production**

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

19 Agricultural cultivation has expanded gradually over much of the past 10 millennia, but
20 acceleration in productivity since the 1700s has enabled human settlement in most arable regions
21 of the planet (Toussaint-Samat 1992). The subsequent green revolution of the 1960s has resulted
22 in the intensification of management, agrichemical, and technical inputs; growth in trade and
23 economic output; changes in land use; and increased yields (Roberts 2008). Between 1961 and

1 2012, the annual growth in average global cereal production ranged between 0.3% and 4.0% (FAO
2 2014b).

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



1

2 **Figure 5. 1 Global cereal production, yield, and harvested area relative to year 2000.**

3 *Global per capita cereal yields have increased since 2000, even as the trend in per capita harvested*
 4 *area has decreased. Source: FAO 2014b.*

5 Since 2000, food production increases have been largely concentrated in countries such as Brazil

6 and China, primarily a result of biotechnology (Paarlberg 2013). In Sub-Saharan Africa,

7 investments in agricultural research and wider adoption of new technologies can lead to improved

8 production, though weak scientific capacity and support can hamper those efforts (Fuglie and Rada

9 2013), and the shrinking size of smallholder farms limits the viability of mechanization (Funk et al.

10 2008).

11 On global average, yields for the four most-traded food crops (maize, rice, wheat, and soybeans) are

12 stagnating or diminishing on 24%–39% of their growing areas (Ray et al. 2012), and the average

13 global yield growth rates for each (1.6%, 1%, 0.9%, and 1.3%, respectively) lag behind the increases

14 required to meet anticipated food production demands by mid-century (Ray et al. 2013) of a 60% -

15 100% increase in production (FAO 2009a). Production trends differ in different locations. Eastern

1 Asian rice and northwestern European wheat account for 31% of total global cereal production, but
2 yields in these regions are declining or stagnating as they approach their biophysical limits and face
3 pressures from land degradation, weather, and limits on fertilizer and pesticide use (Grassini et al.
4 2013). In the three largest rice-producing nations — China, India, and Indonesia — annual yield
5 increases are 0.7%, 1.0%, and 0.4%, respectively (Ray et al. 2013). Annual increases at this level
6 would increase in production increases of 67% for maize, 42% for rice, 38% for wheat, and 55% for
7 soybeans by 2050 in these important rice production countries (Ray et al. 2013), generally
8 inadequate to meet the anticipated need. In the three largest wheat-producing nations — China,
9 India, and the U.S. — yields have been increasing at annual rates of 2.7%, 1.1%, and 0.8%,
10 respectively (Ray et al. 2013). Wheat yields are in decline across much of Eastern Europe (Ray et al.
11 2013). In contrast to these plateauing yields in capital intensive systems, slow growth or
12 stagnation is occurring in many low-yield nations where farmers lack access to basic agricultural
13 inputs (e.g., fertilizers), infrastructure, markets, and extension services (Grassini et al. 2013).
14 Compared with major staple crops, less work has been done on specialty crops such as vegetables,
15 tree crops, fruit and ornamentals, livestock, or fish production, which can be particularly important
16 in developing regions (Zhang and Wilhelm 2011), and therefore represent an useful area for future
17 investigations.

18 In addition to these historical trends, climate and weather influence food production. Climate and
19 weather influence yields directly through physiological changes under varying temperature and
20 moisture levels, and indirectly by altering pest and disease pressures (Malcolm et al. 2012, Sexton
21 et al. 2009, Sutherst 2001).

22 Temperature, precipitation, atmospheric CO₂ concentrations, soil moisture, and nutrient
23 availability interact to determine and how successfully a crop will germinate, flower, and produce
24 seed (Badeck et al. 2004, Chmielewski et al. 2004, Tao et al. 2006). Different crop species and
25 varieties have varying abilities to cope with differing stressors (Chaves et al. 2002); climate change

1 and weather variability will therefore affect different crops, varieties, regions, and production
2 systems in different ways.

3 Each crop and variety has a range of optimal growing and reproductive temperatures, as well as
4 threshold temperatures beyond which the necessary physiological process cannot occur, and yields
5 suffer or cease (Walthall et al. 2012). While global yields are increasing, the effects of recent
6 climate trends may be slowing their growth. Changes in climate may be diminishing rates of yield
7 growth by up to 2.5% per decade, globally (Porter et al. 2014). Yields of corn, soybean, and wheat
8 in the U.S. increased with temperatures up to 29–32° C, depending on the crop, and then decreased
9 sharply for all three (Schlenker and Roberts 2009). Increased temperatures in China between 1980
10 and 2008 appear to have reduced yield growth rates for wheat and corn by approximately 1.5%,
11 though had little effect on the yield growth rates of rice or soybean (Tao et al. 2012). In India,
12 increasing minimum temperatures reduced rice yield growth rates by more than 5% between 1960
13 and 2002 (Auffhammer et al. 2012).

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

21 Increased temperatures have led to an earlier start to, and lengthening of, the global growing
22 season by 10–20 days over the twentieth century (Linderholm 2006, Körner and Basler 2010,
23 Sheffield and Wood 2012). Longer growing seasons can increase yields and allow for double-
24 cropping, particularly in temperate latitudes, provided that sufficient water and nutrients to
25 support additional growth are available, and provided that higher temperatures do not interfere

1 with a crop's cold temperature requirements for germination (vernalization) (Sinclair 1992) or
2 exceed physiological limitations. Warmer temperatures also increase rates of decomposition and
3 may lead to greater soil nutrient availability which can, in turn, increase yields (Melillo et al. 1993,
4 Kirschbaum 2004). Higher temperatures can shorten the time necessary for crop development, but
5 in doing so, may prevent the completion of seed fill and perversely, diminish yields (Harrison et al.
6 2011, Walthall et al. 2012). Early senescence triggered by extremely warm temperatures (greater
7 than 34°C) poses a documented risk to tropical wheat harvests, for example (Lobell et al. 2012).

8 In some regions, however, higher temperatures lead to a shortening of the growing season and to
9 reduced yields as physiological temperature or moisture thresholds are breached (Ericksen et al.
10 2011). In semi-arid zones where temperature and moisture are already approaching biophysical
11 thresholds, increasing temperature stress, an increasing number of dry days, highly variable
12 seasonal rainfall, and increasing rainfall intensity are expected to lead to growing season declines
13 that are important to food security outcomes (Ericksen et al. 2011). This is particularly true in
14 developing regions where local and regional production have a major bearing on food availability.

15 Changing precipitation patterns and variability influence production, and have been demonstrably
16 influential in many corn, soy, rice, and wheat-producing regions around the world (Lobell et al.
17 2011, Fallon and Betts 2010). In 2012, for example, the U.S. Midwest suffered a 13% drop in corn
18 yields following an extremely hot summer coupled with severe drought (NASS 2013). In both 2008
19 and 2013, severe flooding delayed corn planting in some areas of the Midwestern U.S., and drowned
20 already-planted crops (LeComte 2014). A shift to drier weather, together with expanded land area,
21 in the summer of 2013 in the same region, led to record high U.S. corn production that year (NASS
22 2009, 2014). In regions experiencing more rainfall, or more intense rainfall events, increased rates
23 of erosion lead to soil organic carbon and nutrient losses (Walthall et al. 2012). The net influence of
24 such precipitation changes depend on a variety of soil characteristics, physiological crop
25 characteristics, and the response of soil microbe communities (Nearing et al. 2005). Rates of

1 erosion, however, appear to increase disproportionately with annual average rainfall by a ratio of
2 approximately 1.7, indicating that the effects of soil erosion are likely to be important in affected
3 regions (Nearing et al. 2005).

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

9 Elevated atmospheric CO₂ concentrations allow plants to keep their stomata closed for longer
10 periods while still gaining sufficient CO₂ for photosynthesis, which results in improved water use
11 efficiency (Kirschbaum 2004). Elevated atmospheric CO₂ concentrations can also increase the
12 levels of plant residue entering soils, increasing soil organic matter (van de Geijn and van Veen
13 1993), though this effect is mediated by increased soil erosion rates brought on by more intense
14 precipitation in some regions, and more generally by diminished nutrient levels in plant tissues
15 (Walthall et al. 2012).

16 Temperature and precipitation, and atmospheric CO₂ together interact to affect production by
17 means additional to their individual effects described above. Higher average temperatures
18 associated with longer growing seasons increase rates of evaporation and evapotranspiration,
19 diminishing soil moisture stores and increasing crop moisture stress (Kirschbaum 2004, Trenberth
20 2011), even in regions where precipitation remains unchanged. The most severe droughts typically
21 result from a combination of rainfall deficits and abnormally warm temperatures (Trenberth
22 2011); droughts occurring in a warmer climate are of a greater intensity (Trenberth et al. 2014). Of
23 course, not all droughts are climate-change induced (Porter et al. 2014, Dole et al. 2011, Hoerling et
24 al. 2014), as history demonstrates. However, climate change does appear to increase the
25 probability of heat waves associated with drought events across much of the globe (Otto et al. 2012,

1 Knutson et al. 2013, Diffenbaugh and Scherer 2013), perhaps by a factor of four (Otto et al. 2012,
2 Rahmstorf and Coumou 2011, Knutson et al. 2013, Diffenbaugh and Scherer 2013). In East Africa,
3 for example, the drought of 2011 (Funk 2012, Lott et al. 2013) and the low precipitation levels of
4 2012 (Funk et al. 2013) have been linked to changes in climate.

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

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

20 Production changes resulting from changes in underlying climatic conditions can also interact with
21 stressors such as conflict, market stresses, or non-climate-related disaster conditions, to alter the
22 stability of food availability (Davis 2002, Watts 1983). In the 2011 Horn of Africa famine, for
23 example, multiple lower-than-average rainy seasons diminished crop harvests and available forage
24 in Ethiopia, Kenya, and Somalia. However, famine was declared only in one of those countries
25 (Somalia), where a militant group interfered with attempts to deliver adequate relief (Hillbruner

1 and Moloney 2012, Lautze et al. 2012, Maxwell and Fitzpatrick 2012, Menkhaus 2012). As a
2 consequence of the induced scarcity, the number of people selling household assets greatly
3 outnumbered buyers, so that the assets were not effective sources of income — income that could
4 have facilitated *access* to food through purchase rather than by direct production (Maxwell 1996,
5 Watts 1983). When the sold assets include livestock or other means of production, it reduces
6 future production capacity, and can lead to diminished food security outcomes long after the
7 transitory initial cause has passed (Lybbert et al. 2004).

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

16 *5.1.1.2 Livestock Production*

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

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

24 Livestock may also be raised separately, either indoors and fed with crops grown elsewhere (e.g.,
25 poultry houses), or raised outdoors on forage (i.e., grazing systems).

1 The livestock industry contributes over one trillion USD annually to the global economy (Thornton
2 2010). Since the late 1990s, livestock has grown more rapidly than other agricultural sectors, and
3 currently represents 33% of the GDP of developing countries (Thornton 2010). This growth is
4 associated with urbanization and income growth in developing regions (Delgado 2005). In places
5 like East Asia, poultry and swine production have expanded rapidly. The livestock sector plays an
6 important role in agricultural systems and is a critical source of protein and micronutrients;
7 however, comparatively little systematic assessment has been done relative to non-animal based
8 agriculture (Porter et al. 2014).

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

14 Heat stress from higher temperatures diminishes food intake and physical activity for livestock,
15 leading to lower growth, survival, and reproductive rates, as well as lower production of meat, milk,
16 and eggs (Nardone et al. 2010, Walthall et al. 2012, West 2003), though physiological
17 acclimatization is possible to some extent over time (Kadzere et al. 2002, Saxena and
18 Krishnaswamy 2012). Increasing temperatures require greater water intake; *Bos indicus* cattle, for
19 example, require 3 kg of water per kilogram of dry matter feed at 10 °C, but 10 kg of water per
20 kilogram of dry matter feed at 35 °C (Thornton et al. 2007). Indoor livestock (primarily poultry and
21 swine operations in developed countries) face increased heat stress and associated mortality in a
22 changing climate, absent adaptive measures to manage higher air temperatures (Turnpenny et al.
23 2001).

24 Climate change also affects livestock indirectly through disease and pests, pasture and forage crop
25 quality and quantity, and feed-grain production (Rötter and van de Geijn 1999, West 2003, White et

1 al. 2003, Thornton et al. 2009, Nardone et al. 2010). Temperature increases and precipitation shifts
2 may accelerate the development of certain livestock pathogens and parasites, along with
3 distribution of their vectors, exposing livestock to novel pathogens (Harvell et al. 2002, Thornton et
4 al. 2009, Pérez de León et al. 2012). At the same time, heat stress can weaken immune function in
5 livestock. Together this could require an increase in the use of veterinary medications (Nardone et
6 al. 2010, Tirado et al. 2010).

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

13 *5.1.1.3 Fishery Production*

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

20 Fisheries are dynamic social-ecological systems affected by many non-climate stressors that are
21 particularly important for food security, including rapid market changes, exploitation, and
22 governance (Daw et al. 2009). The combined effects of competition for resources, pollution,
23 overfishing, habitat modification, acidification, and temperature and other climate-driven changes
24 on small-scale fisheries and aquaculture in these regions are likely to be damaging to fishery health
25 and sustainability, resulting in decreased incomes for fishing families (affecting food *access*), and

1 overall reductions in food availability for fishing communities (HLPE 2014). Current methods of
2 analysis cannot distinguish the relative importance of each influence upon fishery health (IPCC
3 2014a).

4 Climate-driven changes in water temperature, salinity, and dissolved oxygen content affect the
5 physiology and behavior of wild fisheries species, as well as that of their predator and prey species,
6 affecting population dynamics and distribution (Walther et al. 2002, Roessig et al. 2004, Brander
7 2007, Brander 2010, Ottersen et al. 2001). Warmer weather caused by El Niño offers a glimpse into
8 potential effects of warmer weather on fisheries (Mysak 1986, Fromentin and Planque 1996,
9 Wespestad et al. 2000). An increase in warmer-water fish species in response to higher water
10 temperatures is observed at higher latitudes, and decreases in subtropical species have been
11 observed in the tropics (IPCC 2014a, Cochrane et al. 2009). Short-term changes in fish species type
12 and population size result in changes in fishing opportunities, operational costs, and sales prices,
13 with increased risks of damage or loss of infrastructure and housing for communities relying on
14 marine resources (FAO 2008b). El Niño/La Niña events themselves may also be influenced by
15 climate change, with trends suggesting more frequent warm events since 1977 (McGowan et al.
16 1998), making the changes described above more probable in the future via more frequent
17 oscillations.

18 Climate change has been linked to permanent shifts in the distribution of fish species in wild
19 fisheries. For example, over a span of 25 years, Perry et al. (2005) found that of 36 species of North
20 Sea deep-water fish, 21 shifted their centers of distribution northward or to deeper waters to
21 follow colder water. Temperature increases also affect the food sources of fisheries species by
22 increasing productivity in cooler regions and decreasing productivity in warmer regions
23 (Richardson and Schoeman 2004). Such changes diminish food availability and access for the 90%
24 of capture fishers who are employed by small-scale fisheries (FAO 2012b). Aquaculture allows for a
25 greater degree of control over growth conditions than capture operations in wild fisheries, but

1 nonetheless remains vulnerable to climate pressures, including shifts in water temperature and
2 chemistry, water availability, disease prevalence, damage from extreme events and sea level rise,
3 and changes in fishmeal availability as feed from capture fisheries (Brander 2007).

4 Elevated atmospheric CO₂ leads to higher levels of acidity in both wild and cultured fisheries.
5 Higher acidity prevents the formation of calcium carbonate shells and skeletons in important
6 fisheries species and their predators, leading to population declines with continued acidification
7 (Cooley and Doney 2009).

8 *5.1.1.4 Wild Game*

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

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

22 Much research to date has focused on game species in the Arctic, which is experiencing some of the
23 most rapid and severe climate change on earth, and is home to a large community of subsistence
24 hunters (Arctic Climate Impact Assessment 2004). In Greenland, for example, earlier spring

1 warming has led to a mismatch with caribou's arrival on their calving range, leading to higher
2 offspring mortality (Post and Forchhammer 2008). Inuit communities that rely heavily on caribou
3 as a food source have also observed changes in caribou migration patterns, body condition, and
4 meat quality associated with changes in the Arctic climate (Wesche and Chan 2010).

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

12 *5.1.1.5 The Natural Resource Basis of Food Production*

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

23 At the other end of the spectrum, indigenous and other communities that have close cultural and
24 geographical ties to traditional or wild food production systems are affected by changes in the
25 natural resource base. Shifts resulting from climate change affect the range and distribution of

1 traditional food sources, leading changes to food availability and the cultural appropriateness of
2 available foods (i.e., *food utilization*) (Lynn et al. 2013). Land management and administrative
3 restrictions can hamper the harvest and production of food sources following geographical shifts in
4 where food sources are available (Dougill et al. 2010).

5 Soils provide a substrate and nutrients for plant growth, while mediating water supply and quality;
6 their health is therefore paramount to the underlying ability of ecosystems to produce food
7 (Walthall et al. 2012). A soil's nutrient levels, organic matter content, physical structure and depth,
8 pH, microbial community, and contaminant load determine its productive capacity (Brady and Weil
9 2008). Each is subject to alteration through changing climatic conditions and management
10 practices. Changing temperatures and precipitation patterns alter nutrient turnover rates and
11 consequent plant availability. Soil organic matter better holds water to provide more water to
12 growing crops during drought conditions compared with low organic matter soils (FAO 2005), and
13 influences microbial dynamics and nutrient availability. More intense rainfall events can erode
14 soils and reduce organic matter concentrations, along with altering a soil's physical structure and
15 depth (Walthall et al. 2012). Intensification of agricultural practices may further exacerbate these
16 effects by affecting soil compaction, levels of soil organic matter and nutrients returned to soils, and
17 the concentration of salts and other chemical constituents (Power 2010, Huang et al. 2011,
18 Montgomery 2007).

19 The water cycle is also affected by climate change (IPCC 2007b, Haddeland et al. 2014, Rudorff et al.
20 2014, Barnett and Pierce 2009, Immerzeel et al. 2010, Elliott et al. 2014). Livestock systems are
21 conditioned to respond to seasonally available moisture from precipitation, springs, or
22 groundwater aquifers; or through management of water resources through various well and
23 reservoir developments and therefore respond to changes. Seasonal availability of water may be
24 affected by temperature trends that influence snowmelt timing and rapidity, as well as changes in
25 the timing, amount, seasonality, type, and intensity of precipitation. Precipitation effects may be

1 exacerbated by higher temperatures that increase moisture losses through evaporation and
2 transpiration (Jiménez Cisneros et al. 2014).

3 Regions that use melting snow to supply water to growing crops are vulnerable to climate change
4 as higher temperatures induce earlier peak flow, which leads to reduced water availability in
5 summer and fall. In this situation, irrigation can help to regulate water supply where the necessary
6 reservoir infrastructure exists, though it is not without its limitations. Irrigated Asian rice systems,
7 for example, have experienced increased salinity in the soil and irrigation water (Wassmann et al.
8 2009). Elliott et al. (2014) conclude that even where adequate irrigation water supplies exist, they
9 may be unable to offset greater warmth when combined with reduced precipitation. Changes in the
10 underlying conditions and “natural” surrounding ecosystems influence food production, even with
11 adaptation (Zhang et al 2007).

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

21 The effects of climate change on water availability and food security differed substantially among
22 five important South Asian basins in one study (Immerzeel et al. 2010), upon which 1.4 million
23 people depend. The study estimates that the food security of 60 million people, particularly in the
24 Brahmaputra and Indus basins, are susceptible to anticipated changes in the hydrology of those
25 areas.

1 Agricultural production is based on the natural resources of soil properties and availability of water
2 (Porter et al. 2014). Production systems are managed to alleviate stresses due to soil degradation,
3 reduced soil fertility, pests and disease, and impaired water resources to enhance crop and animal
4 sources of production. Land and water resources have been developed over centuries to meet the
5 regional and local needs (Vandermeer and Perfecto 2012). With the advances of the “green
6 revolution,” agricultural production has been enhanced through technological advances (Pingali
7 2012). However, competition for land and water resources is emerging as a consequence of
8 population growth (Lambin and Meyfroidt 2011, CNA Military Advisory Board 2014); climate
9 change will further affect production systems (Porter et al. 2014, Hatfield et al. 2014). Intensifying
10 agricultural production given available land and water resources, while managing multiple
11 demands and reducing damage to the natural resource base, will be more challenging in a changing
12 climate (Tschaert et al. 2008, Ojima et al. 2009, CNA Military Advisory Board 2014).

13 ***5.1.2 Processing, Packaging, and Storing Food***

14 Processing, packaging, and storing food are frequently prerequisites for it to reach its ultimate
15 consumers. They are present in many food systems, enabling fresh and safe food provision to
16 consumers who may be distant from agricultural areas. Food supply chains are becoming
17 increasingly globalized, with retailers engaging with smallholders (farms with fewer than two
18 hectares) across countries and income levels (Lee et al. 2012).

19 Food processing preserves and adds value to agricultural products (Simon and Thirion 2013).

20 There are two general categories of food processing: Primary and secondary. Primary processing
21 includes actions such as cooling to extend shelf life, and milling. Secondary processing makes
22 agricultural products more readily edible. Secondary processing can also add significant economic
23 value to harvested goods (Meléndez Arjona and Uribe 2012), for example by creating bread from
24 wheat (FAO 2004), corn meal from corn (Simon and Thirion 2013), oils from tree crops (Poku

1 2002), tomato sauce from raw tomatoes (Issahaku 2012), and hot sauce from peppers (Meléndez
2 and Uribe 2012).

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

14 Another example of climate’s influence is the location of processing and packaging facilities,
15 which are often located near the original production site for cost, convenience, and regulatory
16 reasons (FDA 2006). As production shifts to reflect changes in climate, the location of processing
17 facilities will also need to move (Hatfield et al. 2014). For example, corn growing in regions where
18 it historically has not been cultivated requires nearby processing and transport facilities to handle
19 the increased bulk (Petrolia 2008).

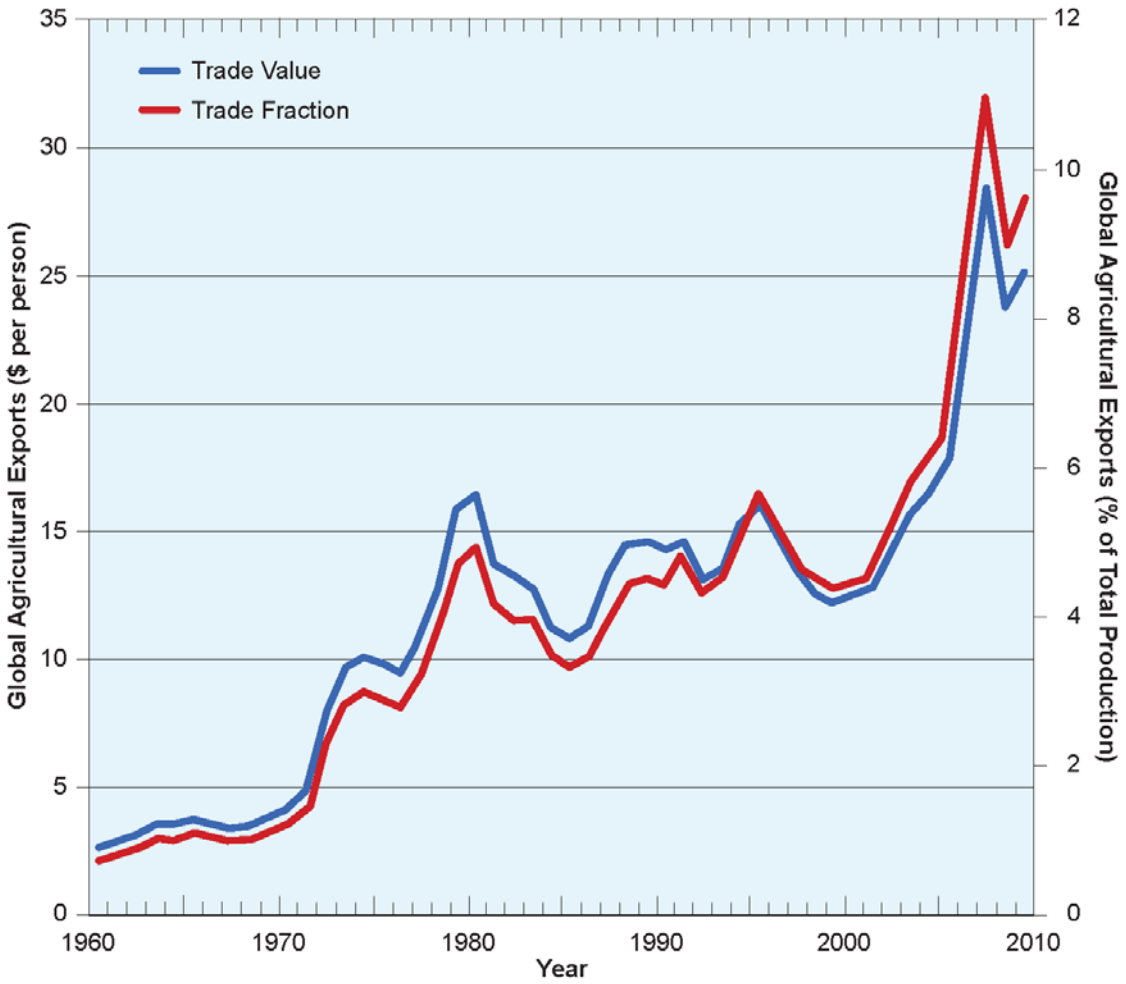
20 The effects of climate change on food processing are a function of multiple choices being made
21 simultaneously among different actors within the food system, and determined by the rapidity of
22 climate change, structural changes within the food system, and changes in consumptive demands.
23 From 1961 to 2007, global average per capita food consumption increased from 2250 kilocalories
24 per person per day, to 2750 kilocalories per person per day; the biggest caloric increases were in
25 the categories of cereals, vegetable oils, and animal products (Kastner et al. 2012). Changing

1 dietary composition is also important, and may become more important than population growth as
2 a driver of agricultural expansion and trade in the near future (Kastner et al. 2012). Urban
3 consumers in West Africa, for example, increasingly demand processed foods that are ready to use,
4 nonperishable, and do not require a great deal of preparation (Simon and Thirion 2013). These
5 foods are often imported, and the lack of domestic supply has led to transitory supply shortages
6 and influenced prices, leading to declines in food intake and higher rates of food insecurity
7 (Becquey et al. 2012).

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

15 ***5.1.3 Trading and Transporting Food***

16 Following production, food is sold to off-farm interests and ultimately to consumers. The role of
17 trade has been growing. For instance, Japan now relies on imports to meet 75% of its annual cereal
18 consumption needs, compared to 26% in 1961 (USDA 2015). In this way, trade influences food
19 availability. Global cereal and meat exports have climbed 27-fold since 1961, and are now worth
20 approximately 192 billion USD a year, or 8%-10% of the total value of global production (Figure
21 5.2). Global trade linkages can provide consumers with access to nonlocal foods, while providing
22 producers a means to earn money through geographically far-reaching trade networks (Bellemare
23 2012).



1

2 **Figure 5.2 Historical trend in global per capita global cereal and meat exports.**
 3 *Global per capita cereal and meat exports have increased as a proportion of total production since*
 4 *1961, reflecting the increased relevance of trade to food availability and stability. Source: FAO 2014d.*

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

10 Transportation is an intermediate activity linking each food system activity. Multiple climate
 11 variables can influence transportation systems and the foods they carry. Transporting food is
 12 particularly sensitive to extreme weather events through damages to infrastructure, such as

1 flooding and storm surge. While immediate effects on the transportation system may be temporary,
2 disruptions can affect food availability, food safety, and impair just-in-time food distribution
3 networks (Wu and Olson 2008, Koetse and Rietveld 2009). Heat waves stress transport systems, as
4 food needs to be moved faster and/or the cold chain needs to be strengthened to avoid spoilage.

5 Extreme weather can influence food transport in vulnerable locations (e.g., along coastlines, near
6 rivers), particularly when maintenance has not taken changes in climate into consideration
7 (Mashayekh et al. 2012). Low water levels in rivers and lakes force inland waterway vessels to use
8 only part of their maximum capacity, which can reduce the export capacity of nations and
9 producers (Attavanich et al. 2013). Storm surge, river floods, and extreme weather affect food
10 transportation and supply chain integrity through effects on sea ports (Becker et al. 2013, Blake et
11 al. 2013). For perishable foods, lack of a cold chain or refrigerated transport can result in large
12 losses due to spoilage, particularly under higher temperatures (Choudhury 2006, Mittal 2007).
13 Intense precipitation increases accident frequency in land transport, and decreases traffic speed
14 (Maze et al. 2006, Brijs et al. 2008). Heavy rains lead to flooding of transportation infrastructure
15 (e.g., roads, railways) and mudslides that can interfere with continued food availability (McGuirk et
16 al. 2009).

17 Regional and national disparities in production, whether chronic or generated by shocks, have
18 resulted in an increasing trend, particularly in less developed nations, to adopt international trade
19 for overcoming food deficits (Jafry 2012). When an area experiences a food shortage, prices rise.
20 This shortage attracts food from areas of surplus production, helping to improve food availability in
21 the area of the shortfall (OECD 2013). Consumers benefit from increases in trade through a greater
22 variety of foods, increased competition, and lower prices. Trade benefits agricultural producers, as
23 well, by supporting their income through sales of surplus production and by improving productivity
24 by providing lower-priced or more varied production inputs, such as seed, fertilizer, pesticides, and
25 machinery (Hebebrand and Wedding 2010, OECD 2013). On a broader scale, trade also helps

1 generate economic growth, boosting households' income and their means to purchase food, while
2 enabling countries to earn foreign exchange for food imports (Schiavone 2010, Cline 2004).

3 However, such a highly linked system also creates the means for distant events, including climate
4 and weather events like heat waves and droughts, to generate local food shocks that are far
5 removed from the site of the original disturbance (Abbott and Battisti 2011). Rapid urbanization
6 compounds this possibility, as millions of people have become more dependent on markets for their
7 primary food supplies (Berazneva and Lee 2013, Porkka et al. 2013).

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

1 Flooding and temperature extremes (IPCC 2012) are examples of climate and weather influencing
2 the stability of food *availability* by hindering the movement of food from its place of production to
3 consumers, by altering food prices in response to changes in the price of transportation (*access*),
4 and by increasing the likelihood of food contamination (*utilization*).

5 **5.2 Adaptation for Food Availability and Stability**

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

9 Adaptive capacity is mediated by a broad set of socioeconomic drivers (Morton 2007). It is limited
10 by the physiology of crops and livestock, research and development, technology adoption, the
11 ability to convey timely and appropriate information to stakeholders, and social issues (Kane and
12 Yohe 2000, Kates 2000). These factors suggest a wide variety of potential strategies to respond to
13 changes in climate, including insurance, engineering responses, land-use allocation changes,
14 management and policy responses, and research and development solutions (Kandlikar and Risbey
15 2000). Depending on income level and access to resources through government and institutional
16 supports, individual actors in the food system may respond to different drivers and prioritize
17 different actions, with climate being just one of many challenges needing to be overcome at a
18 particular time (Risbey et al. 1999).

19 Factors affecting on-farm adaptive capacity under climate change include access to varietal traits
20 that thrive in changing environmental conditions, soil characteristics that improve water-holding
21 characteristics, successfully accessing water for irrigation, and information (Porter et al. 2014).
22 Producers invest in new agronomic practices and genetic resources with the goal of buffering
23 detrimental climate effects or taking advantage of changes to remain profitable (Zilberman et al.
24 2004, Kurukulasuriya and Mendelsohn 2008, Crane et al. 2011). Indicators that specific elements of
25 the food system are not adequately adapting to climate and other stressors (Lemos et al. 2013, Zhu

1 et al. 2013) include soil degradation, falling productivity, and movement beyond ecosystem
2 thresholds that alter functionality (Le Houerou 2002, Moseley 2003, Wessels et al. 2004, Berry et al.
3 2009).

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

12 Challenges to food availability and its stability have already been observed as a result of climate
13 variability and change – food production, processing, packaging, storage, transport, and trade all
14 have dependencies upon temperature, precipitation, and their timing and distribution (IPCC
15 2014b). Food system actors participate within specific environments, using specific tools and crop
16 or livestock varieties suited to a particular environment and available within their means. Because
17 production systems are “optimized” in this way, changes in the surrounding circumstances will
18 require adaptation and altered management practices. As climate change accelerates, food
19 availability is expected to face greater challenges in responding to changing patterns of yield and
20 productivity, production costs, and resource availability (Walthall et al. 2012). The food system will
21 require significant investment to adapt crop production technologies, or apply them in new places
22 (Malcolm et al. 2012). Similar challenges are expected for other elements of the food system that
23 support food availability – processing, packaging, storage, transportation, and trade (Ericksen
24 2008).

1 Farmers have already adopted practices and strategies to reduce the damaging effects from
2 drought, floods, high temperatures, and other climate effects on food production (Malcolm et al.
3 2012), and have significant technical flexibility to adapt to changes in local weather, resource
4 conditions, and price signals by adjusting crop types, locations, rotations, structural modifications,
5 and management practices (FAO 2011b). That said, the existence of technical fixes to maintain or
6 improve food availability under changing conditions is not a guarantee of their application, which
7 may be limited due to lack of knowledge of a technology, social constraints to its application, or
8 financial limitations that prevent a producer or other actor within the food system from obtaining
9 or maintaining it (Kane and Yohe 2000, Kates 2000, Affholder et al. 2013, Tatsumi et al. 2011).

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

19 Smallholders represent 85% of all farms in food-insecure nations, of which 87% are located in Asia
20 (Nagayets 2005, FAO 2013a). Smallholder farmers, in addition to the landless and urban poor, are
21 one of the most disadvantaged and vulnerable groups, with the least ability to respond to climate
22 change and severe weather events through investment in new crops, insurance mechanisms, and
23 inputs to maintain production (IFAD 2001, Majid 2004). Investments in agricultural research, a
24 wider adoption of new technologies and policy reforms can lead to improved production; support

1 for these innovations remains generally low in many areas where smallholders are predominant
2 (Fuglie and Rada 2013).

3 Geographic shifts in production areas are expected as a result of climate change (Lobell et al. 2008).
4 It is not necessarily the case, though, that production increases in some regions (e.g., northern
5 latitudes) can fully compensate for production decreases elsewhere (e.g., tropical latitudes) (Funk
6 and Brown 2009). The world's production of rice and wheat, for example, are geographically
7 constrained by factors such as temperature, precipitation, seasonality, and daylight. Shifting
8 production to new regions in response to changes in these parameters, however, may not fully
9 compensate for lost production (Gourdji et al. 2013).

10 Diverse varieties may be one adaptive approach to managing such shifts in the underlying
11 environmental conditions for production. Successful breeding enabled the rapid expansion of hard
12 red winter wheat across substantial climatic gradients—hot, dry, and cold—in North America
13 during the 20th century (Easterling et al. 2004). Unexploited germplasm can continue to push
14 environmental margins for maize production (Easterling et al. 2004, Carena 2013), for example,
15 much research has focused on improving drought and salt tolerance in food crops (Parida and Das
16 2005). Attempts are underway to collect and protect the genetic diversity of a portfolio of plants
17 that have the characteristics required to adapt food crops to climate change (Dempewolf et al.
18 2014). Such gene banks are critical to the success of future breeding aimed at expanding plant
19 abiotic tolerances. In livestock systems, a delicate balance must be preserved between mining the
20 genetic diversity of native species through breeding programs to develop animals that are better
21 suited to meet expected drought and nutrition challenges, while at the same time maximizing feed
22 conversion efficiencies (Hoffmann 2010).

23 Genetically modified (GM) organisms may also be used toward these ends, as one of multiple
24 solutions aimed at meeting the world's food needs while managing biodiversity, recreation, and
25 ecosystem services (Godfray et al. 2010, Borsari et al. 2014). Commoditized monocropping in much

1 of the globalized food system has resulted in a narrower genetic base for plant and animal
2 production, which may consequently be more susceptible to climate-related threats (Knudsen et al.
3 2005, Young 2013). Enhancing genetic resources, whether through better use of genomics or
4 genetic modification, is important to increasing on-farm resilience to climate change and weather
5 extremes. A range of strategies including GM organisms, enhanced breeding systems, and multi-
6 crop management schemes have the potential to enhance resilience to changes in climate (Jacobsen
7 et al. 2013, Lin 2011).

8 Not all adaptive strategies are universally applicable, however. Heat abatement technologies for
9 livestock are many, but costly from infrastructure and energy perspectives; those costs increase
10 under higher emissions scenarios (do Amaral et al. 2009, Key et al. 2014). Solar radiation, wind,
11 stocking rate, and design will determine the capacity of the building and its livestock to adapt to
12 weather fluctuations and a changing climate (Cooper et al. 1998). The magnitude of improvements
13 needed will vary geographically and in some cases improvements will not prevent considerable
14 economic loss, or will be cost ineffective. For poultry, heat abatement is not economical for broilers,
15 while for layers it is optimal across the U.S. (St-Pierre et al. 2003). This finding would vary based on
16 the livestock type, location of the operation, and economic circumstances; it cannot be applied
17 globally, but exemplifies the specificity and range of considerations where adaptation is called for.
18 The rapid development of the livestock systems in developing countries presents a number of
19 challenges due to a combination of intensified environmental effects and the need for enhanced
20 infrastructure to accommodate the increase in livestock production, especially with swine and
21 poultry (Herrero and Thornton 2013). Recent attention has been focused on developing and
22 implementing sustainable intensification practices associated with expanding animal-sourced
23 products. The demands of beef and swine production for maize and soybean as animal feed
24 highlight some of the challenges faced by intensification efforts (Herrero et al. 2013, Eshel et al.
25 2014).

1 Competition for resources may also diminish adaptive capacity. Competition among different end
2 users for water resources (e.g., agriculture, urban areas, and industry) likely diminishes available
3 water in regions that depend heavily upon irrigation for crop or livestock production (Elliott et al.
4 2014). This type of competition reduces adaptive capacity, particularly in arid regions.

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

19 Transportation of food commodities can be highly vulnerable to climate variability and change, but
20 substantial adaptive capacity exists to manage those risks, particularly in developed countries.
21 Alternative transportation routes, for example, have at times allowed for compromised or
22 disrupted routes to be bypassed, saving producers who had access to those alternatives from
23 significant financial losses while maintaining food distribution functions that generate food
24 availability (Changnon 1989). The use of containers in food trade offers significant advantages over
25 other bulk methods by improving loading efficiencies, and allowing the product to remain

1 untouched from origin to destination, representing a potential adaptation where container ships
2 may dock given changing conditions (O'Reilly 2012).

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

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

17 Corporations have taken notice of the effects climate change can have on food production and the
18 life of a product from farm to consumer. Their assessments are often given in reports to their
19 shareholders and through other public documents. The J.M. Smucker Company ("Smuckers"),
20 which purchases coffee from 25 million farmers worldwide and is one of the four largest coffee
21 companies globally, announced in 2012 a sustainability plan focused on addressing the challenges
22 of climate change on coffee production and for the underlying ecosystem services that support it
23 (Smuckers 2012). In its 2012-2013 Corporate Social Responsibility and Sustainability Report,
24 McDonalds Corporation, for example, states that it is committed to maintaining safe food

1 temperatures through careful food handling (McDonalds 2014), representing one mechanism for
2 adaptation within the food system.

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

10 Sustainable intensification is one means of meeting the challenges to food availability (Tilman et al.
11 2002) — producing more food while minimizing the environmental effects of doing so (Garnett et
12 al. 2013). Sustainable intensification’s three premises are (a) increased production through (b)
13 higher yields rather than land conversions, and (c) long-term environmental sustainability on equal
14 terms with higher productivity. The concept does not specify the techniques to be employed.

15 Diverse approaches, including capital intensive, conventional, high-tech, agro-ecological, or organic,
16 as well as more labor-intensive systems are to be rigorously assessed, with biophysical and social
17 contexts taken into account (Garnett et al. 2013). An example is management that promotes long-
18 term increases in soil organic matter and relies on landscape-scale strategies such as rotational
19 diversity, cover crops, and perennialization (Gregorich et al. 2001).

20 **5.3 Measuring Food Availability and Stability**

21 There are two general methodological categories for assessing food availability. One category
22 involves large-scale production and import/export estimates, the balance of which is then scaled to
23 population. This can provide a high-level indicator of food shortages or excesses, but cannot
24 identify distributional discrepancies at the sub-national scale, and also misses important food
25 insecurity indicators as a consequence. The second measurement category involves household-

1 level surveying to identify consumption patterns and shortages. These methods better represent
2 food availability at the highly relevant household and community scales, but cannot always account
3 for within-household distributional discrepancies and, tend to underestimate overall consumption.
4 The resource-intensiveness of survey methods limits the ability to maintain continuous records,
5 and samples may not always scale to accurately reflect broader conditions. Each measurement type
6 is discussed in further detail below.

7 At the national level, food availability includes products from either domestic or foreign sources
8 (i.e., domestic production or imports), as well as any carryover stock from the previous year.
9 Production can be used for food or nonfood purposes including fuel, fodder, and fiber (Maxwell
10 1996). Because food availability is composed of many different food system components acting and
11 reacting simultaneously, the measurement of food availability typically must integrate several
12 different measures.

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

21 At the national scale, additional information is provided by low-tech agricultural surveys and area-
22 frame sampling. There has been a recent recognition of the need to strengthen these systems and
23 the Global Strategy to Improve Agricultural and Rural Statistics has been developed with
24 participation from international organizations, national governments, and donors (SPARS 2014).

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

7 This measure of food supply simply provides an overall average, but cannot account for
8 distributional effects or variations within a population. To understand differences in availability
9 *within* countries, regions, and even communities, food availability is usually estimated through
10 short-term food consumption surveys, or by looking at food production and food stocks and
11 assuming that the difference between the two represents food consumed (Maxwell 1996). There
12 are several challenges associated with the measurement of availability within populations. First, the
13 differences observed within a given population, particularly at subnational levels down to the
14 community or household, are often a product of access limitations rather than availability.
15 Separating the influences of access and availability on food security outcomes requires site-specific
16 investigation. Further, even the best surveys tend to underestimate consumption and produce
17 estimates that are quite sensitive to survey design (Deaton 1997); this is especially true of
18 household expenditure surveys (Godfray et al. 2010). In contrast to household expenditure surveys,
19 individual and household food-intake surveys are somewhat more accurate, though they still tend
20 to underreport actual intake (FAO 2003, Frankenberger 1992, Smith et al. 2006, de Weerd et al.
21 2014). Finally, few countries have reliable estimates of intrahousehold food waste; this is
22 particularly true of low-income countries (Godfray et al. 2010).

23 The challenges of estimating domestic food availability are important, as estimates of per capita
24 consumption of calories and nutrients are constructed from these supply estimates. For example,
25 the FAO's Food Balance Sheets (FAO 2001) estimate the per capita supply of dietary energy,

1 protein, and fat provided by each food item and by all food items combined. Measuring food supply
2 in terms of energy (calories) and focusing the analysis on staple foods such as coarse grains rather
3 than documenting nutritional composition and adequacy of food is common. However, particularly
4 as incomes grow, dietary composition shifts toward finer grains or from finer grains toward other
5 items such as meat, fish, and dairy (Bennett 1941, Becquey et al. 2012, Popkin 1998, Drewnowski
6 and Popkin 1997). Consequently, the FAO's Food Balance Sheets become increasingly
7 uninformative as populations become more affluent.

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

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

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

8 While official trade is relatively straightforward to track, informal cross-border trade is much
9 harder to capture. Exchange is difficult to monitor in small markets that do not participate in
10 international commodity trading (Fafchamps 2004). Informal, or unofficial, unreported trade could
11 represent a significant portion of total trade in some regions, particularly Sub-Saharan Africa. In the
12 case of Cameroon, for example, Nkendah (2010) found that its unrecorded, informal agricultural
13 exports to neighboring countries in 2008 totaled 38 billion CFA francs, or 96% of official trade. In
14 other words, almost half of total (official plus unrecorded) agricultural exports from Cameroon
15 were not captured by official trade data. And in Somalia, despite closed borders with both Kenya
16 and Ethiopia, unofficial trade in cattle continued and expanded between 1990 and 2003 (Little
17 2005). Exchange can also occur within families or ethnic groups in different countries, without
18 being reflected in standard international trade monitoring means (Aker et al. 2010, Fafchamps
19 2004).

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

1 **5.4 Conclusions and the Future**

2 Food availability is determined by a number of factors described in this chapter. Despite the
3 inherent difficulties, it is feasible and prudent to anticipate that the factors determining food
4 availability will not operate in a static fashion, nor will they operate independently of one another.

5 The inclusion of climate change into this discussion adds another set of interacting conditions
6 which precludes highly specific predictions. However, there are tendencies that can be used to
7 understand the pitfalls, barriers, and/or opportunities where a simple single path-dependent
8 analysis would not alone allow for, due to the complex set of interconnected operations and
9 processes at work in food systems globally.

10 This section addresses lessons and conclusions about the future of food availability and its stability,
11 based on the available literature investigations. Subsection 5.6.1 combines information from the
12 rest of this chapter with the Shared Socioeconomic Pathways described in Chapter 3 of this volume,
13 allowing the report's authors to identify sensitivities under climate change given a range of
14 development pathways.

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

1 Food availability and its stability are highly dependent on relatively stable climatic conditions.
2 Changes in the occurrence of weather and climate extremes are already detectable in many regions
3 (Zhang et al. 2011, Coumou and Rahmstorf 2012, Donat et al. 2013, Zwiers et al. 2013, Coumou and
4 Robinson 2013), and even under lower emission scenarios, higher frequency of some extremes
5 such as very hot days, very dry days, and intense rainfall events may be anticipated (Tebaldi et al.
6 2006, Kharin et al. 2007, Wuebbles et al. 2014), which can influence the seasonal availability of
7 food. Variability in food supply is most likely to affect populations that have less capacity to absorb
8 food shortages over short periods of time, potentially increasing the prevalence of transient food
9 insecurity, particularly if increased variability occurs in the absence of increased incomes to
10 compensate for reduced availability through trade mechanisms (Tiwari et al. 2013, Grace et al.
11 2013, Cornia et al. 2012).

12 The effect of climate change on crop productivity is projected to be mixed in the near term, with
13 detrimental effects becoming more pronounced and geographically widespread over the longer
14 term and with higher emission rates (Schlenker and Lobell 2010). A recent meta-analysis of over
15 1700 studies found that in the absence of adaptation, losses in aggregate production are expected
16 for wheat, rice, and maize in both temperate and tropical regions at 2 °C higher average growing
17 season temperatures, with adaptive measures improving outcomes substantially (Challinor et al.
18 2014).

19 Regional variation is expected, and important to food availability. Crop production is expected to
20 increase in high latitudes and decline in low latitudes (Snyder et al. 2001, IPCC 2007c, IPCC 2007a,
21 Ericksen et al. 2010). The geographic center of U.S. production of maize and soybeans, for example,
22 shifted northward by 160-225 kilometers between 1950 and 2010 (Attavanich et al. 2014), and
23 other regional northward shifts have also been observed (Reilly et al. 2003, Olesena et al. 2011,
24 Tolliver 2012). Significant yield decreases are likely in mid-latitude regions of Africa and South
25 Asia, however, particularly under high-emissions scenarios (Schlenker and Lobell 2010, Knox et al.

1 2012). Hotter average temperatures affect crops through speeding rates of crop development and
2 evapotranspiration, but extreme temperatures can cause damage that is not typically captured by
3 models, particularly during flowering and the reproduction phase (Gourdji et al. 2013). Mid-
4 latitude regions that already have a high mean temperature may also experience yield reductions if
5 they experience heat waves during the critical period of a crop reproductive cycle (Teixeira et al
6 2013).

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

14 All effects are likely to become increasingly pronounced in the latter part of the century, as
15 cumulative emissions grow (Rosenzweig et al. 2013). To 2050, most studies show a small average
16 crop yield decrease globally from a changing climate; this is true even for high-emissions scenarios,
17 because over that relatively short timescale, projections are similar (Rosenzweig et al. 2014,
18 Warszawski et al. 2014). Beyond that, the projections diverge demonstrably based on scenario, and
19 changes are more readily discernible (Challinor and Wheeler 2008), with more detrimental
20 outcomes expected for higher emissions scenarios.

21 Livestock operations in regions requiring high water inputs are likely to be the first to experience
22 livestock production reductions from climate change (Hornbeck and Keskin 2014). Differing
23 responses are expected in different types of livestock systems (Seré and Steinfeld 1996). Mixed
24 crop/livestock systems may face trade-offs between land and water allocations for their crops and
25 for livestock, including the need to supply feed that may have been grown and purchased elsewhere

1 rather than grown on-site (Thornton et al. 2009). Such choices will be influenced by economic and
2 cultural considerations, and prices and property ownership will alter management alternatives.
3 The design of animal housing facilities may increasingly need to consider disease and pest
4 occurrences, and the nutritional needs of the livestock may shift. Trade-offs made between income,
5 food security, and environmental objectives in the livestock sector will influence future outcomes
6 (Thornton et al. 2009).

7 Fish protein will remain important in coming decades, particularly for low-income and vulnerable
8 populations (HLPE 2014). As fishery management develops characteristics of terrestrial food
9 production, and relies increasingly on aquacultural methods over wild-caught fish, the ability to
10 adapt to changes in climate is likely to improve (Boyd and Brummet 2012, World Bank 2013). The
11 World Bank (2013) projects 2% annual average increases in aquaculture fish production between
12 2010 and 2030 (World Bank 2013), though considerable uncertainties exist (Brander 2007).

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

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

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

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

20 Future food availability during climatic shifts and stresses is largely determined by adaptive
21 capacity within the food system, and dependent in many ways upon choices made by actors within
22 the food system. Climate-controlled food storage infrastructure, road systems, and market
23 structures that lack adequate supply during the months preceding harvest are important
24 determinants (Vermeulen and Campbell et al. 2012, Hillbruner and Egan 2008, Handa and Mlay
25 2006), and how each is managed will influence outcomes. Lower emission scenarios with more

1 moderate temperature increases would require fewer large-scale changes than higher emission
 2 scenarios.

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

7 **5.4.1 Food Availability and Stability in the Context of Shared Socioeconomic Pathways (SSPs)**

8 Climate change affects food availability through its key food system elements, with differing effects
 9 under differing socioeconomic trajectories. To illustrate the range of possible outcomes, this
 10 section considers the food production, trade, transport, storage, packaging, and processing for each
 11 of the Shared Socioeconomic Pathways (SSPs) introduced in Section 3.4 of this volume. Many parts
 12 of the food system are not considered by the SSPs or by available modeling frameworks directly;
 13 however, this discussion reflects the informed judgment of its authors based upon the literature
 14 discussed previously in this chapter.

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

15 **Figure 5. 3 Relative risks to key food availability elements for different SSPs.**
 16 *The risks to food availability would be lowest under the economic conditions described by SSP 1 and*
 17 *SSP 5, with poorer nations at higher risk across all food production, distribution and trade categories*
 18 *for all SSPs. Shading represents higher or lower risks for each SSP from climate change. Risks are*
 19 *based upon this report’s authors’ consideration of the available literature.*

20

1 ***Producing Food***

2 The risks to crop production posed by climate change would be greatest under SSPs 2, 3, and 4.

3 Under these scenarios, as yield increases weaken due to reduced agricultural investment and

4 increasing land degradation, extensification onto arid land and areas with more variable climate is

5 likely to continue or increase. This trend exposes producers to more variable and limiting climate

6 conditions. It is therefore likely that under SSPs 2, 3, and 4, variability in temperature and rainfall

7 would increase challenges to local availability for some areas. Under SSPs 3 and 4, this challenge

8 could be particularly pronounced, as those living in the poorest countries under these scenarios are

9 likely to lack access to agricultural technologies that could offset some climate variability effects on

10 production in more arid and marginal lands.

11 The risks posed by climate change to crops would be lowest for SSPs 1 and 5. Under these SSPs,

12 gradual intensification would likely be the principal means of increasing yields. With technological

13 investment and development seen as high priorities, extensification is unlikely to take place in a

14 manner that results in increased production in arid or highly variable environments, lowering the

15 overall exposure of crops to climate stressors under these scenarios.

16 Patterns of climate-related stress on livestock production under the different SSPs are similar to the

17 patterns seen for crops, in part because livestock husbandry depends upon crops for feed in many

18 regions. Wealthy countries, with robust economies and food production systems would have

19 livestock production systems that are more resilient than those in poorer countries. Under SSP 1,

20 although incomes rise, the rate of increase in livestock production and consumption slows as

21 society shifts toward less resource-intensive means of generating calories. That shift, driven by

22 broadly held societal goals of greater sustainability, leads to a livestock sector closely tied to locally

23 available resources. Under SSP 5, relatively open markets and strong investment in technologies to

24 address climate change effects would likely manage most anticipated effects on livestock

1 production. However, the increased likelihood of climate change effects that exceed technological
2 solutions makes agricultural production under this scenario more precarious than under SSP 1.

3 The remaining three scenarios present more significant challenges for agricultural production, and
4 demonstrate that those in wealthy countries are not immune from potentially damaging climate
5 change effects. Under SSP 2, imperfect markets and increasing environmental degradation would
6 likely affect feed prices, making production of cattle and large ruminants less economically
7 sustainable. Under SSPs 3 and 4, markets function even more poorly, making it nearly impossible to
8 effectively smooth out the price impacts of climate shocks that affect local feed supplies. Such
9 events may force at least temporary reductions in herd size, and could result in the abandonment of
10 the husbandry of particular animals.

11 ***Processing, Packaging, and Storing Food***

12 Under nearly all SSPs, climate change is expected to have limited effects on the storage, processing,
13 and packaging of food in wealthy countries. In poorer countries, however, different SSPs produce
14 different outcomes. Under SSPs 1 and 5, investments in education and health generally lead to more
15 hygienic and reliable food storage, processing, and packaging. These outcomes appear more
16 durable under SSP 1, where the increased focus on human well-being creates broader societal
17 conditions under which food storage, processing, and packaging are seen as important
18 contributions to well-being, and investments in these processes and technologies outstrip the
19 effects of climate change. Under SSP 5, food safety gains are predicated on the generation of wealth
20 through the consumption of fossil fuels, which over time are likely to lead to significant climate
21 changes and shocks that can undermine education and health investments under those pathways.

22 In both cases, improvements to storage, processing, and packaging can help to maintain or even
23 improve food availability and stability, even with climate change.

24 Under SSP 2, there are fewer investments in education or health, and a limited social emphasis on
25 human well-being as a metric for successful policy outcomes. Investments in storage, processing,

1 and packaging proceed unevenly and slowly, exposing populations to increased levels of unsafe
2 food. Under SSPs 3 and 4, investments in education and technology decline over time relative to
3 other concerns. As poorer countries struggle to provide sanitary water, improved sanitation, and
4 appropriate healthcare to their populations, the changing climate would expose weaknesses in food
5 storage, processing, and packaging processes that contribute to unsafe or low quality food. Under
6 SSPs 2, 3, and 4, climate change is more likely to lead to higher rates of spoilage and contamination.

7 ***Trading and Transporting Food***

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

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

1 away from poorer populations, and low-functioning markets would inhibit trade to areas of deficit
2 created by this pattern of consumption.

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

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

14

CHAPTER 6: FOOD ACCESS AND STABILITY

Key Chapter Findings

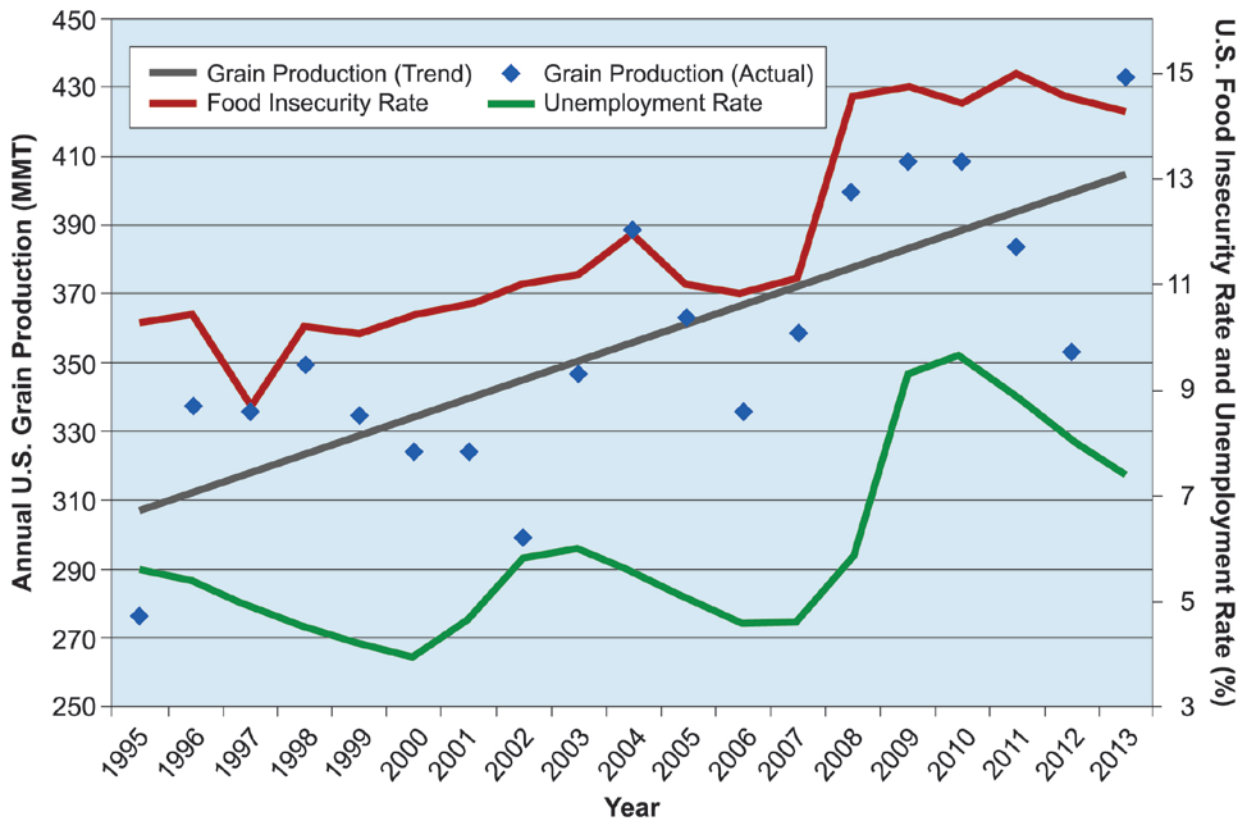
- **Climate and weather have demonstrable effects on food prices, and consequently food access and its stability.**
- **Food access is influenced by multiple factors, both inside and outside the food system; within the food system, trade and wholesaling/retailing of food, each act to alter food access 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 intracommunity and intrahousehold food distribution and food preferences.

1 The existence of food (*availability*), even in abundance, is not a guarantee of food security. The
 2 causes of internal U.S. food security, for example, have been detailed extensively elsewhere
 3 (Gundersen et al. 2011, Takle et al. 2013, USDA ERS 2013a). U.S. domestic agricultural production
 4 was approximately 30% greater (according to regression) in 2013 compared with the mid-1990s
 5 (Figure 6.1); The U.S. produces approximately 3900 calories per person per day as of 2006 (USDA
 6 ERS 2014b) — well in excess of domestic demand. At the same time, U.S. food insecurity is 14.3%
 7 (Coleman-Jensen et al. 2014). This is primarily the result of household-level economic conditions,
 8 that is, *food access* (Figure 6.1), and exemplifies the limitations of high production alone as a means
 9 of managing food insecurity.



10

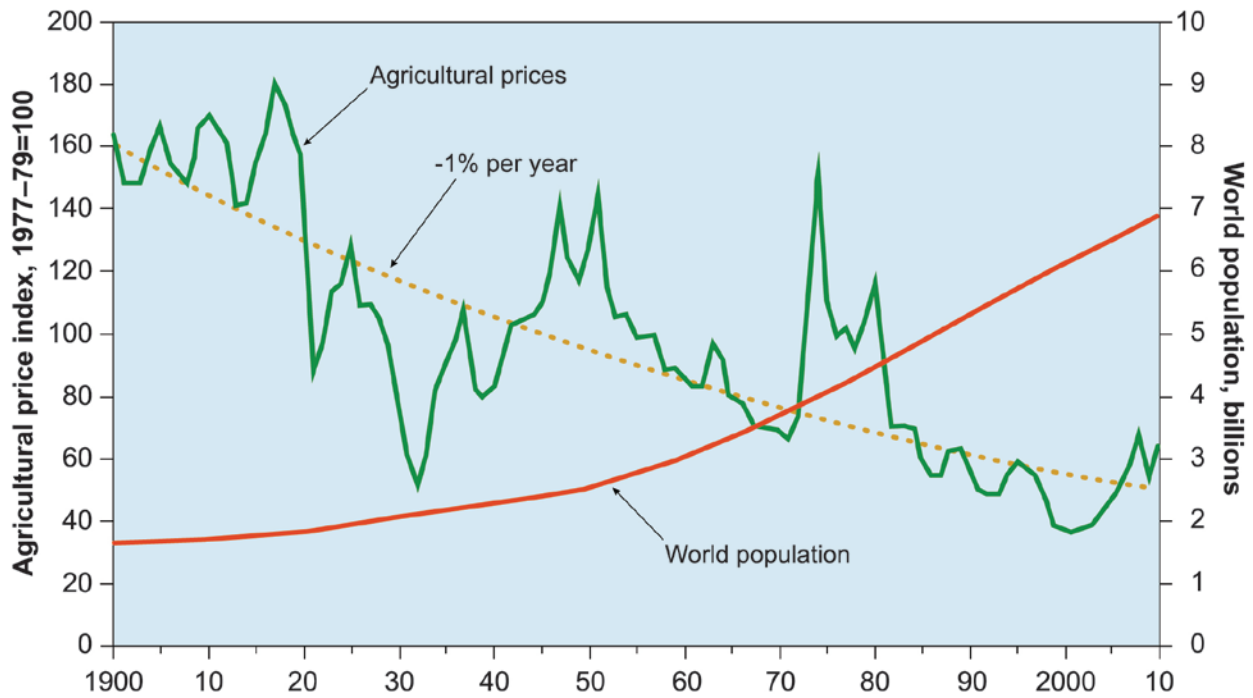
11 **Figure 6.1 Trend in U.S. grain production, food insecurity, and unemployment.**
 12 *U.S. food insecurity has risen even as food production has increased, indicating that food availability*
 13 *and production increases alone do not alone determine food security status. Sources: USDA ERS 1996–*
 14 *2013, USDA NASS 1997–2013, and USBLS 2014.*

1 **6.1 Influences on Food Access and Stability**

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

6 **6.1.1 Food Prices**

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



9
10 **Figure 6.2 Historical trends in real agricultural commodity prices and world population.**
11 *As world population growth increased since 1900, the price of food adjusted for inflation declined.*
12 *Source: Fuglie and Wang 2012.*

13 The real price of food—that is, the price of food adjusted for inflation (a measure of the price of
14 food relative to all other prices)—generally decreased over the last half of the 20th Century. Except
15 for a sharp increase between 1972 and 1974, the real price of food steadily declined from the early
16 1960s until 2000, when the price of food was near an historical low. Since 2000, however, the real

1 price of food has been on an upward trend. The global averages displayed in Figure 6.2 are useful;
2 however, the variability displayed is extremely important to poorer households and regions, whose
3 ability to purchase food is highly influenced by these types of changes, even when they are
4 transitory (Hnatkovska and Loayza 2005, FAO 2011a, Minot 2012). The food crisis of 2008 was the
5 result of a price spike brought on by multiple factors, including weather-induced crop failures in
6 important global exporting regions, changes in demand patterns, and policy shifts in both importing
7 and exporting nations that led to an overall closing of supply relative to demand, driving up prices
8 and resulting in food riots in parts of the developing world (Bellemare 2014, Headey 2011, Nielsen
9 and Vigh 2012, Trostle 2008). Price shocks can exacerbate other causes of food insecurity,
10 including chronic poverty, disease, and a lack of access to a nutritionally adequate diet (Irz et al.
11 2001, Thirtle et al. 2003, Ravallion et al. 2007, Schreiner 2012).

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

19 For poor populations, droughts, floods and other events that destroy housing, reduce agricultural
20 production, or increase the cost of food are major factors in their impoverishment or remaining in
21 poverty (Cutter et al. 2007), thereby limiting food *access*. Weather shocks, in particular, are a key
22 source of vulnerability (Hansen 2002, IFAD 2011, Vermeulen and Campbell et al. 2012). Poor
23 people have low resilience because they have few assets to fall back on when shocks occur (Jayne et
24 al. 2003). When shocks do occur, poor people may resort to incurring debt, selling assets, or
25 foregoing educational opportunities for their children—all of which are adaptive strategies that

1 leave them more vulnerable to future shocks (Kinsey et al. 1998, Prince et al. 1999, IFAD 2011,
2 Gazdar and Mallah 2013). Furthermore, poor farmers with small land holdings may be unable to
3 adapt to climate change due to a lack of resources, lack of social standing, and marginalization
4 (IFAD 2011).

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

10 A number of variables interact to determine the balance between food supplies and demands.
11 Aggregate grain and oilseed production rose on average 2.2% per year between 1970 and 1990, but
12 has declined to about 1.3% since 1990, mostly due to a slowing growth in crop yields (Fuglie and
13 Heisey 2007, Fuglie et al. 2012). The demand for energy increases the cost of agricultural inputs
14 such as fertilizers and fuel, and diverts crop use from feed stocks to biofuels. Global population is
15 expected to grow to a projected 8.6 billion in 2050 (UN 2012), with the sharpest increases in
16 developing countries. The FAO (2009a) estimates that world food production needs to increase by
17 60%–100% to feed a larger, wealthier, and more urban population.

18 The combined effect of slowing growth in agricultural production (*availability*) and an increasing
19 demand for food is higher food prices (Mankiw 2011). In many countries, economic access to food
20 will benefit from increases in per capita income (Mankiw 2011). If the rise in incomes surpasses the
21 rise in food prices, overall access to food, even in developing countries and regions, can be expected
22 to improve. However, higher food prices affect everyone, and some less developed countries may
23 not experience a rise in per capita income due to various obstacles to growth; in such cases, higher
24 prices may cause a reduction in food access for large segments of the population. For example,
25 while global yields grew by 2.4% annually between 2003 and 2012, this growth has been nearly

1 matched by increased demands for cereals (Funk and Brown 2009). If population and economic
2 growth double cereal demands between 2005 and 2050 (Tilman et al. 2011), and climate change
3 slows yield growth (Porter et al. 2014), then overall access would be diminished.

4 The volatility of global food prices (*stability*) has been increasing in recent years due to a
5 combination of factors, including the widespread occurrence of extreme climate events (e.g.,
6 droughts), competition for land by fuel crops, and a change in the commodity markets as global
7 demand for commodities from non-food sectors increases (Bellemare et al. 2013, Haile and Kalkhul
8 2013).

9 **6.1.2 Trading and Transporting Food**

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

14 Damages to the transportation infrastructure that enables trade diminish food access for both
15 consumers who have greater difficulty obtaining food, but also for producers, who have fewer
16 available options to sell their crops (Chamberlin and Jayne 2013). Current weather anomalies offer
17 a preview into the possible effects of climate change on the transportation infrastructure that
18 enables trade. These events influence food access by hindering movement from its place of
19 production to consumers, altering the price of food in response to changes in the price of
20 transportation, and disrupting the timing and operation of logistical supply systems (IPCC 2012).

21 Extreme temperatures can physically damage roadways and railways (Nemry and Demirel 2012).
22 Heavy rainfall, sea-level rise, and storm surges can damage ground transportation and shipping
23 infrastructure in coastal and low-lying areas (Schweikert et al. 2014). Severe drought can disrupt
24 barge shipping in rivers when water levels get too low (Changnon 1989, Yu and Fuller 2005).

1 Extreme temperatures, storm surge, river floods, and other types of extreme weather physically
2 damage transportation infrastructure and the supply chain (Koetse and Rietveld 2009, Becker et al.
3 2013). For example, in 2012, Hurricane Sandy led to a week-long shutdown of one of the largest
4 container ports in the U.S., generating economic damages that could reach 66 billion USD (Blake et
5 al. 2013). Low water levels in rivers and lakes force inland waterway vessels to use only part of
6 their maximum capacity, which leads to an increase in shipping costs and the number of trips they
7 must make (Attavanich et al 2013, Jonkeren et al. 2014, Millerd 2005 and 2011). In the U.S.,
8 Attavanich et al. (2013) estimate that lower water levels in the Great Lakes, by which many goods
9 (bulk freight, including agricultural products) are transported by barges, reduce the ability of U.S.
10 farmers to export their grain to international markets. These transportation changes will affect
11 both the ability of farmers to get their goods to market as well as the access of consumers to the
12 goods.

13 **6.1.3 Wholesaling and Retailing Food**

14 Food for consumption is sold to distributors for onward sale through large supermarkets, small
15 vendors, or directly to consumers. Infrastructure is susceptible to damage from climate and
16 weather, and through climate's influence on economic drivers by affecting consumer traffic or
17 increasing local demand during times of crisis (Burrus et al. 2002, Murray et al. 2010).
18 More than half of the world's population lives in urban areas (Seto et al. 2012). With increased
19 urbanization has come the rise of supermarkets and other highly efficient retail outlets in
20 developing countries (Reardon et al. 2003, Pingali 2007). In coastal cities, imported food that caters
21 to changing urban dietary preferences competes with food supplied by inland producers (Pingali
22 2007). Capital-intensive and labor-intensive production systems frequently coexist in developing
23 economies, and most agrifood sectors include food from both. The result is a diverse exposure to climate
24 and weather shocks, for which the retail sector has increasingly assigned risk to the producer (Lee et al.
25 2012).

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

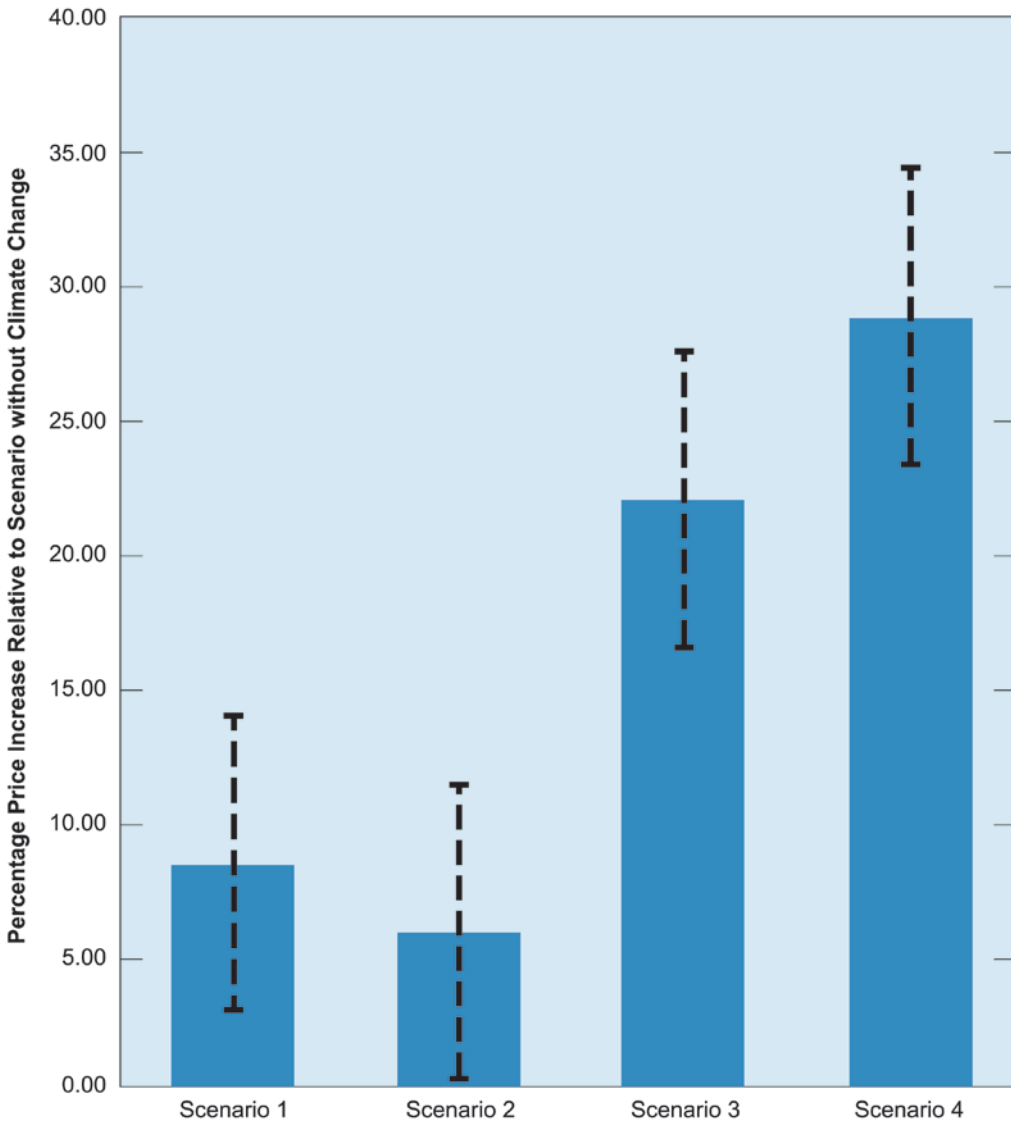
9 **6.2 Adaptation for Food Access and Stability**

10 The effects of climate and food price changes depend upon vulnerability; the ability to effectively
11 respond to shocks depends on adaptive capacity, which varies greatly within and across societies.
12 The future evolution and distribution of vulnerability and adaptive capacity will strongly influence
13 the effects of climate change on food access (Dunford et al. 2015, Krishnamurthy et al. 2014).
14 With respect to climate change, the adaptive capacity of the food system depends upon how
15 effectively risk is managed to minimize its effects on the overall supply chain. Risk and uncertainty
16 take many forms in the food chain: weather and climate, biological processes critical to successful
17 production, financial risk, geographical separation of production and consumption, market cycles,
18 and the political economy of food systems (Krishnamurthy et al. 2014, Vermeulen and Campbell et
19 al. 2012). The degree to which different aspects are sensitive is very case-specific (Johnson and
20 Brown 2014, Murphy et al. 2012, Cole et al. 2009). In some situations, a severe storm can destroy
21 crops in the field and hence lead to local food shortages and price increases. More widespread food
22 insecurity may arise if a larger region depends on a critical element of infrastructure (e.g., rail) that
23 can be destroyed by a major flood. Although it is not possible to pinpoint a specific risk to the food
24 system from climate change that applies universally, the interdependence of different food system

1 activities means that effects on post-farm-gate activities can outweigh farm-level production effects
2 (Rosenzweig et al. 2001).

3 Food prices are affected by access to markets and by trade decisions. In an extension of previous
4 AgMIP research, five global economic models extend their analysis to look at the effects of trade.
5 Four scenarios explore the differences in socioeconomic, climate, and trade assumptions. Two
6 scenarios (scenario 1 and 2) assume relatively low emissions and high levels of international
7 cooperation in adapting to and mitigating climate change (SSP 1). Two other scenarios (scenario 3
8 and 4) make the opposing assumptions: high emissions and low levels of international cooperation
9 in adapting to and mitigating climate change (SSP 3). Each pair of scenarios differs in their
10 assumptions on trade. One scenario (Scenarios 1 and 3) assumes that the status quo remains for
11 global trade while the other two scenarios assume freer (Scenario 2) or more restricted (Scenario
12 4) trade (Wiebe et al. 2015). Figure 6.3 provides the mean results of the five global models, with
13 error bars representing the uncertainty in results between the set of five models.

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



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Figure 6.3 Mean price changes of five agricultural models in 2050 under four scenarios. The scenarios vary assumptions regarding emissions, trade, adaptation, and mitigation assumptions relative to 2050 baseline price when climatic conditions stay constant at current levels. Scenarios 1 and 2 are based on SSP1, scenarios 3 and 4 on SSP3. All scenarios show increased prices due to climate change effects with smaller price increases seen in the lower emissions scenarios (1 and 2) and freer trade scenarios (1 and 3). Source: Wiebe et al. 2015.

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.

1 The opportunities of a more resilient food chain depend upon location and product (Kaplinsky
2 2004, Lee et al. 2012). Participation in agricultural markets is often uncertain, risky, and conducted
3 on unfavorable terms for smallholders in rural areas (IFAD 2011). There is a positive relationship
4 between average farm size and the level of economic development: The higher the per capita GDP
5 of a country, the larger the average farm size (Eastwood et al. 2010), and the greater the adaptive
6 capacity (Brooks et al. 2005). Differences in adaptive capacity can drive household choices to grow
7 their own food rather than buy it at local markets, or to limit their production to market-oriented
8 crops (Nin-Pratt et al. 2011). If remunerative and reliable produce markets are available, it enables
9 farm households to increase their incomes and reduce their vulnerability during poor production
10 years (Lloyd et al. 2011), though the risks of market participation are context- and value-chain
11 specific (IFAD 2011, Zant 2013, Haile and Kalkhul 2013). However, it is generally a challenge for
12 poor rural people to seize rewarding opportunities in produce markets and cope well with the
13 attached risks (Reardon et al. 2003, Neven et al. 2009).

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

24 For wholesaling and retailing activities, adaptation might take a number of forms. Adaptation to
25 higher temperatures may be accomplished with increased refrigeration, though that would likely

1 come at increased costs for industry (James and James 2010). Disruptions in delivery systems due
2 to extreme events also may also require adaptive adjustments. “Just-in-time” logistical systems,
3 which match the rate of food production to the rate of food consumption to avoid the need for large
4 storage areas and maintenance, may be at greater risk under more severe climate extremes, and it
5 appears possible that adaptive measures, such as greater supply-chain redundancy, may be one
6 possible approach (Stecke and Kumar 2009, Altay and Ramirez 2010). Repairs, modifications,
7 changes to shipping logistics, and transportation substitutions (e.g., switching from barge to rail
8 transport) may be applied to a greater degree, as well, to adapt to changing conditions (Brown et al.
9 2013, Rodrigue et al. 2013).

10 **6.3 Measuring Food Access and Stability**

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

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

20 Because of the heterogeneity of food items, and because access depends on cost, the real rate in the
21 growth of food supply is typically measured in monetary terms. A money metric for real growth
22 involves correcting for price variation over time (i.e., changes in the general price level) within a
23 country and for differences in exchange rates and purchasing power across countries. To account
24 for these factors, international food production statistics are usually expressed in terms of a
25 reference currency (e.g., the U.S. dollar, or USD). For instance, FAO data on the value of food

1 production currently use average producer prices for each product and country for the period
2 2004–2006 as converted into USD at purchasing power parity (PPP) conversion rates (FAO 2014d).
3 Income statistics in PPP dollars are also available from the United Nations (UN) International
4 Comparison Program and included in the World Bank’s World Development Indicators (World
5 Bank 2014). Indicators of monetary access to food based on these or other figures, however, are not
6 currently available, except for some specific places and times. The closest substitutes are poverty
7 rates, which measure the purchasing power of households relative to the cost of covering their food
8 requirements and other basic needs (Deaton and Dupriez 2011).

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

18 **6.4 Conclusions and the Future**

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

1 **Price**

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

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

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

18 Food allocation between different groups (e.g., ethnic, gender) can be affected by food price
19 changes as well, resulting in increased vulnerability to food insecurity by more marginalized
20 segments of a population (Raleigh 2010).

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

1 ***Trade and Transportation***

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

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

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

20 Damage to transportation infrastructure can diminish food access for consumers as it becomes
21 more difficult to obtain food (Kneafsey et al. 2013), but also for producers who have fewer available
22 options to sell their crops (Emran and Hou 2013). Repairs, modifications, changes to shipping
23 logistics, and transportation substitutions (e.g., switching from barge to rail transport) can improve
24 food access (Omamo 1998, Koetse and Rietveld 2009). Increased refrigeration during transport

1 can keep food unspoiled, but increases costs (James and James 2010). The smaller the changes in
2 climate, the lower the costs are likely to be.

3 ***Wholesaling and Retailing***

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

12 The rapidity of adaptive changes in the sector will be affected by changing climate effects upon
13 trade and transportation systems and vulnerabilities along the supply chain, particularly under
14 higher emissions scenarios over the longer term and operating in tandem with changes in
15 consumptive demand. The nature of these changes can only be fully understood by working in
16 cooperation with industry, which is a fundamental food system actor, but whose internal data,
17 metrics, and indicators are not often available for peer-reviewed analysis to inform this discussion.

18 ***6.4.1 Food Access and Stability in the Context of Shared Socioeconomic Pathways (SSPs)***

19 The influence of climate change upon food access and its stability depends on responses by each of
20 its key food system elements under differing socioeconomic trajectories. Food access is shaped by
21 prices and affordability, trade and transportation, and wholesaling and retailing. Each of these
22 factors is highly context-specific. Many parts of the food system are not considered by the SSPs or
23 within available modeling frameworks directly, but applicable lessons emerge from the exercises
24 that have been conducted. For these reasons, this section focuses on price as a principal shaper of

1 future food access, considered for each of the SSPs introduced in Section 3.4 of this volume. Trade
 2 significantly influences food prices, but anticipated effects of climate change on trade were
 3 discussed in detail in Chapter 5 (Section 5.4.1), and are not reiterated here. Figure 6.4 reflects
 4 informed judgment of the report’s authors on the relative risks that contribute to food access and
 5 stability for each of the five SSPs.

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

(P: poorer nations, W: wealthier nations)

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

6 **Figure 6.4 Relative risks to food access for different SSPs.**

7 *The risks to food access would be lowest under the economic conditions described in SSP 1 and SSP 5,*
 8 *with poorer nations at higher risk across almost all food affordability and allocation categories for all*
 9 *SSPs. Shading represents higher or lower risks for each SSP from climate change. Risks are based*
 10 *upon this report’s authors’ consideration of the available literature.*

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

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

15

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 which 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

1 to inadequate diet, care, feeding, and health practices, and/or compromised sanitation and hygiene.
2 These factors can lead to infection, weight loss, nutrient depletion, and immunosuppression, which
3 decreases the body's ability to fight infection and further reduces the absorption of nutrients,
4 leading to a cycle of undernutrition and infection (Kau et al. 2011). For example, vitamin A
5 deficiency can lead to immunosuppression and blindness; iron deficiency can lead to anemia; and
6 iodine deficiency can lead to goiter (Ramakrishnan and Semba 2008, Semba and Delange 2008,
7 West and Darnton-Hill 2008).

8 In 1980, the prevalence of child stunting in the developing world was approximately 47% (de Onis
9 et al. 2000). By 2010, the prevalence had decreased to 29.2% and is expected to decrease to 23.7%
10 by 2020 (de Onis et al. 2012). In the developed world over the same time period, the prevalence of
11 stunting has remained at about 6% (de Onis et al. 2012). While the developing world has seen an
12 overall decrease in stunting and other measures of undernutrition over time, vast regional
13 differences have been observed (Black et al. 2008). With the exception of North Africa, most regions
14 of Africa have maintained a consistent level of child and maternal undernutrition (with stunting at
15 38%–40%). Asia and Latin America have seen the most dramatic decreases and are expected to
16 reduce their stunting levels to 19% and 10%, respectively, by 2015 (de Onis et al. 2012).

17 *Overnutrition* refers to the consumption of too many calories or specific nutrients relative to the
18 required levels for normal activities and/or growth and can manifest, for example, as an increase in
19 weight or mineral poisoning. Overnutrition has been attributed to increased urbanization as well
20 as changing lifestyles and diets (specifically, an increase in the consumption of processed foods,
21 animal-source foods, fats, and sugars), and it is associated with diabetes, heart disease, and stroke
22 (Kennedy et al. 2006, Popkin 2006, UN Standing Committee on Nutrition 2010, WHO 2003a).

23 Although studies in the U.S. have shown conflicting results on the link between food insecurity and
24 overnutrition (Dinour et al. 2007, Lohman et al. 2009, Martin and Ferris 2007), in developing
25 countries undergoing a nutrition transition (e.g., Brazil, China, Guatemala, Indonesia, Vietnam,

1 Russia, the Kyrgyz Republic), there has been a rise in the double burden of undernutrition and
2 overnutrition occurring in the same populations and even in the same households (Doak et al. 2005,
3 Kennedy et al. 2006).

4 Trends in overweight children have only recently been documented and are limited by available
5 data, but they suggest that the prevalence of obesity since 1970 has increased for all developed
6 countries and for a number of developing countries (Wang and Lobstein 2006). North America and
7 Europe report the highest prevalence of obese and overweight children (as high as 30%, with the
8 expectation that this figure could increase to 46%). Southeast Asia and much of Africa report the
9 lowest prevalence of overweight children and the slowest rate of obesity (Wang and Lobstein,
10 2006). Some countries that have experienced rapid economic development are now coping with
11 both childhood undernutrition and overnutrition, particularly among the lowest socioeconomic
12 groups (Jones-Smith et al. 2011, Wang and Lobstein 2006).

13 In addition to these types of individual manifestations reflecting food utilization, there are societal
14 elements, as well. Individuals may place high value on locally produced food, culturally important
15 food, or food that they themselves produce (Altieri and Toledo 2011, Rosset 2008). Alternatively,
16 they may have limited knowledge regarding the preparation of unfamiliar food types. These issues
17 of cultural appropriateness, individual values, and preparation skill may be particularly acute for
18 women, who are often the household food preparers (Ibnouf 2009, Quisumbing et al.
19 1995). Changes in the geography of food production, and/or changes in trade patterns that may
20 make some familiar foods less available or accessible and/or increase the availability or
21 accessibility of unfamiliar foods, may alter utilization patterns.

22

1 **7.1 Influences on Food Utilization and Stability**

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

5 **7.1.1 Food Safety**

6 Climate change can affect food safety throughout various stages of the food supply chain (Jacxsens
7 et al. 2010, Tirado et al. 2010). Food safety is a critical means by which changes in climate can affect
8 the utilization of food by influencing vectors of food contamination and levels of toxins in food.
9 Elongated supply chains expose food products to greater risk of potential contamination and make
10 it harder to verify the quality of the products at various stages (Swinnen 2007).

11 Vulnerability of transport infrastructure to extreme events (IPCC 2012) can affect utilization by
12 hindering the movement of food from its place of production to consumers and increasing the
13 likelihood of food contamination. Temperature increases have been associated with illness from
14 Salmonella and Campylobacteria, which may be related to poor food storage and handling practices
15 in the supply chain. In general, increased temperatures are known to cause an increase in diarrheal
16 diseases, (which can lead to malnutrition); bacterial foodborne diseases that grow and reproduce
17 faster at elevated temperatures (Bandyopadhyay et al. 2012, Tirado et al. 2010). For example, in
18 one study in Peru, the incidence of diarrheal diseases increased by 8% for every 1 °C increase in
19 temperature (Checkley et al. 2000). However, some viruses, such as noroviruses, which can be
20 transferred when contaminated foods or liquids are ingested, show an increased prevalence in
21 children in winter, particularly during times of low immunity in the population and the emergence
22 of novel genetic variants (Velázquez et al. 2004, Levy et al. 2009, Cook et al. 1990, Tirado et al.
23 2010). A decrease in infection rates could therefore result from warmer winters. These health
24 challenges are not confined to low-income countries. For instance, a study in England found that for

1 every 1 °C increase in temperature, there was a 5% increase in the number of reports of
2 *Campylobacter enteritis*, up to a threshold of 14 °C (Tam et al. 2006).

3 Fungal infections of crops, particularly of the genus *Aspergillus*, can have severe effects on human
4 health and nutrition whether consumed directly or through the milk produced by livestock who
5 have themselves consumed infected crops (Wagacha and Muthomi 2008, Williams et al. 2004).
6 Aflatoxin, a potent mycotoxin, is produced by *Aspergillus* and is known to lead to cancer, as well as
7 developmental and immune system suppression; in severe cases it can lead to death (Williams et al.
8 2004, Wu et al. 2011). Fungal contamination is a result of preharvest practices; timing of harvest;
9 handling of produce; moisture levels during harvest, storage, transportation, and processing; and
10 insect damage (Wagacha and Muthomi 2008, Cotty and Jaime-Garcia 2007, Miraglia et al. 2009,
11 Tirado et al. 2010). Climate change can affect crop contamination, which can increase during the
12 warm and dry periods of crop development, as some mycotoxin-producing fungi grow best in
13 warmer temperatures (Paterson and Lima 2011, Sanders et al. 1984, Schmitt and Hurburgh 1989).
14 Crops such as maize and peanuts, staple foods for large populations, can be affected, though effects
15 vary depending on the region and temperature and rainfall changes within the region (Paterson
16 and Lima 2011). In low-income countries, the problem of mycotoxin contamination in food and feed
17 due to lack of refrigeration or climate-controlled containers is becoming more widely recognized
18 (Groopman et al. 2008). A synergistic effect between mycotoxin exposure and some critical diseases
19 in Africa, such as malaria, kwashiorkor, and HIV/AIDS, is also suggested by several studies
20 (Wagacha and Muthomi 2008, Williams et al. 2010).

21 Aquatic and fishery food sources are important, both as a protein source and for income generation
22 (FAO 2009b). The warming of the Upper Ocean and uneven changes in the nutrient density of the
23 water (Barange and Perry 2009) can promote harmful algal blooms, which produce toxins that
24 contaminate seafood and can cause illnesses such as paralytic shellfish poisoning, diarrhetic
25 shellfish poisoning, and neurotoxic shellfish poisoning in humans. In addition, fluctuations in sea

1 salinity (influenced by climate) can cause a more rapid uptake of toxic chemicals by fungi, bacteria,
2 mollusks, and crustaceans, and an increased uptake and bioaccumulation by crustaceans and
3 mollusks (Marques et al. 2010).

4 **7.1.2 Nutrition**

5 The body's utilization of macro- and micro-nutrients, required vitamins and minerals, and related
6 dietary compounds is a critical component of food utilization. Micronutrients are nutrients that are
7 needed in relatively small quantities in the diet. They play important roles in sight, immune
8 function, and cellular signaling, among other biological processes. Climatic factors can potentially
9 affect the availability and use of micronutrients in several ways, which can lead to micronutrient
10 deficiencies (Loladze 2002). In one example, the concentration of iron and zinc found in staple
11 grains and legumes is reduced under elevated atmospheric carbon dioxide, a driver of climate
12 change (Myers et al. 2014). Protein (a macronutrient) content in milk declined with increased
13 temperature and humidity above threshold values (Bahashwan 2014, Nardone et al. 2010, Renna et
14 al. 2010). Other nutritional effects are more uncertain under changing climate (Renna et al. 2010).
15 Evidence of climatic effects on nutrient content in fruits and vegetables, for example, remains
16 limited (Burke and Lobell 2010).

17 The nutritional quality of a number of staple foods is diminished by elevated atmospheric CO₂
18 concentrations (Ceccarelli et al. 2010). Under increasingly high concentrations of atmospheric CO₂,
19 nitrogen concentration, a proxy for protein content, appears to diminish by 10% to 14% in the
20 edible portions of wheat, rice, barley, and potato, and 1.5 % in soybeans (Müller et al. 2014, Taub
21 and Wang 2008). Mineral and micronutrient concentrations in the edible portions of crops are also
22 likely to diminish under elevated CO₂ concentrations (IPCC 2014a). The overall nutritional quality
23 of many important food sources is therefore diminished in a changing climate.

1 **7.1.3 Environmental Enteropathy**

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

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

17 **7.1.4 Storing, Processing, and Packaging Food**

18 Food storage, processing, and packaging activities often include both capital-intensive and labor-
19 intensive systems coexisting in the same region, each system having different vulnerabilities to
20 weather and climate (Lee et al. 2012). Poor storage is a major cause of food loss, and proper
21 packaging prevents damage and contamination. In developing countries, there are significant
22 postharvest losses due to financial and structural limitations in harvest techniques, inadequate or
23 poorly managed storage and transport infrastructures, and climatic conditions favorable to food
24 spoilage (FAO 2013a). Higher temperatures can also prolong damage by pests (e.g., rodents,
25 insects) after harvest, absent appropriate storage methods (Magan et al. 2003, de Lima 1979).

1 Postharvest losses vary by region and industrial process, as losses are dependent on the specific
2 conditions and local situation in a given country or region. For example, lack of appropriate storage
3 facilities for food crops can lead to pest infestations or mold growth that render the crops inedible
4 (Parfitt et al. 2010). As temperatures rise, postharvest losses may increase in regions without
5 appropriate processing and storage facilities.

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

15 **7.1.5 Consumption and Disposing of Food**

16 The final stage in the food system is consuming food, which involves buying, preparing, and eating
17 food at the individual or household level (Ericksen 2008). Food consumption has increased over the
18 past 50 years by 400 kcal per person per day, with dramatic decreases in the prevalence of hunger
19 in many areas (Kearney 2010). Large increases in the consumption of vegetable oils (199%), meat
20 (119%), and sugar (199%) in low-income countries between 1963 and 2003 reveal significant
21 expansion of food availability across all income brackets (Alexandratos and Bruinsma 2012). At the
22 same time, declines were seen in the consumption of pulses and roots over these 4 decades
23 (Kearney 2010). These changes have been driven largely by technological and socioeconomic
24 factors, and how climate change will further affect these changes is uncertain.

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

9 Estimates suggest that 30% to 50% of total food production is lost globally as waste (Gustavsson et
10 al. 2011). Similar levels of waste are observed in developed and developing nations, with differing
11 causes in each case. In developing nations, the absence of adequate food-system infrastructure is a
12 primary cause of food waste (Godfray et al. 2010), and was discussed in the *Food Availability and*
13 *Stability* chapter of this report. Waste in retail, food service, and at home accounts for the majority
14 of food waste in developed regions (Parfitt et al. 2010), and hence is less efficiently utilized.

15 **7.2 Adaptation for Food Utilization and Stability**

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

21 A variety of techniques exist to reduce postharvest losses resulting from food spoilage, and include
22 varietal selection, biological control, storage structures, chemical treatments, botanical and inert
23 dusts, and improved handling and processing (Affognona et al. 2015). Additional monitoring for
24 food pathogens and contaminants will be adaptive under higher temperatures and humidities as a
25 means of managing food safety (Gregory et al. 2009). Pre-refrigeration methods of food storage (e.g.,

1 drying, salting, pickling) may be used effectively in a changing climate (Shepherd 2012, Gitonga et al.
2 2013. Reduced intervals between harvest and storage can diminish the faster rates of spoilage that
3 occur under higher temperatures and humidity. Cold storage is another possible adaptation,
4 though costs increase with additional refrigeration (James and James 2010). High levels of food
5 processing can reduce the need for cold storage (Young 2013), and may consequently represent a
6 means of adaptation that ameliorates refrigeration costs.

7 Disruptions in delivery systems may become more probable in a changing climate (Stecke and
8 Kumar 2009), with implications for “just-in-time” logistical supply systems, which attempt to match
9 the rate of food production to the rate of food consumption to avoid the need for the maintenance
10 of large storage areas. Greater supply-chain redundancy, may be one productive approach (CDP
11 2015, Altay and Ramirez 2010), and becomes more economically feasible under more rapid levels
12 of change (Global Commerce Initiative 2009).

13 As the nutritional value of food diminishes under elevated atmospheric CO₂, adaptations might
14 include greater cultivation of protein-rich crops (Linnemann and Dijkstra 2002), the inclusion of
15 animal protein sources (Golden et al. 2011), or cultivation of less familiar protein sources for some,
16 such as insects (Shockley and Dossey 2014), particularly in cases where inadequate protein
17 presents a limitation on food security status. Such adaptations might require the economic means
18 to purchase animal protein sources, farmland for additional leguminous crops, or a willingness to
19 eat unfamiliar protein sources. Feedbacks from this adaptation might include potential changes to
20 other components of food security, such as overall global food demand in cases where grains are
21 used as feed (Kearney 2010, West et al. 2014).

22 Changing production geography may make familiar foods become less available or accessible in
23 some cases, and unfamiliar or less familiar foods may take their place. This can result in reduced
24 utilization, perhaps transient, due to lack of familiarity with preparation methods for the new food
25 types (Axelson 1986), and may disproportionately affect women (Ibnouf 2009, Quisumbing et al.

1 1995). The greater the change in familiar foods as a consequence of changes in climate, the greater
2 the adaptation required, whether that entails paying more for familiar foods that are grown at a
3 greater distance, purchasing the less familiar foods and learning how to prepare them in a
4 culturally appropriate way, or a combination of multiple adaptive habits.

5 Increased disease prevalence and distribution in a changing climate may lead to increased use of
6 veterinary drugs or pesticides, bringing with it the possibility of higher residue concentrations in
7 food and possible effects on consumption choices (FAO 2008a, Tirado et al. 2010, Cooper et al.
8 2014). This illustrates that where adaptation is possible, it may have consequences of its own.

9 **7.3 Measuring Food Utilization and Stability**

10 Food utilization outcomes, expressed by anthropometric, clinical, or biochemical indicators of
11 nutritional status, are usually measured by health and nutrition surveys carried out every 4–6
12 years, and thus do not always reflect seasonal and annual situations (Grace et al. 2014, Shively et al.
13 2015). Both poverty and undernourishment indicators refer to habitual consumption, usually over
14 the span of a year (or the average of a 3-year period), and can help to identify issues where
15 utilization of food is impaired.

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

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

9 **7.4 Conclusions and the Future**

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

16 Fruit and vegetable crops harvested with higher pulp temperatures require more energy for proper
17 cooling (Moretti et al. 2010). Higher temperatures and humidity generally cause increased
18 mycotoxin accumulation (Magan et al. 2003, Fandohan et al. 2003, Rossi et al. 2001, Coakley et al.
19 1999). While exceeding a fungus' biophysical temperature threshold will reduce mycotoxin-related
20 food spoilage, fungal populations can adapt to local conditions (Coakley et al. 1999). The need for
21 refrigeration and dehumidification to reduce fungal growth can lead to strains on electricity grids
22 (James and James 2010) and comes at increased cost. Managing food security outcomes requires a
23 comprehensive understanding of the interactive effects of adaptive choices throughout the food
24 system, and indicates that single-point adaptation itself may not, in many cases, be a panacea for
25 managing systemic food security outcomes (Ludwig 2011).

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

6 The rapid expansion of food transport to supply supermarket-type retailing structures lengthens
7 the period of time between harvest and consumption, potentially exposing food to conditions that
8 may result in higher rates of contamination (Ercsey-Ravasz et al. 2012). As a consequence, some
9 food products may require updated processing, packaging, and storage, or may require protective
10 packaging for the first time (Parfitt et al. 2010). Industry addresses food processing, packaging, and
11 storage requirements to meet meeting legal trade and food safety specifications (CDP 2015, WHO
12 2003b), but such data are not often available for scientific analysis. Documented relationships
13 between food safety and climate variables that are expected to change, however, imply an increased
14 need for adaptation in food processing, packaging, and storage (Parfitt et al. 2010).

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

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

21 **7.4.1 Food Utilization in the Context of Shared Socioeconomic Pathways (SSPs)**

22 The influence of climate change upon food utilization and its stability depends on how key elements
23 of the food system respond to changes in climate under differing socioeconomic trajectories. Many
24 parts of the food system are not considered by the SSPs or by existing modeling frameworks; Figure

1 7.1 reflects informed judgments of the authors on the relative risks to food safety and
 2 environmental enteropathy from climate change for different development pathways, based on
 3 inferences from the available literature on the subjects.

Shared Socioeconomic Pathway	Food Safety		Environmental Enteropathy	
	P	W	P	W
SSP1	Low Risk	Low Risk	Low Risk	Low Risk
SSP2	Medium Risk	Low Risk	Medium Risk	Low Risk
SSP3	High Risk	Low Risk	Medium Risk	Low Risk
SSP4	Medium Risk	Low Risk	Medium Risk	Low Risk
SSP5	Low Risk	Low Risk	Low Risk	Low Risk

(P: poorer nations, W: wealthier nations)

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

4 **Figure 7.1 Relative risks to food utilization for different SSPs.**

5 *The risks to food utilization would be lowest under the economic scenarios described in SSP1 and SSP5,*
 6 *with poorer nations at higher risk across all food utilization categories for all SSPs. Shading*
 7 *represents higher or lower risks for each SSP from climate change. Risks are based upon this report's*
 8 *authors' consideration of the available literature.*

9 **Food Safety**

10 Across all SSPs, in wealthy countries where effective controls exist, food safety is not likely to be
 11 significantly affected by climate change. Poor countries, however, could experience significant
 12 variability in food safety across the SSPs. Economic growth and technology transfer under SSP1 is
 13 likely to ameliorate the effects of changing temperatures on food safety in poorer countries.
 14 Similarly, high rates of economic growth under SSP5 might produce income increases and increase
 15 expectations of improved food safety.
 16 Under SSP2, technology transfer and economic growth would be somewhat lower than under SSP1,
 17 but the globalized trade regime might compel investment in or transfer of food safety technologies
 18 due to international certification requirements, limiting significant food safety impacts. Another
 19 possibility is that more globalized trade could facilitate the movement of unsafe food into wealthy
 20 countries at higher rates than occur today. Under SSP3, more modest economic growth would limit
 21 additional education and infrastructural developments that might otherwise contribute to

1 improved food safety. Technology transfer, which is expected to be low under this scenario, would
2 not fill that gap. In SSP4, poor countries would experience similar challenges as under SSP3, given
3 low rates of economic growth and low technology transfer. However, the globalized trade regime
4 might compel the international transfer of food safety technologies to meet international
5 certification requirements, which would address food safety challenges in these countries. If not,
6 food exports from these countries could result in more unsafe food consumption in importing
7 countries.

8 ***Environmental Enteropathy***

9 Given existing infrastructure and levels of public health, wealthy countries are likely to maintain
10 low rates of EE under all SSPs in a changing climate. Rates of economic growth are expected to be
11 high and environmental quality would be expected to be high or improve in poor countries under
12 SSPs 1 and 5, expanding the ability of poor countries to manage climate change and respond quickly
13 to climate-related disasters may allow cholera and similar conditions to spread, contributing to EE.
14 Environmental quality is expected to deteriorate under SSPs 2, 3, and 4. For these SSPs, changing
15 patterns of climate-related disasters are more likely to result in higher rates of EE-based diseases in
16 places with little capacity to address them. Under SSP4, high levels of intra-country inequality could
17 produce highly variable outcomes within a country, with the wealthy largely insulated from EE-
18 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 U.S. 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 U.S. 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 U.S. (CCGA 2013).

According to the CCGA (2013), improvement in food security in low-income countries assists the U.S. in its humanitarian goals of helping improve quality of life, promotes global stability, and helps create future trading partners. To these ends, the U.S. 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 U.S. is not independent of these changes (Walthall et al. 2012).

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

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

14 **8.1 The U.S. as a Global Food System Actor**

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

1 countries and subpopulations of other countries, that significant food insecurity will persist
2 (Alexandratos and Bruinsma 2012).

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

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

12 **8.1.1 Food Production**

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

22 Concern exists that many countries are divesting agricultural research focusing on increasing crop
23 yields, including the U.S. (World Bank 2008a). Very little of the total genetic material from original
24 landraces of modern crops is actually exploited in today's crops (Godfray et al. 2010). Preserving

1 heretofore unused genetic material is important to pushing yield limitations. International
2 collections and gene banks are valuable repositories of genetic variation. The U.S. is a major
3 repositior of landraces and other genetic material. The USDA's National Center for Genetic
4 Resources Preservation (Williams 2005) is one of the world's largest collections of seeds, genetic
5 material for livestock, microbes, and endangered plants. The mission of the NCGRP is to act as
6 genetic and germplasm conservator into the future to protect the nation's and world's ability to
7 develop new traits, especially those oriented toward increasing food supplies (Williams 2005).

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

22 **8.1.2 Food Waste**

23 Globally, 30-50% of food is lost to waste (Gustavsson et al. 2011, Godfray et al. 2010). Causes differ
24 between high- and low-income countries. In low-income countries, the majority of wastage occurs
25 on-farm, and in transporting and processing food. In high-income countries most waste occurs in

1 home consumption and very little is lost on-farm or in transportation and processing. Food waste
2 at home by consumers in high-income nations primarily takes the form of discarding usable food
3 because of qualitative deficiencies or failure to consume food within a certain period of time,
4 regardless of its continued edibility.

5 Three global trends are posited to influence rates of waste in the food supply chain (Parfitt et al.
6 2010). First is urbanization and the contraction of the agricultural sector. Nearly 50% of the
7 world's population now lives in urbanized areas and the number is expected to grow to 70% by
8 2050. This trend will lengthen food supply chains, which places food at increased risk of wastage
9 due to added exposure during transportation, processing, and final consumption. Second is dietary
10 transition. As incomes rise in many currently low income countries, diets are changing. Parfitt et al
11 (2010) reference Bennett's Law that states that the food share of starchy staples declines as income
12 increases. Higher incomes are accompanied by increased consumption of fresh fruit and
13 vegetables, dairy, meat, and fish. Those foods tend to have shorter shelf-lives and contribute to
14 increased waste. The third trend is increased globalization of trade. International trade is leading
15 to increased imports of high-quality foods that undercut domestically produced equivalents in
16 many countries. Those imports are marketed in major supermarkets that dispose of large
17 quantities of edible food for reasons of freshness and appearance.

18 The past seven decades have seen technological advances, such as improved genetics, fertilization,
19 and mechanization, which have greatly increased total agricultural capacity and productivity in the
20 U.S. Many of those advances also helped increase the resilience of the U.S. food system to weather
21 and climate extremes. For example, Tester and Langridge (2010) point out that recent transgenic
22 crop modifications aimed at increasing yield stability have improved resistance to abiotic stresses
23 such as drought. The advent of high-efficiency irrigation systems has improved water conservation,
24 making more irrigation water available during droughts than was possible with lower efficiency
25 systems. Such technological advances are likely, many of which are piloted in the U.S., to play a

1 significant role in helping the nations across the globe deal with the consequences of climate
2 change for food security for their citizens. The U.S. food system will continue to be vulnerable to
3 climate variability and change, and will likely be an important actor in helping other nations cope
4 with climate threats to food security.

5 **8.2 Climate and Weather Effects on U.S. Agriculture**

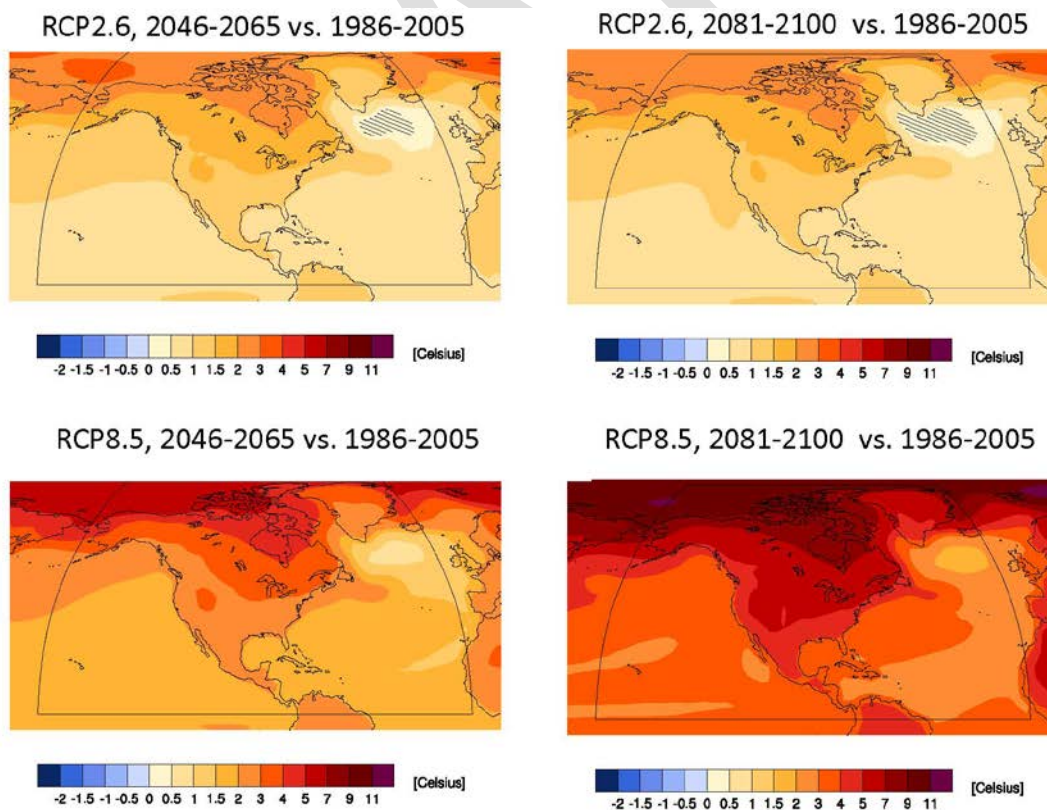
6 The USDA sponsored an assessment report entitled “Climate Change and Agriculture in the United
7 States: Effects and Adaptation,” published in 2012 (Walthall et al. 2012). The information in this
8 section is drawn from that recent work, unless otherwise cited.

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

14 All regions of the U.S. have experienced climate change during the last century. Alaska has changed
15 the most, with average temperatures going up by 1-2° C. Average temperatures have also increased
16 in the northern Midwest, and the Southwest has also become warmer. The only region in the U.S.
17 that cooled over the last century is the Southeast, although it has seen temperature increases
18 during the last several decades. In most regions, summer has warmed more than winter, and
19 spring is also warmer in most places (Walthall et al. 2012). In the U.S., as in most other parts of the
20 globe, the observed number of record highs during each year is now about three times the number
21 of record lows (Meehl et al. 2009). Much of the Northwest, Central, and Southern U.S. now receive
22 more precipitation than 100 years ago, while parts of the Eastern seaboard, the Rocky Mountains,
23 and the Southwest receive less. The intensity of precipitation has also increased in most areas of
24 the U.S. But increases in precipitation totals and intensity do not necessarily mean that additional
25 water is available for agriculture. More intense rain leads to faster runoff, and higher temperatures

1 increase evapotranspiration losses to the atmosphere, both of which result in less moisture
2 retention in soils (Walthall et al. 2012).

3 The entire U.S. is projected to warm substantially in the future. Even under a scenario of limited
4 emissions increases and GHG concentrations (e.g., RCP 2.5), average temperatures are likely to
5 increase by 1-2 °C over the next 40 years, which is substantially faster than the rate observed over
6 the last 100 years (Figure 8.1). Temperatures would then remain at about this level throughout the
7 rest of the century. If emissions follow a higher scenario (e.g., RCP 8.5), average U.S. temperatures
8 could increase by 2-3 °C by mid-century. Looking ahead to 2100, a high-emissions scenario results
9 in warming of 4-5 °C in most regions, and 5-7 °C in parts of the interior West and Midwest. This
10 widespread warming could increase the length of the growing season by a month or more and lead
11 to 20-40 fewer frost days per year in most areas.



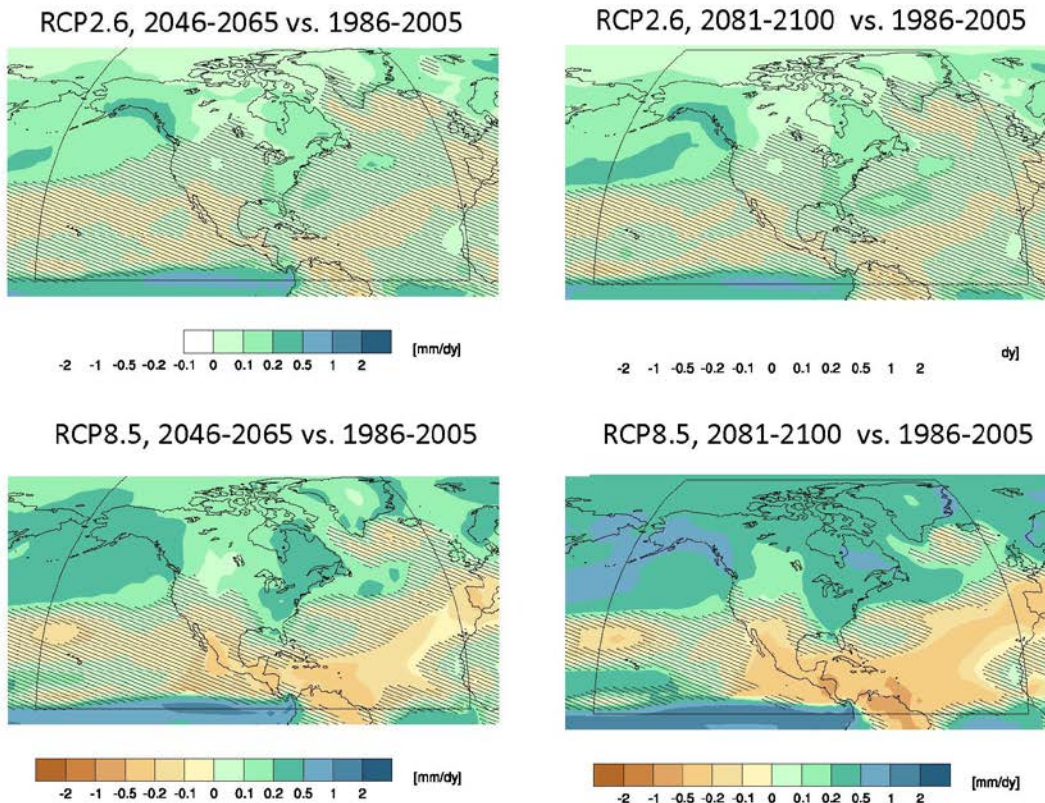
12

13 **Figure 8.1 Projections of U.S. surface temperatures.**

14 *U.S. average surface temperature projections for the low future GHG concentration scenario (upper*
15 *panels) for mid-century (left panel) and end of century (right panel). Lower panels show projections*

1 based on high GHG concentrations for mid-century (left) and end of century (right). Plots show
2 multimodel ensemble means with gray dashes indicate areas where changes are small (less than one
3 standard deviation) compared to natural variability. Source: This figure was produced using CMIP5
4 model output through the web application "Climate Explorer," available at <http://climexp.knmi.nl/>

5



6

7 **Figure 8.2 Projections of changes in U.S. precipitation.**

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

14 The picture of future precipitation shows more geographic variation (Figure 8.2). Over the next 40
15 years under a low-emissions scenario, most of the U.S. is projected to see increased average
16 precipitation but with some notable exceptions. Increases are greatest in the East. Only parts of the
17 Southwest and the Pacific coast are projected to become drier. If emissions remain on a low
18 trajectory, these conditions do not change significantly by 2100, except for a switch from drying to
19 slightly increased precipitation in some parts of the Southwest. Under a high-emissions scenario,

1 the pattern of change is similar in the near term, but with larger increases in precipitation in much
2 of the eastern US and larger decreases over a slightly larger area of the Southwest. Over the longer-
3 term, there is a further increase in precipitation in more of the Eastern U.S., with the exception of
4 Florida, which is projected to see decreased precipitation.

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

13 Agriculture is also sensitive to indirect effects, such as increases in diseases and pests, and
14 degradation of the natural resource base, such as high quality soil and water, upon which
15 agriculture depends. Climate change is projected to increase the growth and range of many weeds,
16 insect pests, and pathogens harmful to agriculture, although the ranges of some invasive weeds,
17 such as knapweed, could decrease. Projected increases of intense precipitation coupled with
18 increased drying of soils from higher temperatures increases the risk of accelerated erosion of soils
19 in many areas, which both degrades soil quality and increases the runoff of agricultural chemicals.
20 Projected changes in precipitation are also likely to increase water management challenges in
21 agriculture. For example, the combination of decreased snowfall and snowpack, increased rainfall
22 (from less precipitation falling in frozen form and more in liquid form), earlier snowmelt, and
23 decreased summer flows in streams and rivers could increase the need for water storage in many
24 areas of the western U.S.

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

11 **8.3 The U.S. Role in a World Adapting to Climate Change**

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

17 **8.3.1 Trade**

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

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

1 An estimated 20% of U.S. agricultural production (based on volume) is exported (USDA ERS
2 2012b), making the U.S. the largest food exporter in the world, responsible for 16% of global
3 agricultural exports (GTIS 2015). The U.S. is the largest producer of corn in the world, responsible
4 for over one-third of the world's corn crop, and is grown on over 400,000 U.S. farms (EPA 2013).
5 More than 275,000 farms in the U.S. produce soybeans, making the U.S. the largest producer of that
6 commodity, as well (U.S. EPA 2013). The U.S. is also among the top wheat and rice suppliers, and is
7 responsible for one quarter of the world's meat exports (USDA 2015).

8 Top markets for U.S. agricultural products include China, Canada, Mexico, Japan, and the European
9 Union (USDA ERS 2014a). China is one of the fastest growing agricultural markets, driven primarily
10 by its burgeoning demand for soybeans, and limited arable land base. Since international trade can
11 contribute to global land savings if trade flows from a relatively efficient country to a less efficient
12 country, it is estimated that China's import of land-intensive crops led to global land savings by
13 3.27 million ha on annual average during 1986–2009 (Qiang et al. 2013). The U.S. comparative
14 advantage in land has enabled it to be the largest agricultural supplier to China, thus contributing to
15 global land savings. In terms of global crop trade, the U.S., Canada, Australia, and Argentina are net
16 virtual land exporters, while some Asian and Mediterranean countries are net importers (Qiang et
17 al. 2013, Fader et al. 2013).

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

1 growth in developing countries is expected to create additional opportunities for U.S. agricultural
2 exports, although the U.S. will continue to compete with other major exporting countries (USDA
3 2014).

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

13 A significant aspect of U.S. agricultural trade with respect to climate change is the ability of the U.S.
14 to export virtual water in the commodities being traded. Virtual water refers to the water that is
15 embodied throughout the entire production process of a traded commodity (Hoekstra and
16 Chapagain 2008). Many of the regions of the world where the risk of food insecurity is high are
17 likely to simultaneously experience severe climate changes in the form of diminished precipitation
18 and drought, including especially the tropics and semi-arid tropics (Porter et al. 2014). Water will
19 be a key limiting factor for food production in those areas. Konar et al. (2013) estimate that by
20 2030, if climate change causes moderate crop yield decreases globally, the U.S. would lead the
21 world by a large margin in the amount of virtual water embedded in exported commodity crops. It
22 is worth noting that only minimal global yield decreases are likely by 2030 (Porter et al. 2014).
23 However, it can be inferred from the Konar et al. (2012) estimates, that as global yield decreases
24 become moderate later in the century, the U.S. might maintain or even strengthen its role as a major
25 exporter of food, especially commodities that require water (for production, processing, or

1 transporting). Yet, it is important to recognize that agriculture in some parts of the U.S., particularly
2 the arid West, may be similarly constrained by reduced precipitation and increasing demands on
3 non-agricultural uses of water as other parts of the world (Walthall et al. 2012).

4 Trade is beneficial to the U.S. domestic economy. It is estimated that each dollar of U.S. farm exports
5 stimulates an additional \$1.22 in U.S. economic output (USDA ERS 2015b). Agricultural exports
6 create additional economic output due to its effect on other non-agricultural industries. Farmers
7 purchase additional machinery, durable goods, or other inputs to produce the exportable
8 agricultural commodities. These purchases generate jobs, income, and wages for other sectors of
9 the U.S. economy. In 2013, the most recent year for which trade impact analysis is available, the
10 \$144.38 Billion U.S. farm exports supported almost 1.1 million jobs, three-quarters of which were in
11 nonfarm sectors (USDA ERS 2015b). In addition to direct, on-farm employment, agricultural
12 exports also support economic off-farm activities associated with procuring production inputs such
13 as fertilizers and fuel, processing, packaging, manufacturing, transporting, and financing and
14 logistics activities. Similarly, agricultural imports generate economic output through transporting
15 and retailing food (Paggi et al. 2012), though the multiplier effects are more difficult to quantify
16 (USDA ERS 2015b).

17 U.S. imports play an indirect role in global food security. The U.S. is the third largest food importer
18 in the world; it imported \$112 billion of agricultural products in 2014 including coffee beans, cocoa,
19 fresh fruit, and rubber, as well as an additional \$20 billion of fishery products (USDA FAS 2015b).
20 Imports generate income for overseas producers through export sales of surplus production, and,
21 in some cases become the main source of income for farmers who have limited options. For
22 instance, the U.S. is the largest importer of Guatemalan coffee, buying about 40% of the country's
23 exported coffee beans (GTIS 2015). Coffee production supports 150,000 full-time and 300,000 part-
24 time jobs in Guatemala, contributing 1.5% of that country's total GDP (USDA FAS 2015b). About
25 70% of the coffee production there is concentrated at high altitudes, where few alternative

1 agricultural options are available. For a discussion on the importance of coffee to the Central
2 American economy, the region's food security, and how climate change affects both, see Box 8.1.
3 U.S. food imports from all regions are growing to meet consumer demand for variety, quality, and
4 convenience (USDA ERS 2015a). Retailers and processors also seek low-cost ingredients sourced
5 from all over the world, raising concerns about the safety of supplies from far-flung locations that
6 have different safety standards and quality control (Gale and Buzby 2009). Food import refusal
7 reports indicate that vegetables and vegetable products, fishery and seafood products, and fruits
8 and fruit products are among the top imported food categories refused due to safety and other
9 violations under FDA law, which includes sanitary, pesticide, labeling, and packaging violations
10 (Buzby et al. 2008). Improved safety in imported food is likely to entail higher costs, as exporting
11 countries invest in sanitary facilities, equipment, water treatment, worker hygiene, changes in
12 production processes, and third-party certification (Gale and Buzby 2009).

13

Box 8.1

Central American Coffee, the U.S., 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 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.

The U.S. 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 Panama¹ - \$1.05 Billion) are approximately equivalent to those from Brazil (\$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 B8.1.

Table B8.1.

Country	Coffee Exports to the U.S. (\$ 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.

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).

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 which 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.

1
2 The AgMIP projections described in Chapters 3 and 4 of this volume can also be used to describe
3 some possible climate change effects on food production in the U.S. With the exception of domestic
4 U.S. food prices, the effects of varying climate scenarios on U.S. imports and exports can be studied
5 using AgMIP data. Within the models, the U.S. is classified as a region, and the effects of climate
6 change can be assessed specifically for the U.S. (Valin et al. 2014). Several results from these
7 projections provide additional information on the domestic climate change effects; changes in

1 domestic U.S. food prices are not possible to glean from these models, however. The models use
2 global commodity prices to determine when supply equals demand, which then calculate prices and
3 other outputs for future commodities. Therefore, prices in the U.S. are the same as those observed
4 in other regions of the world, except for costs associated with transportation, tariffs, and other
5 trade-related price adjustments.

6 Table 8.1 provides information from the publicly available AgMIP data for U.S. imports and exports
7 (Valin et al. 2014, Nelson and Valin et al. 2014). The table reports the average results of six
8 different economic models to more clearly illustrate the effects of changes in agricultural imports
9 and exports under different climate scenarios. The baseline scenario maintains the 2005 climate,
10 while the alternative scenario is the average change based on four similar climate scenarios, all of
11 which use emissions and concentrations from RCP 8.5. The AgMIP data use 2005 as a base year and
12 for these tables, agricultural imports and exports are normalized to their 2005 values. Under both
13 the baseline and climate scenarios, global population is expected to reach 9.3 billion people in 2050
14 and global GDP is expected to exceed \$147 trillion (Valin et al. 2014). Over time, the table shows
15 large increases in imports and exports for both scenarios. By 2050, the agricultural imports to the
16 U.S. are projected to increase by 67% under the baseline scenario (relative to 2005). Under a
17 scenario that includes climate change, imports into the U.S. would increase by almost 73% relative
18 to 2005. Similarly, exports are also expected to increase substantially, by 85% in 2050 under the
19 baseline scenario and increase by 91% under a scenario that includes climate change.

20

1 **Table 8.1. U.S. Agricultural Imports and Exports (AgMIP Projections)**

Year	% Change in Imports Relative to 2005		% Change in Exports Relative to 2005	
	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%

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: derived from Nelson and Valin et al. 2014.

2 While agricultural imports and exports are expected to increase over time, regardless of climate
 3 change, Table 8.2 shows the changes in agricultural imports and exports from climate scenarios
 4 expected relative to the baseline scenario in 2030 and 2050. Agricultural imports increase in a
 5 world with climate change relative to the baseline scenario. In 2030, the average increase in
 6 imports is almost 5% above agricultural imports relative to a world where climate is held constant
 7 at 2005 levels (the baseline). Agricultural exports also increase, with slightly smaller increases in
 8 exports relative to the baseline scenario. The U.S. agricultural balance of trade would therefore be
 9 expected to change based on these projections by 2050, with imports increasing slightly more
 10 relative to exports under the climate change scenario.

11 **Table 8.2 Change in U.S. Agricultural Imports and Exports Relative to Constant 2005 Climate**

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

12 When only climate change influences are considered, U.S. imports and exports are expected to both increase in the
 13 years 2030 and 2040. Units are percentage changes relative to the import and export volumes at 2030 and 2050 in a
 14 world where climate is held constant at 2005 levels. The climate scenario results are the average of six economic
 15 models over four different climate scenarios. The climate scenarios are generated from all possible pairings of two
 16 crop models and two general circulation models and all use RCP 8.5. Source: derived from Valin et al. 2014.

17

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

9 Major destinations for U.S. agricultural exports are presented in Table 8.3. Currently, the second
10 and third largest trading partners are Canada and Mexico, which have common borders with the
11 U.S. However, the remaining major agricultural trading partners are distributed around the world,
12 with the majority located in Asia, Europe, and South America. Adequate infrastructure in the U.S. is
13 required to exchange goods with trading partners, but is also required for the trading partners, and
14 requires that goods be exchanged in a timely manner to prevent food waste as well as the excessive
15 costs associated with perishable good storage.

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

24

1 **Table 8.3: Top 15 Countries for U.S. Agricultural Exports**

Rank	Country (Region)	Value (US. 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.

2
3

1 **Table 8.4 Top 20 Port Cities with Severe Potential Impacts from Sea-level Rise and Tropical**
 2 **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	3513.04
2	China	Guangzhou Guangdong	84.17	3357.72
3	United States	New York-Newark	320.2	2147.35
4	India	Kolkata (Calcutta)	31.99	1961.44
5	China	Shanghai	72.86	1771.17
6	India	Mumbai (Bombay)	46.2	1598.05
7	China	Tianjin	29.62	1231.48
8	Japan	Tokyo	174.29	1207.07
9	China	Hong Kong	35.94	1163.89
10	Thailand	Bangkok	38.72	1117.54
11	China	Ningbo	9.26	1073.93
12	United States	New Orleans	233.69	1013.45
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

3 *Source: Nicholls et al. 2008*

4 **8.3.2 U.S. Foreign Assistance**

5 In addition to helping countries meet agricultural development and long-term food security
 6 objectives, U.S. foreign assistance, including both development and international food assistance, is
 7 an important instrument for meeting the needs of vulnerable populations, including those
 8 experiencing food shortages brought on by drought and other climate-related factors (Rosen et al.
 9 2004). Food assistance will likely continue to be a major tool for ameliorating food insecurity in the
 10 early stages of climate change when many low-income nations are just beginning to experience
 11 rising incomes (Barrett and Maxwell 2005). Increasing emphasis is being placed on building

1 resilience to recurrent crises in order to reduce the need for humanitarian assistance over the
2 longer term (see, for example, Executive Order 13677). Both emergency food assistance and longer
3 term development programs are important to building more resilient, food-secure communities.
4 The consequences of climate change for food security in different regions globally likely will
5 influence, and be influenced by, development efforts.

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

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

21 USAID delivers both foreign humanitarian and development assistance. USDA provides non-
22 emergency food assistance programs to help meet recipients' nutritional needs and support
23 agricultural development and education. Each of these assistance programs, combined with trade
24 capacity building efforts, support long-term economic development and can help countries
25 transition from food assistance recipients to commercial buyers. Programs focus on the world's

1 poor, particularly those living in rural areas and dependent on agriculture for their livelihoods.
2 These programs and initiatives address the nexus of climate change and global food security, and
3 have implications for U.S. food systems. They include alternative livelihoods programs; the Food for
4 Peace development food assistance programs authorized primarily by the Agricultural Act; the U.S.
5 Government's Global Climate Change Initiative; and the U.S. Government's flagship global hunger
6 and food security initiative called Feed the Future (www.feedthefuture.gov).

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

15 Such programs can help increase food security and improve maternal and child health.
16 Programmatic assessment indicates that Feed the Future and other U.S. Government-led efforts
17 have contributed to reductions in poverty and child stunting in the areas of Bangladesh where Feed
18 the Future operates, a 9% reduction in stunting in Ethiopia over the most three-year evaluation
19 period, a 33% reduction in stunting in Ghana, and a 55% increase in the average Honduran income
20 between 2012 and 2014 which elevated 36,000 above the 1.25 USD per person per day poverty
21 threshold (Feed the Future 2015 Progress Report). The five-year USAID-funded development food
22 assistance program (through Food for Peace) Shouhardo II, implemented a number of agricultural
23 and maternal and child health activities in Bangladesh from 2010-2015, and demonstrated a
24 significant increase in the number of months of adequate household food provisioning from 5.9% at
25 the start of the program to 11% in the final evaluation, and an 81% increase in the average

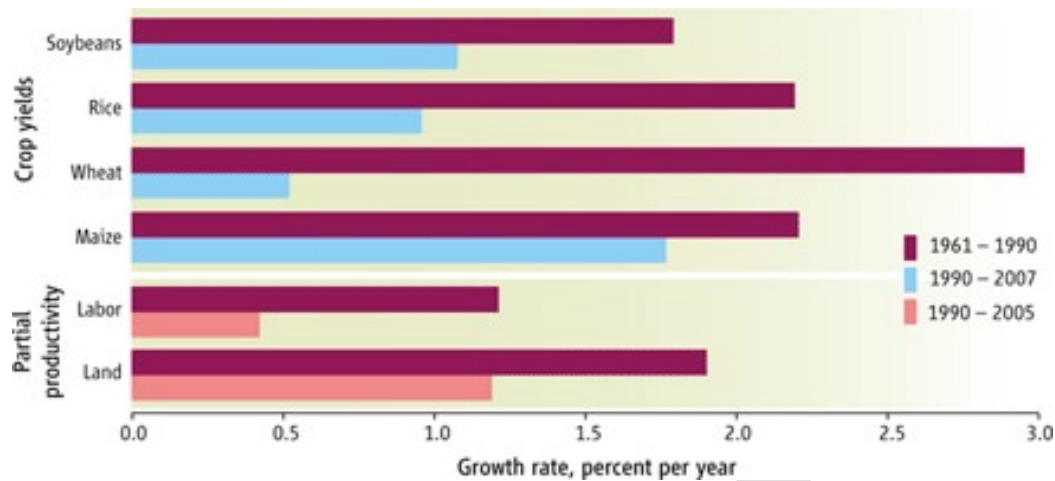
1 household dietary diversity, an indication of household socioeconomic status in the target area. In
2 addition, the program saw a significant decrease in stunting of nearly 21% in children 6-59 months
3 (from 61.7% to 48.8%) and a significant increase in the percent of women receiving antenatal care
4 from 47.1% to 85.3% (TANGO 2015). In another example, the WALA program produced a
5 significant reduction in stunting of 12.5% in Malawi among children 6-59 months (from 42.4% to
6 37.1%) from the start of the program to final evaluation, and an increase in the proportion of
7 deliveries attended by a skilled health professional from 78% to 88.5% in target areas. In addition,
8 the WALA program enabled an increase in the modified household of 14% between the start of the
9 program and final evaluation, and a decrease in the proportion of households that reported losses
10 of livelihood assets due to shocks and stresses from 7.8% to 6.8% (CRS 2014). Finally, USAID funds
11 the Famine Early Warning System Network (FEWS NET). Every three months, FEWS NET analysts
12 conduct scenario-building exercises to estimate food security outcomes for the coming six months.
13 The situation in areas of concern is assessed and assumptions are made about the future in order to
14 consider how those assumptions might affect food and income for poor households. Then, the most
15 likely scenario is determined and the expected level of food insecurity is classified. Finally, major
16 events or changes that could affect the outcome, including climate-related events, are identified to
17 inform decision makers and contribute to emergency response planning. FEWS NET has used
18 scenario building to assess the impact of drought on poor farming households in Somalia and
19 project the impact of extensive flooding in Nigeria on the regional market (Husak et al. 2013).

20 **8.3.3 Technology and Information Assistance**

21 The U.S. has been a world leader in the development of new technologies that have greatly
22 increased the quantity and quality of food over the past 100 years (Mowery and Rosenberg 1998 p.
23 6). Organized public and private investment in agricultural research was a major contributor to the
24 rapid growth in agricultural productivity experienced since the 1950s (Evenson et al. 1979). Wang
25 et al. (2013) find a strong direct relationship between public investment in agricultural R&D and

1 total factor productivity (TFP). Fuglie and Rada (2013) argue that changes in TFP are a robust
2 measure of the effect of new agricultural technologies, an indication of the rate at which basic
3 research is translated into practical applications. TFP has been rising in many developing countries
4 (Ray et al. 2012). In many regions, crop yields and TFP have remained low; it is possible this may
5 be the result of little agricultural research and investment.

6 Alston et al. (2009) observe that in the past, most countries (especially low-income countries) have
7 relied heavily on knowledge and technology resulting from agricultural research by a small number
8 of developed countries, including the U.S. Some such technologies include crop breeding that
9 increased crop tolerance to drought, heat, and salinity, as well as early maturation breeds that
10 shorten the growing season and reduce farmers' exposure to risk of extreme weather events
11 (Lybbert and Sumner 2012). Such technologies are expected to provide critical climate change
12 adaptation possibilities for developing countries. Looking into the future, technology will need to
13 play a large role in helping farmers everywhere increase the productivity of their operations,
14 especially in the face of challenging climate changes. However, current productivity trends are not
15 promising. Alston et al. (2009) note a global slow-down in the rate of yield growth in wheat, rice,
16 maize, and soybeans over the period 1990-2007 versus the period 1960-1990. They postulate that
17 declining investment in agricultural research and development globally, but especially in high-
18 income countries like the U.S., is a primary driver of lower yield growth. There has been a global
19 commitment to increase investments in agricultural development, hunger, and undernutrition,
20 which may result in an increased rate of yield growth (Flora 2010). Figures 8.3 and 8.4
21 demonstrate a relatively close correspondence in growth rates between U.S. public investment in
22 agricultural research and development and global crop yield and productivity growth over the
23 period of 1950-2007. While increasing private-sector research has compensated for some of the
24 loss of public investment in agricultural research and development to some extent, public
25 divestment comes at a time when concerns about stagnating yields for major crops such as rice,
26 maize, and soybeans have been raised (Cassman et al. 2003).

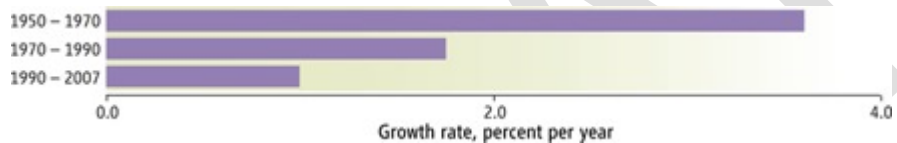


1

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

6

7



8

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

13 Conventional breeding approaches to increasing climate-resilience in crops will be important in the
 14 future (Tester and Langridge 2010). Especially important are the development of new technologies
 15 that improve genotyping and phenotyping methods and the expansion of available genetic diversity
 16 in breeding germplasm. The biggest opportunity to improve food security with those technologies
 17 is to deliver them to developing countries in a form that is economically accessible and readily
 18 disseminated (Tester and Langridge 2010). Recent experiences with the development and use of
 19 GM crops such as maize and soybeans in the U.S. illustrate the potential for GM crops to increase
 20 yields in other areas (Xu et al. 2013). There is insufficient evidence to assess the degree to which
 21 GM crops can potentially contribute to overall global food security in the future, but it does appear

1 that genetic engineering, along with conventional breeding approaches (section 8.1.2), have the
2 technical potential to play a significant role in expanding global agricultural capacity.

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

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

24 The recent emergence of "Climate-Smart Agriculture" (CSA) (FAO 2014a), which intends to
25 simultaneously increase productivity, conserve natural resources, and adapt to changing climate

1 patterns, is one example of an organized movement to engage governments to expedite and focus
2 adaptation to climate change. The FAO (2014a) states that “CSA integrates the three dimensions of
3 sustainable development (economic, social, and environmental) by jointly addressing food security
4 and climate challenges. It is composed of three main pillars: 1) sustainably increasing agricultural
5 productivity and incomes; 2) adapting and building resilience to climate change; and 3) reducing
6 and/or removing GHG emissions, where possible.” Rather than a set of prescribed technologies or
7 policies, CSA is a conceptual framework that encourages governments and other food-related
8 institutions to take an organized approach to preparing food systems to cope with climate change.
9 CSA has four operational goals (Lipper et al. 2014). Firstly, CSA seeks to build an evidence-based
10 catalog of adaptation options that are shown to be effective in certain situations and locations
11 (Lipper et al. 2014). Secondly, it focuses on improving institutional efficiency in disseminating
12 adaptive strategies. Four main areas that require public support to complement private efforts in
13 that regard are identified: “(1) extension and information dissemination, particularly on using
14 evidence to adapt practices to local conditions; (2) coordinated efforts where practices generate
15 positive spillover benefits, for instance by reducing flood risks or pest outbreaks, or preserving
16 biodiversity; (3) comprehensive risk-management strategies for managing extreme weather events
17 that affect many farmers simultaneously; and (4) reliable, timely and equitable access to inputs to
18 support resource-use efficiency” (Lipper et al. 2014). Thirdly, CSA aims to improve coordination
19 between national agricultural, climate change/environmental and food system policies. Fourthly,
20 CSA seeks to improve the targeting of financing to support the transition to CSA. In particular, the
21 linkage of climate-related financing (e.g., Global Environment Fund and others) with traditional
22 sources of agricultural finance is an important part of these efforts.

23 **8.4 Domestic Changes Resulting from Global Changes**

24 Given changes in the expectations of U.S. producers, then, to participate in the world market,
25 changes in transportation infrastructure for moving food from its place of origin to its ultimate

1 consumer can be decisive. For example, given a globally averaged 0.61m rise in sea level – roughly
2 that which might be expected under RCPs 6.0 or 8.5 (Church et al. 2013) - Kafalenos et al. (2008)
3 predict that 64% of the U.S. Gulf Coast region’s port facilities may be inundated, while an additional
4 20% of highway arterial miles and 19% of total interstate miles would be at risk by 2100. A 1.22 m
5 sea-level rise, which exceeds current RCP 8.5 estimates (Church et al. 2013), would likely inundate
6 nearly three-quarters of Gulf-region port facilities; 28% of highway arterial miles and 24% of
7 interstate miles would also be at risk. The study also found that storm surge could significantly
8 affect rail transport, though sea-level rise alone was a lesser concern for that mode of food
9 shipment. A 5.5 m storm surge would place one-third of the rail lines in the region at risk, while a
10 7 m storm surge would place 41% of rail lines and 51% of freight facilities in the region at risk by
11 2100, challenging the transportation system’s capacity for the timely export of food.

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

24 U.S. agricultural producers respond to changing global market conditions by altering what they
25 grow, or other elements of their operations. Changes in climate are one source of change. As

1 consumptive demands expand and ideal production zones shift, alterations to the global food
2 supply and demand equation are likely to occur, making some foods more profitable, and others
3 less so. U.S. producers are sensitive to changes in the global market, and are likely to respond as the
4 geography of agriculture adjusts to new climatic circumstances.

5 **8.5 Conclusions**

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

15 Answers to these questions are conditioned in part by how climate change is likely to affect the U.S.
16 food system. Climate change has been ubiquitous across the U.S. over the past century. All parts of
17 the country except the Southeast have warmed and precipitation intensity has increased nearly
18 everywhere in the country. But there are important regional variations in precipitation amounts.
19 For the future, all of the U.S. is projected to warm considerably, regardless of the path of future GHG
20 emissions. Much of the Corn Belt is expected to receive less summer precipitation, although most of
21 the country is projected to receive higher winter precipitation than current. Such climate changes
22 are likely to have important effects on U.S. agricultural production. While production across most
23 of the U.S. should be able to accommodate the initial stages of climate change without major yield
24 loss by implementing simple agronomic adjustments such as irrigation timing and amounts and
25 cultivar choices, as climate change continues, crop yields, livestock production and revenues are

1 expected to decline. Decline estimates are likely to be on the low end because of less well-known
2 indirect climate effects on factors, such as pest and pathogens, which are currently excluded from
3 yield and livestock loss modeling and estimates.

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

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

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

21 The U.S. has been influential in developing and disseminating new technologies designed to help
22 farmers worldwide cope with climate change. The U.S. has been a major source of innovations that
23 have helped increase agricultural productivity, not just for U.S. producers, but for producers in
24 other countries, too. Investment in agricultural research and development is important to
25 improving yields. Many tools exist or may be developed to maintain or improve robust food

1 systems under climate change, including agronomic and conventional crop breeding adjustments,
2 GM crops, and sophisticated computerized decision-making tools for managing risk. Climate Smart
3 Agriculture is among the first organized efforts to encourage investment in adapting food systems
4 to climate change by integrating sustainable development goals with locally tailored adaptation
5 strategies. CSA is gaining momentum in the research, translational, and popular literature.

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

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

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CHAPTER 9: REPORT CONCLUSIONS

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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. The sustainable development goals currently being negotiated in the United Nations include a call to “End hunger, achieve food security and improved nutrition and promote sustainable agriculture” by 2030 (UN 2014). 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 1990-92, or 19% of 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). So the number of food insecure people in the world has been reduced by about 20%, and the proportion almost halved in the last quarter century, but at least two 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 temperatures have already increased 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, accompanied by increases in precipitation, precipitation intensity, floods, extreme heat events (day and night), and droughts, rising sea level, 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.

1 **Climate change is very likely to affect global, regional, and local food security by disrupting**
2 **food availability, decreasing access to food, and making utilization more difficult.** Climate
3 change is projected to result in more frequent disruption of food production in many regions and
4 increased overall food prices. Climate risks to food security are greatest for poor populations and in
5 tropical regions. Wealthy populations and temperate regions that are not close to limiting
6 thresholds for food availability, access, utilization, or stability are less at risk. Some high-latitude
7 regions may actually experience near-term productivity increases due to high adaptive capacity,
8 CO₂ fertilization, higher temperatures, and precipitation increases. However, damaging outcomes
9 become increasingly likely in all cases from 2050-2100 under higher emissions scenarios.

10
11 **Climate change's potential to affect global food security is important for food producers and**
12 **consumers in the United States.** The U.S. is part of a highly integrated global food system:
13 Climate-driven changes in the U.S. influence other nations, and changes elsewhere influence the U.S.
14 The U.S. appears likely to experience changes in the types and cost of foods available for import.
15 The U.S. is similarly likely to experience increased demand for agricultural exports from regions
16 that experience production difficulties yet have sufficient wealth to purchase imports; the U.S. is
17 likely to be able to meet increased export demand in the near-term. Demand for food and other
18 types of assistance from the U.S. could increase in nations that lack purchasing power. In the
19 longer-term and for higher emissions scenarios, increased water stress associated with climate
20 change could diminish the export of "virtual water" in agricultural commodities. Climate change is
21 likely to increase demand from developing nations with relatively low per hectare yields for
22 advanced technologies and practices, many of which are developed in the U.S.

23
24 **Climate change risks extend beyond agricultural production to other elements of global food**
25 **systems that are critical for food security, including processing, storage, transportation, and**
26 **consumption of food.** Production is affected by temperature increases, changes in the amount,

1 timing, and intensity of precipitation, and reduced availability of water in dry areas. Processing,
2 packaging, and storage, are very likely to be affected by temperature increases that could increase
3 costs and spoilage. Temperature increases could also make utilization more difficult by increasing
4 food safety risks. Sea level rise and precipitation changes alter river and lake levels, and extreme
5 heat can impede waterborne, railway, and road transportation. Constraints in one component of
6 food security may often be compensated through another – e.g., food insecurity may be avoided
7 when production decreases (*availability*) are substituted with food acquired through purchase
8 (*access*). Alternatively, constrictions at one point within the food system may be so severe, or have
9 no feasible alternative possibilities within a local context, that food security may be compromised –
10 e.g., a country with ample food production, but inadequate transport conduits, has more limited
11 capacity for food purchases by remote populations. As a consequence of these interactions and
12 dependencies, a systems-based approach is needed to understand the implications of climate
13 change.

14
15 **Climate risks to food security increase as the magnitude and rate of climate change**
16 **increases. High emissions and concentrations of greenhouse gases are much more likely to**
17 **have damaging effects than lower emissions and concentrations.** Worst case projections based
18 on high GHG concentrations, high population growth, and low economic growth imply that the
19 number of people at risk of undernourishment would increase by as much as 175 million above
20 today's level by 2080. The same socioeconomic conditions with GHG concentrations of about 550
21 parts per million result in up to 60 million additional people at risk, while concentrations of about
22 350 ppm – less than today's level – do not increase risk. Scenarios with lower population growth
23 and more robust economic growth result in large reductions in the number of food insecure people
24 compared to today, even when climate change is included, but higher emissions still result in more
25 food insecurity than lower emissions.

26

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

10
11 **The complexity of the food system within the context of climate change allows for the**
12 **identification of multiple food security intervention points which are relevant to decision**
13 **makers at every level.** The future need for, and cost of, adaptation are lower under lower
14 emissions scenarios. Trade decisions could help to avoid large-scale price shocks and maintain
15 food availability in the face of regional production difficulties such as drought. Improved
16 transportation systems help to reduce food waste and enable participation in agricultural markets.
17 Public and private sector investments in agricultural research and development, coupled with rapid
18 deployment of new techniques, can help to ensure continued innovation in the agricultural sector.
19 Refined storage and packaging techniques and materials could keep foods safer for longer, and
20 allow for longer-term food storage where refrigeration is absent and food availability is transient.

21
22 **Accurately projecting climate change risks to food security requires consideration of other**
23 **large-scale changes.** Ecosystem and land degradation, technological development, population
24 growth, and economic growth affect climate risks and food security outcomes. Population growth,
25 which is projected to add another two billion people to Earth's population by 2050, increases the
26 magnitude of the risk, particularly when coupled with economic growth that leads to changes in the

1 types of foods demanded by consumers. Sustained economic growth can help to reduce
2 vulnerability if it reduces the number of poor people and if income growth exceeds increases in
3 food costs in vulnerable populations. Analyses based on hypothetical scenarios of sustained
4 economic growth and moderate population growth without climate change suggest that the
5 number of food insecure people could be reduced by 50% or more by 2040, with further reductions
6 over the rest of the century. Such analyses should not be misinterpreted as projections, since
7 climate change is already occurring, but they clearly indicate that socioeconomic factors have large
8 effects on food insecurity.

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APPENDIX B: COMMONLY USED ABBREVIATIONS

AAAS	American Association for the Advancement of Science
AgMIP	Agricultural Model Inter-comparison and Improvement Project
AR	Assessment Report
CGE	Computable General Equilibrium
CCGA	Chicago Council on Global Affairs
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	Inter-governmental Panel on Climate Change
ISI-MIP	Inter-sectoral Impact Model Inter-comparison 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	U.S. 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)

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APPENDIX C: GLOSSARY

1

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

4 **Access:** Having sufficient resources to obtain appropriate foods for a nutritious diet.

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

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

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

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

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

18 **Availability:** Sufficient quantities of food available on a consistent basis; addresses the “supply
19 side” of food security and is determined by the level of food production, stock levels, and net trade.
20 Availability doesn’t guarantee access.

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

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

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

6 **Biophysical:** Describes biotic and abiotic factors in biological systems.

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

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

10 **Carbon sequestration:** The uptake (i.e., the addition of a substance of concern to a reservoir) of
11 carbon-containing substances, in particular carbon dioxide (CO₂), in terrestrial or marine
12 reservoirs. Biological sequestration includes direct removal of CO₂ from the atmosphere through
13 land-use change, afforestation, reforestation, revegetation, carbon storage in landfills, and practices
14 that enhance soil carbon in agriculture (e.g., cropland management, grazing land management).

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

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

22 **Climate change:** A long-term change, or trend, in the state of the climate generally driven by an
23 external factor, persisting for decades to centuries, or longer. Climate change is usually described

1 statistically by changes in the mean and/or the variability of atmospheric properties such as
2 temperature and precipitation.

3 • **Natural climate change** is caused by internal climate system processes, such as cyclical
4 changes in atmospheric and ocean circulation, or natural forces external to the climate
5 system, such as volcanic eruptions or a decrease or increase in solar energy entering the
6 atmosphere.

7 • **Anthropogenic climate change** is caused by human activities, such as land-use change or
8 industrial processes that result in GHG emissions that change the composition of the
9 atmosphere, and is in addition to natural climate variability observed over comparable time
10 periods.

11 • **Climate change impact assessment** – the practice of identifying and evaluating, in
12 monetary and/or non-monetary terms, the effects of climate change on natural and human
13 systems.

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

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

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

22 **Climate projection:** The simulated response of the climate system to a scenario of future emission
23 or concentration of GHG and aerosols generally derived using climate models.

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

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

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

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

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

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

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

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

9 **Downscaling:** A method that derives local- to regional-scale (generally one to a few tens of
10 kilometers) information from larger scale models or data analyses. There are two main methods:
11 dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the
12 output of regional climate models, global models with variable spatial resolution, or high-resolution
13 global models. The empirical/statistical method employs observed statistical relationships that link
14 the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality
15 of the driving model remains an important limitation on the quality of the downscaled information.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

13 **Food supply chain:** a network of food-related business enterprises through which food products
14 move from production through consumption, including preproduction and post consumption
15 activities.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

11 **Just In Time** - An inventory strategy companies employ to increase efficiency and decrease waste
12 by receiving goods only as they are needed in the production process, thereby reducing inventory
13 costs.

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

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

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

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

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

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

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

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

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

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

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

21 **Processing:** Processing is the transformation of raw ingredients into food, or of food into other
22 forms. Food processing typically takes harvested crops or animal products and adds value to these

1 to produce attractive, marketable and often long shelf-life food products that can be purchased in a
2 store.

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

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

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

13 **Representative Agricultural Pathways:** A consistent narrative together with quantitative
14 information about the economic, technological, social and institutional context in which agricultural
15 development occurs that can be used for agricultural model inter-comparison, improvement and
16 impact assessment in a manner consistent with the new global pathways and scenarios.

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

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

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

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

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

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

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

20 **Senesce:** The process by which plants age, leading to organ or plant death while metabolites are
21 recycled.

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

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

6 **Socioeconomic:** Relating to or concerned with social or economic factors.

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

12 **Stability:** The consistency of the three other components of food security (availability, access, and
13 utilization) on a seasonal or annual basis or as a result of unpredictable events.

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

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

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

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

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

6 **Uncertainty:** An expression of the degree to which a value (e.g., the future state of the *climate*
7 *system*) is unknown. Uncertainty can result from lack of information or from disagreement about
8 what is known or even knowable. It may have many types of sources, from quantifiable errors in
9 the data to ambiguously defined concepts or terminology, or uncertain *projections* of human
10 behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a range of values
11 calculated by various models) or by qualitative statements (e.g., reflecting the judgement of a team
12 of experts).

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

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

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

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

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

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

9 **Wasting:** Acute malnutrition, or “wasting”, results from a rapid decrease in food consumption over
10 a short period of time and from illness. It is measured by calculating a child’s weight for age and
11 comparing that to the median of a reference population. If the child’s weight-for-height falls below
12 two standard deviations of the median the child is considered wasted. Wasting can also be
13 measured through checking a child’s or adult’s Mid-Upper Arm Circumference.

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

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

20

APPENDIX D: REFERENCES

- 1
- 2 Abatzoglou, J. T., & Brown, T. J. (2012). A comparison of statistical downscaling methods suited for
3 wildfire applications. *International Journal of Climatology*, 32(5), 772–780. doi: 10.1002/joc.2312
- 4 Abbott, P. C., & de Battisti, A. B. (2011). Recent global food price shocks: Causes, consequences and
5 lessons for African government and donors. *Journal of African Economies*, 20(1), i12–i62. doi:
6 10.1093/jae/ejr007
- 7 Acemoglu, D. (2008). *Introduction to modern economic growth*. Princeton, NJ: Princeton University
8 Press.
- 9 Adger, W. N., Agrawala, S., Mirza, M. M. Q., Conde, C., O'Brien, K., Pulhin, J., Takahashi, K. (2007).
10 Assessment of adaptation practices, options, constraints and capacity. In M. L. Parry, O. F. Canziani,
11 J. P. Palutikof, P. J. v. d. Linden, & C. E. Hanson (Eds.), *Contribution of working group II to the fourth
12 assessment report of the Intergovernmental Panel on Climate Change* (pp. 717–743). Cambridge,
13 United Kingdom: Cambridge University Press.
- 14 Affholder, F., Poeydebat, C., Corbeels, M., Scopel, E., & Tittone, P. (2013). The yield gap of major
15 food crops in family agriculture in the tropics: Assessment and analysis through field surveys and
16 modelling. *Field Crops Research*, 143, 106–118. doi: 10.1016/j.fcr.2012.10.021
- 17 Affognona, H., Mutungi, C., Sanginga, P., & Borgemeister, C. (2015). Unpacking postharvest losses in
18 Sub-Saharan Africa: A meta-analysis. *World Development*, 66, 49–68.
- 19 Agrios, G. N. (2005). *Plant pathology* (5th ed.). New York, NY: Academic Press.
- 20 Aker, J., Klein, M. W., O'Connell, S. A., & Yang, M. (2010). *Are borders barriers? The impact of
21 international and internal ethnic borders on agricultural markets in West Africa* (Working Paper
22 208). Washington, DC: Center for Global Development.
- 23 Alexandratos, N., & Bruinsma, J. (2012). *World agriculture towards 2030/2050: The 2012 revision*
24 (ESA Working Paper No. 12-03). Rome, Italy: FAO.
- 25 Alston, J. M., Pardey, P. G., James, J. S., & Andersen, M. A. (2009). The economics of agricultural R&D.
26 *Annual Review of Resource Economics*, 1, 537–565.
- 27 Altay, N., & Ramirez, A. (2010). Impact of disasters on firms in different sectors: Implications for
28 supply chains. *Journal of Supply Chain Management*, 46(4), 59–80. doi: 10.1111/j.1745-
29 493X.2010.03206.x
- 30 Altieri, M. A., & Toledo, V. M. (2011). The agroecological revolution in Latin America: Rescuing
31 nature, ensuring food sovereignty and empowering peasants. *Journal of Peasant Studies*, 38, 587–
32 612.
- 33 Altizer, S., Ostfeld, R. S., Johnson, P. T. J., Kutz, S., & Harvell, C. D. (2013). Climate change and
34 infectious diseases: From evidence to a predictive framework. *Science*, 341, 514–519. doi:
35 10.1126/science.1239401
- 36 Anderson, K. (2010). Globalization's effects on world agricultural trade, 1960–2050. *Philosophical
37 Transactions of the Royal Society B*, 365(1554), 3007–3021. doi: 10.1098/rstb.2010.0131
- 38 Anderson, K., Rausser, G., & Swinnen, J. (2013). Political economy of public policies: Insights from
39 distortions to agricultural and food markets. *Journal of Economic Literature*, 51(2), 423–477.
40 doi: 10.1257/jel.51.2.423
- 41 Anderson, P. K., Cunningham, A. A., Patel, N. G., Morales, F. J., Epstein, P. R., & Daszak, P. (2004).
42 Emerging infectious diseases of plants: Pathogen pollution, climate change and agrotechnology
43 drivers. *Trends in Ecology & Evolution*, 19(10), 535–544.

- 1 Andrady, A. L., Hamid, H. S., & Torikai, A. (2003). Effects of climate change and UV-B on materials.
2 *Photochemical and Photobiological Sciences*, 2, 68–72.
- 3 Angel, J. R., & Kunkel, K. E. (2010). The response of Great Lakes water levels to future climate
4 scenarios with an emphasis on Lake Michigan–Huron. *Journal of Great Lakes Research*, 36, 51–58.
- 5 Antle, J. M. (2011). Parsimonious multi-dimensional impact assessment. *American Journal of*
6 *Agricultural Economics*, 93, 1292–1311.
- 7 Antle, J. M., Valdivia, R. O., Boote, K. J., Janssen, S., Jones, J. W., Porter, C. H., . . . Thorburn, P. J. (2015).
8 AgMIP’s trans-disciplinary agricultural systems: Approach to regional integrated assessment of
9 climate impact, vulnerability and adaptation. In C. Rosenzweig & D. Hillel (Eds.), *Handbook of*
10 *climate change and agroecosystems: The Agricultural Model Intercomparison and Improvement*
11 *Project integrated crop and economic assessments, Part 1*. London, United Kingdom: Imperial College
12 Press.
- 13 Arctic Climate Impact Assessment. (2004). *Impacts of a warming Arctic: Arctic Climate Impact*
14 *Assessment (ACIA) overview report*. Cambridge, United Kingdom: Cambridge University Press.
- 15 Attavanich, W., McCarl, B. A., Ahmedov, Z., Fuller, S. W., & Vedenov, D. V. (2013). Effects of climate
16 change on US grain transport. *Nature Climate Change*, 3, 638–643.
- 17 Attavanich, W., Rashford, B. S., Adams, R. M., & McCarl, B. A. (2014). Land use, climate change, and
18 ecosystem services. In J. M. Duke & J. J. Wu (Eds.), *Oxford handbook of land economics* (pp. 255–280).
19 Oxford, United Kingdom: Oxford University Press.
- 20 Auffhammer, M., Ramanathan, V., & Vincent, J. R. (2012). Climate change, the monsoon, and rice
21 yield in India. *Climatic Change*, 111, 411–424.
- 22 Avelino, J., Cristancho, M., Georgiou, S., Imbach, P., Aguilar, L., Bornemann, G., . . . Morales, C. (2015).
23 The coffee rust crises in Colombia and Central America (2008–2013): Impacts, plausible causes and
24 proposed solutions. *Food Security*, 7(2), 303–321. doi: 10.1007/s12571-015-0446-9
- 25 Avelino, J., Hoopen, G. M., & DeClerck, F. A. J. (2011). Ecological mechanisms for pest and disease
26 control in coffee and cacao agroecosystems of the neotropics. In B. Rapidel, F. A. J. DeClerck, J.-F. Le
27 Coq, & J. Beer (Eds.), *Ecosystem services from agriculture and agroforestry measurement and*
28 *payment* (pp. 91–117). London, United Kingdom: Earthscan.
- 29 Axelson, M. L. (1986). The impact of culture on food-related behavior. *Annual Review of Nutrition*, 6,
30 345–363. doi: 10.1146/annurev.nu.06.070186.002021
- 31 Azadi, H., & Ho, P. (2010). Genetically modified and organic crops in developing countries: A review
32 of options for food security. *Biotechnology Advances*, 28(1), 160–168. doi:
33 10.1016/j.biotechadv.2009.11.003
- 34 Badeck, F. W., Bondeau, A., Bottcher, K., Doktor, D., Lucht, W., Schaber, J., & Sitch, S. (2004).
35 Responses of spring phenology to climate change. *New Phytologist*, 162, 295–309.
- 36 Bahashwan, S. (2014). Effect of cold and hot seasons on fat, protein and lactose of Dhofari cow’s
37 milk. *Net Journal of Agricultural Science*, 2(1), 47–49.
- 38 Baigorria, G. A., Jones, J. W., Shin, D.-W., Mishra, A., & O’Brien, J. J. (2007). Assessing uncertainties in
39 crop model simulations using daily bias-corrected regional circulation model outputs. *Climate*
40 *Research*, 34, 211–222.
- 41 Baker, B. B., Hanson, J. D., Bourdon, R. M., & Eckert, J. B. (1993). The potential effects of climate
42 change on ecosystem processes and cattle production on U.S. rangelands. *Climatic Change*, 25(2),
43 97–117. doi: 10.1007/BF01661200

- 1 Bale, J. S., Masters, G. J., Hodkinson, I. D., Awmack, C., Bezemer, T. M., Brown, V. K., . . . Whittaker, J. B.
2 (2002). Herbivory in global climate change research: Direct effects of rising temperatures on insect
3 herbivores. *Global Change Biology*, 8(1), 1–16. doi: 10.1046/j.1365-2486.2002.00451.x
- 4 Bandyopadhyay, S., Kanji, S., & Wang, L. (2012). The impact of rainfall and temperature variation on
5 diarrheal prevalence in Sub-Saharan Africa. *Applied Geography*, 33, 63–72.
- 6 Barange, M., & Perry, R. I. (2009). Physical and ecological impacts of climate change relevant to
7 marine and inland capture fisheries and aquaculture. In K. Cochrane, C. De Young, D. Soto, & T.
8 Bahri (Eds.), *Climate change implications for fisheries and aquaculture: Overview of current scientific*
9 *knowledge* (FAO Fisheries and Aquaculture Technical Paper No. 530). (pp. 7–106). Rome, Italy: FAO.
- 10 Barnett, T. P., & Pierce, D. W. (2009). Sustainable water deliveries from the Colorado River in a
11 changing climate. *Proceedings of the National Academy of Sciences*, 106, 7334.
- 12 Barrett, C. (2010). Measuring food insecurity. *Science*, 327, 825–828. doi: 10.1126/science.1182768
- 13 Barrett, C. B., Bachke, M. E., Bellemare, M. F., Michelson, H. C., Narayanan, S., & Walker, T. F. (2012).
14 Smallholder participation in contract farming: Comparative evidence from five countries. *World*
15 *Development*, 40(4), 715–730. doi: 10.1016/j.worlddev.2011.09.006
- 16 Barrett, C. B., & Bevis, L. E. M. (2015). The micronutrient deficiencies challenge in African food
17 systems. In D. E. Sahn (Ed.), *The fight against hunger and malnutrition: The role of food, agriculture,*
18 *and targeted policies* (pp. 61–88). Oxford, United Kingdom: Oxford University Press.
- 19 Barrett, C. B., & Maxwell, D. G. (2005). *Food aid after fifty years: Recasting its role*. London, United
20 Kingdom: Routledge.
- 21 Beach, R. H., Adams, D., Alig, R., Baker, J., Latta, G. S., McCarl, B. A., . . . White, E. (2010). *Model*
22 *documentation for the Forest and Agricultural Sector Optimization Model with Greenhouse Gases*
23 *(FASOMGHG)*. Retrieved from
24 http://www.cof.orst.edu/cof/fr/research/tamm/FASOMGHG_Model_Documentation_Aug2010.pdf
- 25 Becker, A. H., Acciaro, M., Asariotis, R., Cabrera, E., Cretegny, L., Crist, P., . . . Velegrakis, A. F. (2013).
26 A note on climate change adaptation for seaports: A challenge for global ports, a challenge for global
27 society. *Climatic Change*, 120, 683–695.
- 28 Becker, A., Inoue, S., Fischer, M., & Schwegler, B. (2012). Climate change impacts on international
29 seaports: Knowledge, perceptions, and planning efforts among port administrators. *Climatic*
30 *Change*, 110, 5–29.
- 31 Becquey, E., Delpeuch, F., Konaté, A. M., Delsol, H., Lange, M., Zoungrana, M., & Martin-Prevel, Y.
32 (2012). Seasonality of the dietary dimension of household food security in urban Burkina Faso.
33 *British Journal of Nutrition*, 107(12), 1860–1870. doi: 10.1017/S0007114511005071
- 34 Beddington, J., Asaduzzaman, M., Clark, M., Fernandez, A., Guillou, M., Jahn M., . . . Wakhungu, J.
35 (2012). *Achieving food security in the face of climate change: Final report from the Commission on*
36 *Sustainable Agriculture and Climate Change*. Copenhagen, Denmark: CGIAR Research Program on
37 Climate Change, Agriculture and Food Security (CCAFS). Retrieved from
38 www.ccafs.cgiar.org/commission
- 39 Belan, L. L., de Jesus Jr., W. C., de Souza, A. F., Zambolim, L., Tomaz, M. A., Alvez, F. R., . . . do Amaral, J.
40 F. T. (2015). Monitoring of leaf rust in conilon coffee clones to improve fungicide use. *Australasian*
41 *Plant Pathology*, 44(1), 5–12.
- 42 Bellemare, M. (2012). As you sow, so shall you reap: The welfare impacts of contract farming. *World*
43 *Development*, 40(7), 1418–1434.
- 44 Bellemare, M. F. (2014). Rising food prices, food price volatility, and social unrest. *American Journal*
45 *of Agricultural Economics*. Advance online publication. doi: 10.1093/ajae/aau038

- 1 Bellemare, M. F., Barrett, C. B., & Just, D. R. (2013). The welfare impacts of commodity price
2 volatility: Evidence from rural Ethiopian households. *American Journal of Agricultural Economics*,
3 95(4), 877–899.
- 4 Benestad, R. E., Hanssen-Bauer, I., & Chen, D. (2008). *Empirical-statistical downscaling*. Singapore:
5 World Scientific.
- 6 Benestad, R. E., Nychka, D., & Mearns, L. O. (2012). Spatially and temporally consistent prediction of
7 heavy precipitation from mean values. *Nature Climate Change*, 2(7), 544–547. doi:
8 10.1038/nclimate1497
- 9 Bennett, M. K. (1941). Wheat in national diets. *Wheat Studies of the Food Research Institute*, 18, 37–
10 76.
- 11 Berazneva, J., & Lee, D. R. (2013). Explaining the African food riots of 2007–2008: An empirical
12 analysis. *Food Policy*, 39, 28–39. doi: 10.1016/j.foodpol.2012.12.007
- 13 Berry, N., Utila, H., Clunas, C., Viergever, K., & Tipper, R. A. (2009). *Avoiding unplanned mosaic*
14 *degradation and deforestation in Malawi*. Blantyre, Malawi: PLANVIVO.
- 15 Bhutta, Z. A., Ahmed, T., Black, R. E., Cousens, S., Dewey, K., Giugliani, E., . . . Shekar, M. (2008). What
16 works? Interventions for maternal and child undernutrition and survival. *Lancet*, 371(9610), 417–
17 440. doi: 10.1016/S0140-6736(07)61693-6
- 18 Black, R. E., Allen, L. H., Bhutta, Z. A., Caulfield, L. E., de Onis, M., Ezzati, M., . . . Rivera, J. (2008).
19 Maternal and child undernutrition: Global and regional exposures and health consequences.
20 *Lancet*, 371(9608), 243–260.
- 21 Blake, E. S., Kimberlain, T. B., Berg, R. J., Cangialosi, J. P., & Beven, J. L., II. (2013). *Tropical cyclone*
22 *report: Hurricane Sandy*. National Hurricane Center. Retrieved October 3, 2014, from
23 http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy
- 24 Borsari, B., Neri, D., Ferretti, G., Tavoletti, S., & Yu, W. W.-C. (2014). Critical evaluation of genetic
25 manipulation for improved productivity: Is this a sustainable agenda? *Issues in Agroecology—*
26 *Present Status and Future Prospectus*, 3, 43–83.
- 27 Boughton, D., & Reardon, T. (1997). Will promotion of coarse grain processing turn the tide for
28 traditional cereals in the Sahel? Recent empirical evidence from Mali. *Food Policy*, 22, 307–316.
- 29 Boyd, C., Li, L., & Brummett, R. E. (2012). Relationship of freshwater aquaculture production to
30 renewable freshwater resources. *Journal of Applied Aquaculture*, 24(2), 99–106.
- 31 Brady, N. C., & Weil, R. R. (2008). *The nature and properties of soils* (14th ed). Upper Saddle River,
32 New Jersey: Pearson Education.
- 33 Branca, G., Hissa, H., Benez, M. C., Medeiros, K., Lipper, L., Tinlot, M., . . . Bernoux, M. (2013).
34 Capturing synergies between rural development and agricultural mitigation in Brazil. *Land Use*
35 *Policy*, 30(1), 507–518. doi: 10.1016/j.landusepol.2012.04.021
- 36 Brander, K. (2010). Impacts of climate change on fisheries. *Journal of Marine Systems*, 79, 389–402.
- 37 Brander, K. M. (2007). Global fish production and climate change. *Proceedings of the National*
38 *Academy of Sciences*, 104(50), 19709–19714. doi: 10.1073/pnas.0702059104
- 39 Brashares, J. S., Golden, C. D., Weinbaum, K. Z., Barrett, C. B., & Okello, G. V. (2011). Economic and
40 geographic drivers of wildlife consumption in rural Africa. *Proceedings of the National Academy of*
41 *Sciences*, 108(34), 13931–13936. doi: 10.1073/pnas.1011526108
- 42 Brijs, T., Karlis, D., & Wets, G. (2008). Studying the effect of weather conditions on daily crash
43 counts using a discrete time-series model. *Accident Analysis and Prevention*, 40, 1180–1190.

- 1 Brooks, N., Adger, W. N., & Kelly, P. M. (2005). The determinants of vulnerability and adaptive
2 capacity at the national level and the implications for adaptation. *Global Environment Change*, 15(2),
3 151–163. doi: 10.1016/j.gloenvcha.2004.12.006
- 4 Brown, M. E. (2008). *Famine early warning systems and remote sensing data*. Heidelberg, Germany:
5 Springer Verlag.
- 6 Brown, M. E., Hintermann, B., & Higgins, N. (2009). Markets, climate change and food security in
7 West Africa. *Environmental Science and Technology*, 43(21), 8016–8020. doi: 10.1021/es901162d
- 8 Brown, M. E., Silver, K. C., & Rajagopalan, K. (2013). A city and national metric measuring isolation
9 from the global market for food security assessment. *Applied Geography*, 38, 119–128. doi:
10 10.1016/j.apgeog.2012.11.015
- 11 Brown, M. E., Tondel, F., Essam, T., Thorne, J. A., Mann, B. F., Leonard, K., . . . Eilerts, G. (2012).
12 Country and regional staple food price indices for improved identification of food insecurity. *Global*
13 *Environmental Change*, 22(3), 784–794. doi: j.gloenvcha.2012.03.005
- 14 Bryan, E., Deressa, T. T., Gbetibouo, G. A., & Ringler, C. (2009). Adaptation to climate change in
15 Ethiopia and South Africa: Options and constraints. *Environmental Science & Policy*, 12(4), 413–426.
16 doi: 10.1016/j.envsci.2008.11.002
- 17 Burfisher, M. (2011). *Introduction to computable general equilibrium models*. Cambridge, United
18 Kingdom: Cambridge University Press.
- 19 Bürger, G., Murdock, T. Q., Werner, A. T., Sobie, S. R., & Cannon, A. J. (2012). Downscaling
20 extremes—An intercomparison of multiple statistical methods for present climate. *Journal of*
21 *Climate*, 25, 4366–4388. doi: <http://dx.doi.org/10.1175/JCLI-D-11-00408.1>
- 22 Burke, M., & Lobell, D. (2010). Climate effects on food security: An overview. In D. Lobell & M. Burke
23 (Eds.), *Climate change and food security: Advances in global change research* (pp. 13–30). New York,
24 NY: Springer Science and Business Media.
- 25 Burrus, R., Jr., Dumas, C., Farrell, C., & Hall, W., Jr. (2002). Impact of low-intensity hurricanes on
26 regional economic activity. *Natural Hazards Review*, 3, 118–125.
- 27 Bush, R. (2009). Food riots: Poverty, power and protest. *Journal of Agrarian Change*, 10, 119–129.
- 28 Buzby, J. C., Unnevehr, L. J., & Roberts, D. (2008). *Food safety and imports: An analysis of FDA food-*
29 *related import refusal reports* (Economic Information Bulletin 39). Washington, DC: USDA ERS.
- 30 Byerlee, D., Diao, X., & Jackson, C. (2005). *Agriculture, rural development, and pro-poor growth:*
31 *Country experiences in the post-reform era* (Agriculture and Rural Development Discussion Paper
32 21). Washington, DC: World Bank.
- 33 Campbell, D. I., Elia, M., & Lunn, P. G. (2003). Growth faltering in rural Gambian infants is associated
34 with impaired small intestinal barrier function, leading to endotoxemia and system inflammation.
35 *Journal of Nutrition*, 133(5), 1332–1338.
- 36 Canning, D., & Bennathan, E. (2000). *The social rate of return on infrastructure investments*.
37 Washington, DC: World Bank.
- 38 Carena, M. J. (2013). Developing the next generation of diverse and healthier maize cultivars
39 tolerant to climate changes. *Euphytica*, 190, 471–479.
- 40 Carr, E. R. (2006). Postmodern conceptualizations, modernist applications: Rethinking the role of
41 society in food security. *Food Policy*, 31, 14–29.
- 42 Cassman, K., Dobermann, A., Walters, D. T., & Yang, H. (2003). Meeting cereal demand while
43 protecting natural resources and improving environmental quality. *Annual Review of Environment*
44 *and Resources*, 28, 315–358. doi: 10.1146/annurev.energy.28.040202.122858

- 1 CCGA. (2013). *Advancing global food security: The power of science, trade and business*. Chicago, IL.
- 2 CDP. (2015). *Supply chain sustainability revealed: A country comparison*. London, United Kingdom.
- 3 Ceccarelli, S., Grando, S., Maatougui, M., Michael, M., Slash, M., Haghparast, R., . . . Nachit, M. (2010).
4 Plant breeding and climate changes. *Journal of Agricultural Science*, *148*(6), 627–637. doi:
5 10.1017/S0021859610000651
- 6 Challinor, A. J., Parkes, B., & Ramirez-Villegas, J. (2015). Crop yield response to climate change
7 varies with cropping intensity. *Global Change Biology*, *21*(4), 1679–1688. doi: 10.1111/gcb.12808
- 8 Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-
9 analysis of crop yield under climate change and adaptation. *Nature Climate Change*, *4*, 287–291.
- 10 Challinor, A. J., & Wheeler, T. R. (2008). Crop yield reduction in the tropics under climate change:
11 Processes and uncertainties. *Agricultural and Forest Meteorology*, *148*(3), 343–356. doi:
12 10.1016/j.agrformet.2007.09.015
- 13 Chamberlin, J., & Jayne, T. S. (2013). Unpacking the meaning of ‘market access’: Evidence from rural
14 Kenya. *World Development*, *41*, 245–264. doi: 10.1016/j.worlddev.2012.06.004
- 15 Changnon, S. A. (1989). The 1988 drought, barges and diversion. *Bulletin of the American*
16 *Meteorological Society*, *70*, 1092–1104. doi: [http://dx.doi.org/10.1175/1520-](http://dx.doi.org/10.1175/1520-0477(1989)070<1092:TDBAD>2.0.CO;2)
17 [0477\(1989\)070<1092:TDBAD>2.0.CO;2](http://dx.doi.org/10.1175/1520-0477(1989)070<1092:TDBAD>2.0.CO;2)
- 18 Chao, P. (1999). Great Lakes water resources: Climate change impact analysis with transient GCM
19 scenarios. *Journal of the American Water Resources Association*, *35*, 1499–1507.
- 20 Chaves, M. M., Pereira, J. S., Maroco, J., Rodrigues, M. L., Ricardo, C. P. P., Osorio, M. L., . . . Pinheiro, C.
21 (2002). How plants cope with water stress in the field? Photosynthesis and growth. *Annals of*
22 *Botany*, *89*(7), 907–916. doi: 10.1093/aob/mcf105
- 23 Checkley, W., Epstein, L. D., Gilman, R. H., Figueroa, D., Cama, R. I., Patz, J. A., & Black, R. E. (2000).
24 Effects of El Niño and ambient temperature on hospital admissions for diarrhoeal diseases in
25 Peruvian children. *The Lancet*, *355*(9202), 442–450. doi: 10.1016/S0140-6736(00)82010-3
- 26 Chen, C. C., & McCarl, B. A. (2001). An investigation of the relationship between pesticide usage and
27 climate change. *Climatic Change*, *50*, 475–487.
- 28 Chen, J. (2007). Rapid urbanization in China: A real challenge to soil protection and food security.
29 *Catena*, *69*, 1–15.
- 30 Chen, R. S., & Kates, R. W. (1994). World food security: Prospects and trends. *Food Policy*, *19*(2),
31 192–208.
- 32 Chmielewski, F. M., Muller, A., & Bruns, E. (2004). Climate changes and trends in phenology of fruit
33 trees and field crops in Germany, 1961–2000. *Agricultural and Forest Meteorology*, *121*, 69–78.
- 34 Chotikapanich, D., Prasada Rao, D. S., Griffiths, W. E., Valencia, V. (2007). *Global inequality: Recent*
35 *evidence and trends* (Research Paper). Helsinki, Finland: UNU-WIDER.
- 36 Choudhury, M. L. (2006). Recent developments in reducing post-harvest losses in the Asia-Pacific
37 regio. In R. S. Rolle (Ed.), *Reports of the APO seminar on reduction of postharvest losses of fruit and*
38 *vegetables* (pp. 5–11). Tokyo, Japan: Asian Productivity Organization and the FAO.
- 39 Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., . . . Unnikrishnan A.
40 S. (2013). Sea level change. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, .
41 . . P. M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of working*
42 *group I to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge,
43 United Kingdom: Cambridge University Press.

- 1 Claessens, L., Antle, J. M., Stoorvogel, J. J., Valdivia, R. O., Thornton, P. K., & Herrero, M. (2012). A
2 method for evaluating climate change adaptation strategies for small-scale farmers using survey,
3 experimental and modeled data. *Agricultural Systems*, 111, 85–95.
- 4 Clapper, J. R. (2014). *Worldwide threat assessment of the U.S. intelligence community: Statement to*
5 *the Senate Select Committee on Intelligence*. Retrieved from
6 http://www.dni.gov/files/documents/Intelligence%20Reports/2014%20WWTA%20%20SFR_SSC
7 [I_29_Jan.pdf](http://www.dni.gov/files/documents/Intelligence%20Reports/2014%20WWTA%20%20SFR_SSC)
- 8 Clark, X., Dollar, D., & Micco, A. (2004). Port efficiency, maritime transport costs and bilateral trade.
9 *Journal of Development Economics*, 75(2), 417–450. doi: 10.3386/w10353
- 10 Cline, W. R. (2004). *Trade policy and global poverty*. Washington, DC: Peterson Institute for
11 International Economics.
- 12 CNA Military Advisory Board. (2014). *National security and the accelerating risks of climate change*.
13 Alexandria, VA: CNA.
- 14 Coakley, M., Scherm, H., & Chakraborty, S. (1999). Climate change and plant disease
15 management. *Annual Review of Phytopathology*, 37, 399–426.
- 16 Cochrane, K., De Young, C., Soto, D., & Bahri, T. (Eds.). (2009). *Climate change implications for*
17 *fisheries and aquaculture: Overview of current scientific knowledge* (FAO Fisheries and Aquaculture
18 Technical Paper No. 530). Rome, Italy: FAO.
- 19 Cole, S., Giné, X., Tobacman, J., Topalova, P., Townsend, R., & Vickery, J. (2009). *Barriers to household*
20 *risk management: Evidence from India*. New York, NY: Federal Reserve Bank.
- 21 Coleman-Jensen, A., Gregory, C., & Singh, A. (2014). *Household food security in the United States in*
22 *2013* (Economic Research Report No. 173). Washington, DC: USDA ERS.
- 23 Collier, P., & Dercon, S. (2014). African agriculture in 50 years: Smallholders in a rapidly changing
24 world? *World Development*, 63, 92–101. doi: 10.1016/j.worlddev.2013.10.001
- 25 Confalonieri, U., Menne, B., Akhtar, R., Ebi, K. L., Hauengue, M., Kovats, R. S., . . . Woodward, A.
26 (2007). Human health. Climate change 2007: Impacts, adaptation and vulnerability. In M. L. Parry,
27 O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Contribution of working*
28 *group II to the fourth assessment report of the Intergovernmental Panel on Climate Change* (pp. 391–
29 431). Cambridge, United Kingdom: Cambridge University Press.
- 30 Cook, K. H., & Vizzy, E. K. (2012). Impact of climate change on mid-twenty-first century growing
31 seasons in Africa. *Climate Dynamics*, 39(12), 2937–2955.
- 32 Cook, S. M., Glass, R. I., LeBaron, C. W., & Ho, M. S. (1990). Global seasonality of rotavirus infections.
33 *Bulletin of the World Health Organization*, 68(2), 171–177.
- 34 Cooley, S. R., & Doney, S. C. (2009). Anticipating ocean acidification's economic consequences for
35 commercial fisheries. *Environmental Research Letters*, 4(2), 024007. doi: 10.1088/1748-
36 9326/4/2/024007
- 37 Cooper, K. M., McMahon, C., Fairweather, I., & Elliott, C. T. (2014). Potential impacts of climate
38 change on veterinary medicinal residues in livestock produce: An island of Ireland perspective. -
39 *Trends in Food Science and Technology*. Advance online publication. doi: 10.1016/j.tifs.2014.03.007
- 40 Cooper, K., Parsons, D. J., & Demmers, T. (1998). A thermal balance model for livestock buildings for
41 use in climate change studies. *Journal of Agricultural Engineering Research*, 69(1), 43–52. doi:
42 10.1006/jaer.1997.0223
- 43 Cornia, G. A., Deotti, L., & Sassi, M. (2012). *Food price volatility over the last decade in Niger and*
44 *Malawi: Extent, sources and impact on child malnutrition*. Rome, Italy: UN Development Programme.

- 1 Cotty, P. J., & Jaime-Garcia, R. (2007). Influences of climate on aflatoxin producing fungi and
2 aflatoxin contamination. *International Journal of Food Microbiology*, 119(1-2), 109-115. doi:
3 10.1016/j.ijfoodmicro.2007.07.060
- 4 Cotula, L., Vermeulen, S., Leonard, R., & Keeley, J. (2009). *Land grab or development opportunity?*
5 *Agricultural investments and international land deals in Africa*. London, United Kingdom:
6 International Institute for Environment and Development.
- 7 Coughlan de Perez, E., van Aalst, M., Deva, C., van den Hurk, B., Jongman, B., Klose, T., . . . Suarez, P.
8 (2014). *Managing the risk of extreme events in a changing climate: Trends and opportunities in the*
9 *disaster-related funding landscape*. Geneva, Switzerland: UNISDR.
- 10 Coulomb, D. (2008). Refrigeration and cold chain serving the global food industry and creating a
11 better future: Two key IIR challenges for improved health and environment. *Trends in Food Science*
12 *and Technology*, 19, 413-417.
- 13 Coumou, D., & Rahmstorf, S. (2012). A decade of weather extremes. *Nature Climate Change*, 2, 491-
14 496. doi: 10.1038/nclimate1452
- 15 Coumou, D., & Robinson, A. (2013). Historic and future increase in the global land area affected by
16 monthly heat extremes. *Environmental Research Letters*, 8, 034018. doi: 10.1088/1748-
17 9326/8/3/034018
- 18 Crane, T. A., Roncoli, C., & Hoogenboom, G. (2011). Adaptation to climate change and climate
19 variability: The importance of understanding agriculture as performance. *Wageningen Journal of*
20 *Life Sciences*, 57, 179-185.
- 21 CRS. (2014). *Final evaluation: CRS Malawi WALA program 2009-2014* (Volume I - Main Report).
22 Retrieved from http://pdf.usaid.gov/pdf_docs/PA00K2WJ.pdf
- 23 Crush, J., & Frayne, B. (2011). Supermarket expansion and the informal food economy in southern
24 African cities: Implications for urban food security. *Journal of Southern African Studies*, 37, 781-807.
- 25 Cutter, S. L., Arnold, M., Balk, D., Hovy, B., Kwan, M. -P., Mayer, J. D., . . . Zuberi, T. (2007). *Tools and*
26 *methods for estimating populations at risk from natural disasters and complex humanitarian crises*.
27 Washington, DC: National Academies Press.
- 28 Dahdouh-Guebas, F., Jayatissa, L. P., Nitto, D. D., Bosire, J. O., Seen, D. L., & Koedam, N. (2005). How
29 effective were mangroves as a defence against the recent tsunami? *Current Biology*, 15(12), R443-
30 R447. doi: 10.1016/j.cub.2005.06.008
- 31 Dangour, A. D., Green, R., Häsler, B., Rushton, J., Shankar, B., & Waage, J. (2012). Linking agriculture
32 and health in low- and middle-income countries: An interdisciplinary research agenda. *Proceedings*
33 *of the Nutrition Society*, 71, 222-228. doi: 10.1017/S0029665112000213
- 34 Davis, C. G., Thomas, C. Y., & Amponsah, W. A. (2001). Globalization and poverty: Lessons from the
35 theory and practice of food security. *American Journal of Agricultural Economics*, 83, 714-721.
- 36 Davis, M. (2002). *Late Victorian holocausts: El Niño famines and the making of the third world*.
37 London, United Kingdom: Verso.
- 38 Daw, T., Adger, W. N., Brown, K., & Badjeck, M.-C. (2009). Climate change and capture fisheries:
39 Potential impacts, adaptation and mitigation. In K. Cochrane, C. De Young, D. Soto, & T. Bahri (Eds.),
40 *Climate change implications for fisheries and aquaculture: Overview of current scientific knowledge*
41 (FAO Fisheries and Aquaculture Technical Paper No. 530) (pp. 107-150). Rome, Italy.
- 42 Deaton, A. (1989). Household survey data and pricing policies in developing countries. *World Bank*
43 *Economic Review*, 3(2), 183-210.
- 44 Deaton, A. (1997). *The analysis of household surveys*. Washington, DC: World Bank.

- 1 Deaton, A., & Dupriez, O. (2011). Purchasing power parity exchange rates for the global poor.
2 *American Economic Journal: Applied Economics*, 3(2), 137–166. doi: 10.1257/app.3.2.137
- 3 de Haen, H., Klasen, S., & Qaim, M. (2011). What do we really know? Metrics for food insecurity and
4 undernutrition. *Food Policy*, 36, 760–769. doi: 10.1016/j.foodpol.2011.08.003
- 5 Delgado, C. (2005). Rising demand for meat and milk in developing countries: Implications for
6 grasslands-based livestock production. In D. A. McGilloyay (Ed.), *Grassland: A global resource* (pp.
7 29–39). Netherlands: Wageningen.
- 8 De Lima, C. P. F. (1979). The assessment of losses due to insects and rodents in maize stored for
9 subsistence in Kenya. *Tropical Stored Products Information*, 38, 21–26.
- 10 Dellink, R., Chateau, J., Lanzi, E., & Magné, B. (2015). Long-term economic growth projections in the
11 shared socioeconomic pathways. *Global Environmental Change* (in press). Retrieved from
12 <http://dx.doi.org/10.1016/j.gloenvcha.2015.06.004>
- 13 Deloitte. (2013). *The food value chain: A challenge for the next century*. London, United Kingdom.
- 14 Dempewolf, H., Eastwood, R. J., Guarino, L., Khoury, C. K., Müller, J. V., & Toll, J. (2014). Adapting
15 agriculture to climate change: A global initiative to collect, conserve, and use crop wild relatives.
16 *Agroecology and Sustainable Food Systems*, 38(4), 369–377. doi: 10.1080/21683565.2013.870629
- 17 de Onis, M., Blössner, M., & Borghi, E. (2012). Prevalence and trends of stunting among pre-school
18 children, 1990–2020. *Public Health Nutrition*, 15(1), 142–148.
- 19 de Onis, M., Frongillo, E. A., & Blössner, M. (2000). Is malnutrition declining? An analysis of changes
20 in levels of child malnutrition since 1980. *Bulletin of the World Health Organization*, 78(10), 1222–
21 1233.
- 22 Devereux, S. (2006). *Distinguishing between chronic and transitory food insecurity in emergency*
23 *needs assessments* (Technical Report). Rome, Italy: Institute of Development Studies, WFP.
- 24 Devereux, S. (2012). *Social protection for enhanced food security in Sub-Saharan Africa* (WP 2012-
25 010). Brighton, United Kingdom: Institute of Development Studies.
- 26 de Weerd, J., Beegle, K., Friedman, J., & Gibson, J. (2014). *The challenge of measuring hunger*
27 (Working Paper). Washington, DC: World Bank.
- 28 Diffenbaugh, N. S., Hertel, T. W., Scherer, M., & Verma, M. (2012). Response of corn markets to
29 climate volatility under alternative energy futures. *Nature Climate Change*, 2, 514–518. doi:
30 10.1038/nclimate1491
- 31 Diffenbaugh, N. S., & Scherer, M. (2013). Likelihood of July 2012 U.S. temperatures in pre-industrial
32 and current forcing regimes: Explaining extreme events of 2012 from a climate perspective. *Bulletin*
33 *of the American Meteorological Society*, 94(9), S6–S9.
- 34 Dinour, L. M., Bergen, D., & Yeh, M.-C. (2007). The food insecurity-obesity paradox: A review of the
35 literature and the role food stamps may play. *Journal of the American Dietetic Association*, 107(11),
36 1952–1961. doi: 10.1016/j.jada.2007.08.006
- 37 Doak, C. M., Adair, L. S., Bentley, M., Monteiro, C., & Popkin, B. M. (2005). The dual burden household
38 and the nutrition transition paradox. *International Journal of Obesity*, 29(1), 129–136. doi:
39 10.1038/sj.ijo.0802824
- 40 do Amaral, B. C., Connor, E. E., Tao, S., Hayen, J., Bubolz, J., & Dahl, G. E. (2009). Heat-stress
41 abatement during the dry period: Does cooling improve transition into lactation? *Journal of Dairy*
42 *Science*, 92(12), 5988–5999. doi: 10.3168/jds.2009-2343

- 1 Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Zhang, T., . . . Murray, D. (2011). Was there a
2 basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters*, 38(6).
3 doi: 10.1029/2010GL046582
- 4 Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R., Dunn, R. J. H., . . . Kitching, S. (2013).
5 Updated analyses of temperature and precipitation extreme indices since the beginning of the
6 twentieth century: The HadEX2 dataset. *Journal of Geophysical Research: Atmospheres*, 118(5),
7 2098–2118. doi: 10.1002/jgrd.50150. 2013
- 8 Dougill, A. J., Fraser, E. D. G., & Reed, M. S. (2010). Anticipating vulnerability to climate change in
9 dryland pastoral systems: Using dynamic systems models for the Kalahari. *Ecology and Society*,
10 15(2). Retrieved from <http://www.ecologyandsociety.org/vol15/iss2/art17/>
- 11 Douglas, I., Alam, K., Maghenda, M., McDonnell, Y., Mclean, L., Uccellini, J., & Campbell, J. (2008).
12 Unjust waters: Climate change, flooding and the urban poor in Africa. *Environment and*
13 *Urbanization*, 20, 187–205.
- 14 Drewnowski, A., & Popkin, B. M. (1997). The nutrition transition: New trends in the global diet.
15 *Nutrition Reviews*, 55(2), 31–43. doi: 10.1111/j.1753-4887.1997.tb01593.x
- 16 Dronin, N., & Kirilenko, A. (2008). Climate change and food stress in Russia: What if the market
17 transforms as it did during the past century? *Climatic Change*, 86(1–2), 123–150.
- 18 D’Souza, R. M., Becker, N. G., Hall, G., & Moodie, K. B. (2004). Does ambient temperature affect
19 foodborne disease? *Epidemiology*, 15(1), 86–92. doi: 10.1097/01.ede.0000101021.03453.3e
- 20 Dunford, R., Harrison, P. A., Jäger, J., Rounsevell, M. D. A., & Tinch, R. (2015). Exploring climate
21 change vulnerability across sectors and scenarios using indicators of impacts and coping capacity.
22 *Climatic Change*, 128(3–4), 339–354. doi: 10.1007/s10584-014-1162-8
- 23 Easterling, D. R., & Karl, T. R. (2001). Potential consequences of climate change and variability for
24 the midwestern United States. In National Assessment Synthesis Team (Ed.), *Climate change*
25 *impacts on the United States: Overview report* (pp. 167–188). Cambridge, United Kingdom:
26 Cambridge University Press.
- 27 Easterling, W. E., Hurd, B. H., & Smith, J. B. (2004). *Coping with global climate change: The role of*
28 *adaptation in the United States*. Arlington, VA: Pew Center on Global Climate Change.
- 29 Eastwood, R., Lipton, M., & Newell, A. (2010). Farm size. In P. Pingali & R. Evenson (Eds.), *Handbook*
30 *of agricultural economics*. (pp. 3323–3397). Amsterdam, Netherlands: Elsevier.
- 31 Ebi, K. L., Hallegatte, S., Kram, T., Arnell, N. W., Carter, T. R., Edmonds, J., . . . Zwickel, T. (2014). A
32 new scenario framework for climate change research: Background, process, and future directions.
33 *Climatic Change*, 122(3), 363–372. doi: 10.1007/s10584-013-0912-3
- 34 Economist Intelligence Unit. (2015). *Global food security index, countries: Singapore*. Retrieved April
35 30, 2015, from <http://foodsecurityindex.eiu.com/Country/Details#Singapore>
- 36 Elad, Y., & Pertot, I. (2014). Climate change impacts on plant pathogens and plant diseases. *Journal*
37 *of Crop Improvement*, 28(1). doi: 10.1080/15427528.2014.865412
- 38 Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., . . . Wisser, D. (2014).
39 Constraints and potentials of future irrigation water availability on agricultural production under
40 climate change. *Proceedings of the National Academy of Sciences*, 111(9), 3239–3244.
- 41 Emran, M. S., & Hou, Z. (2013). Access to markets and rural poverty: Evidence from household
42 consumption in China. *Review of Economics and Statistics*, 95(2), 682–697. doi:
43 10.1162/REST_a_00354

- 1 Ercsey-Ravasz, M., Toroczkai, Z., Lakner, Z., & Baranyi, J. (2012). Complexity of the international
2 agro-food trade network and its impact on food safety. *PLoS One*, 7(5), e37810. doi:
3 10.1371/journal.pone.0037810
- 4 Ericksen, P. J. (2008). Conceptualizing food systems for global environmental change research.
5 *Global Environmental Change*, 18, 234–245.
- 6 Ericksen, P. J., Ingram, J. S., & Liverman, D. M. (2009). Food security and global environmental
7 change: Emerging challenges. *Environmental Science & Policy*, 12, 373–377.
- 8 Ericksen, P., Stewart, B., Dixon, J., Barling, D., Loring, P., Anderson, M., & Ingram, J. (2010). The value
9 of a food system approach. In J. Ingram, P. Ericksen, & D. Liverman (Eds.), *Food security and global
10 environmental change* (pp. 25–45). London, United Kingdom: Earthscan.
- 11 Ericksen, P., Thornton, P., Notenbaert, A., Cramer, L., Jones, P., & Herrero, M. (2011). *Mapping
12 hotspots of climate change and food insecurity in the global tropics*. London, United Kingdom: CGIAR
13 Research Program on Climate Change, Agriculture and Food Security.
- 14 Eshel, G., Shepon, A., Makov, T., & Milo, R. (2014). Land, irrigation water, greenhouse gas, and
15 reactive nitrogen burdens of meat, eggs, and dairy production in the United States. *Proceedings of
16 the National Academy of Sciences*, 111(33), 11996–12001. doi: 10.1073/pnas.1402183111
- 17 Evenson, R. E., Waggoner, P. E., & Ruttan, V. W. (1979). Economic benefits from research: An
18 example from agriculture. *Science*, 205, 1101–1107.
- 19 Ezeh, A. C., Bongaarts, J., & Mberu, B. (2012). Global population trends and policy options. *Lancet*,
20 380(9837), 142–148.
- 21 Fader, M., Gerten, D., Krause, M., Lucht, W., & Cramer, W. (2013). Spatial decoupling of agricultural
22 production and consumption: Quantifying dependences of countries on food imports due to
23 domestic land and water constraints. *Environmental Research Letters*, 8(1), 014046. doi:
24 10.1088/1748-9326/8/1/014046
- 25 Fafchamps, M. (2004). *Market institutions in Sub-Saharan Africa: Theory and evidence*. Cambridge,
26 MA: MIT Press.
- 27 Fallon, P., & Betts, R. (2010). Climate impacts on European agriculture and water management in
28 the context of adaptation and mitigation: The importance of an integrated approach. *Science of the
29 Total Environment*, 408(23), 5667–5687.
- 30 Fandohan, P., Hell, K., Marasas, W. F. O., & Wingfield, M. J. (2003). Infection of maize by
31 *Fusarium* species and contamination with fumonisin in Africa. *African Journal of Biotechnology*,
32 2(12), 570–579.
- 33 FAO. (1996). *United Nations World Food Summit: Rome declaration on world food security*. Rome,
34 Italy.
- 35 FAO. (2001). *Food balance sheets: A handbook*. Rome, Italy.
- 36 FAO. (2002a). *Crops and drops: Making the best use of water for agriculture*. Rome, Italy.
- 37 FAO. (2002b). *World agriculture: Towards 2015/2030* (Summary report). Rome, Italy.
- 38 FAO. (2003). *The state of food insecurity in the world*. Rome, Italy.
- 39 FAO. (2004). *Processed foods for improved livelihoods*. Rome, Italy.
- 40 FAO. (2005). *The importance of soil organic matter: The key to drought-resistant soil and sustained
41 food production* (FAO Soils Bulletin 80). Rome, Italy.
- 42 FAO. (2007). *Reducing fisherfolk's vulnerability leads to responsible fisheries: Policies to support
43 livelihoods and resource management* (New Directions in Fisheries Policy Brief 01). Rome, Italy.

- 1 FAO. (2008a). *Climate change and food security: A framework document*. Rome, Italy. Retrieved from
2 <http://www.fao.org/forestry/15538-079b31d45081fe9c3dbc6ff34de4807e4.pdf>
- 3 FAO. (2008b). *Climate change for fisheries and aquaculture* (Technical background document from
4 the expert consultation held on 7 to 9 April 2008). Rome, Italy.
- 5 FAO. (2008c). *Climate change: Implications for food safety*. Rome, Italy.
- 6 FAO. (2008d). *An introduction to the basic concepts of food security*. Retrieved from
7 <http://www.fao.org/docrep/013/a1936e/a1936e00.pdf>
- 8 FAO. (2009a). *From land grab to win-win: Seizing the opportunities of international investments in
9 agriculture*. Retrieved March 2012 from <ftp://ftp.fao.org/docrep/fao/011/ak357e/ak357e00.pdf>
- 10 FAO. (2009b). *The state of world fisheries and aquaculture*. Rome, Italy.
- 11 FAO. (2011a). *Price volatility in food and agricultural markets: Policy responses*. Rome, Italy.
- 12 FAO. (2011b). *The state of the world's land and water resources for food and agriculture*. New York,
13 NY: Earthscan Press.
- 14 FAO. (2012a). *The state of food insecurity in the world*. Rome, Italy.
- 15 FAO. (2012b). *The state of world fisheries and aquaculture*. Rome, Italy: FAO Fisheries and
16 Aquaculture Department.
- 17 FAO. (2013a). *Food wastage footprint impacts on natural resources* (Summary Report). Rome, Italy.
- 18 FAO. (2013b). *The state of food insecurity in the world: The multiple dimensions of food security*.
19 Rome, Italy.
- 20 FAO. (2014a). *Climate-smart agriculture*. Retrieved July 16, 2014, from
21 <http://www.fao.org/climate-smart-agriculture/en/>
- 22 FAO. (2014b). *Crop production database*. Retrieved April 10, 2014, from
23 <http://faostat.fao.org/site/339/default.aspx>
- 24 FAO. (2014c). *Refinements to the FAO methodology for estimating the prevalence of
25 undernourishment indicator*. Retrieved October 12, 2014, from <http://www.fao.org/3/a-i4046e.pdf>
- 26 FAO. (2014d). *Trade statistics database*. Retrieved April 10, 2014, from
27 <http://faostat.fao.org/site/342/default.aspx>
- 28 FAO, IFAD, & WFP. (2014). *The state of food insecurity in the world: Strengthening the enabling
29 environment for food security and nutrition*. Rome, Italy. Retrieved from [http://www.fao.org/3/a-
30 i4030e.pdf](http://www.fao.org/3/a-i4030e.pdf)
- 31 FAOSTAT. (2014a). *Country profile: Singapore*. Retrieved July 26, 2014, from
32 http://faostat.fao.org/CountryProfiles/Country_Profile/Direct.aspx?lang=en&area=200
- 33 FAOSTAT. (2014b). *Country profile: United States of America*. Retrieved July 26, 2014, from
34 <http://faostat.fao.org/site/666/default.aspx>.
- 35 FAOSTAT. (2014c). *Land use database*. Retrieved April 24, 2015, from
36 <http://faostat.fao.org/site/377/default.aspx#ancor>
- 37 FAOSTAT. (2015a). *Statistics database*. Retrieved April 15, 2015, from <http://faostat3.fao.org/>
- 38 FAOSTAT. (2015b). *Top imports – world (2011)*. Retrieved May 19, 2015, from
39 <http://faostat.fao.org/site/342/default.aspx>
- 40 FDA. (2006). *Commodity specific food safety guidelines for the lettuce and leafy greens supply chain*.
41 Washington, DC.

- 1 Fernandez-Cornejo, J., Wechsler, S., Livingston, M., & Mitchell, L. (2014). *Genetically engineered*
2 *crops in the United States* (Economic Research Report No. 162). Washington, DC: USDA ERS.
- 3 FEWS NET, RUTA, & PROMECAFE. (2014). *Coffee producer and laborer income to decline for a*
4 *second consecutive year* (Special Report Central America). Retrieved from
5 [http://www.fews.net/sites/default/files/documents/reports/FEWS%20NET%20coffee%20rust%](http://www.fews.net/sites/default/files/documents/reports/FEWS%20NET%20coffee%20rust%20shock%20report%20update_2014_02_en_0.pdf)
6 [20shock%20report%20update_2014_02_en_0.pdf](http://www.fews.net/sites/default/files/documents/reports/FEWS%20NET%20coffee%20rust%20shock%20report%20update_2014_02_en_0.pdf)
- 7 Fischer, G., Frohberg, K., Parry, M., & Rosenzweig, C. (1994). Climate change and world food supply,
8 demand and trade. *Global Environmental Change, 4*, 7–23.
- 9 Fischer, G., Frohberg, K., Parry, M. L., & Rosenzweig, C. (1996). Impacts of potential climate change
10 on global and regional food production and vulnerability. *NATO ASI Series: Climate Change and*
11 *World Food Security, 37*, 115–159.
- 12 Fischer, G., Shah, M., Tubiello, F. N., & van Velhuizen, H. (2005). Socio-economic and climate change
13 impacts on agriculture: An integrated assessment, 1990–2080. *Philosophical Transactions of the*
14 *Royal Society B, 360*, 2067–2083.
- 15 Flora, C. B. (2010). Food security in the context of energy and resource depletion: Sustainable
16 agriculture in developing countries. *Renewable Agriculture and Food Systems, 25*(S02), 118–128.
17 doi: 10.1017/S1742170510000177
- 18 Frankenberger, T. (1992). Indicators and data collection methods for assessing household food
19 insecurity. In S. Maxwell & T. Frankenberger (Eds.), *Household food security: Concepts, indicators,*
20 *measurements. A technical review* (pp. 73–134). New York, NY: UN International Children’s
21 Emergency Fund and IFAD.
- 22 Frankenberger, T., Spangler, T., Nelson, S., & Langworthy, M. (2012). *Enhancing resilience to food*
23 *security shocks in Africa* (Discussion Paper, November 2012): TANGO International and USAID.
- 24 Fromentin, J. M., & Planque, B. (1996). Calanus and environment in the eastern North Atlantic:
25 Influence of the North Atlantic oscillation on *C-finmarchicus* and *C-helgolandicus*. *Marine Ecology*
26 *Progress Series, 134*, 111–118.
- 27 Fuglie, K., & Heisey, P. (2007). *USDA Economic Research Service economic brief* (EB-10). Washington,
28 DC: USDA.
- 29 Fuglie, K., Heisey, P., King, J., Pray, C., & Schimmelpfennig, D. (2012). The contribution of private
30 industry to agricultural innovation. *Science, 338*, 1031–1032.
- 31 Fuglie, K., & Rada, N. (2013). *Resources, policy and agricultural productivity in Sub-Saharan Africa*
32 (Economic Research Report No. 145). Washington, DC: USDA ERS.
- 33 Fuglie, K., & Wang, S. L. (2012). Productivity growth in global agriculture shifting to developing
34 countries. *Choices, 27*(4), 1–7.
- 35 Fuglie, K., & Wang, S. L. (2014). *New evidence points to robust but uneven productivity growth in*
36 *global agriculture*. Retrieved July 25, 2014, from [http://www.ers.usda.gov/amber-waves/2012-](http://www.ers.usda.gov/amber-waves/2012-september/global-agriculture.aspx#.U9U2GKjc0vA)
37 [september/global-agriculture.aspx#.U9U2GKjc0vA](http://www.ers.usda.gov/amber-waves/2012-september/global-agriculture.aspx#.U9U2GKjc0vA)
- 38 Funk, C. (2012). Exceptional warming in the western Pacific-Indian Ocean warm pool has
39 contributed to more frequent droughts in eastern Africa. *Bulletin of the American Meteorological*
40 *Society, 7*(93), 1049–1051. Retrieved from [http://www1.ncdc.noaa.gov/pub/data/cmb/bams-](http://www1.ncdc.noaa.gov/pub/data/cmb/bams-sotc/extreme-events/2011/Funk.pdf)
41 [sotc/extreme-events/2011/Funk.pdf](http://www1.ncdc.noaa.gov/pub/data/cmb/bams-sotc/extreme-events/2011/Funk.pdf)
- 42 Funk, C., & Brown, M. (2009). Declining global per capita agricultural production and warming
43 oceans threaten food security. *Food Security, 1*(3), 271–289. doi: 10.1007/s12571-009-0026-y

- 1 Funk, C. C., & Budde, M. E. (2009). Phenologically-tuned MODIS NDVI-based production anomaly
2 estimates for Zimbabwe. *Remote Sensing of Environment*, 113, 115–125.
- 3 Funk, C., Dettinger, M. D., Michaelsen, J. C., Verdin, J. P., Brown, M. E., Barlow, M., & Hoell, A. (2008).
4 Warming of the Indian Ocean threatens eastern and southern African food security but could be
5 mitigated by agricultural development. *Proceedings of the National Academy of Sciences*, 105,
6 11081–11086.
- 7 Funk, C., Husak, G., Michaelsen, J., Shukla, S., Hoell, A., Lyon, B., . . . Rowland, J. (2013). Attribution of
8 2012 and 2003–12 rainfall deficits in eastern Kenya and southern Somalia. *Bulletin of the American*
9 *Meteorological Society*, 94, S45–S48.
- 10 Gale, F., & Buzby, J. C. (2009). *Imports from China and food safety issues* (Economic Information
11 Bulletin No. 52). Washington, DC: USDA ERS.
- 12 Gan, J. (2004). Risk and damage of southern pine beetle outbreaks under global climate change.
13 *Forest Ecology and Management*, 191, 61–71.
- 14 Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., . . . Godfray, H. C. J.
15 (2013). Sustainable intensification in agriculture: Premises and policies. *Science*, 341, 33–34.
- 16 Gazdar, H., & Mallah, H. B. (2013). Impact and coping strategies. *IDS Bulletin*, 44, 31–37.
- 17 Giorgi, F. (1990). On the simulation of regional climate using a limited area model nested in a
18 general circulation model. *Journal of Climate*, 3(9), 941–963.
- 19 Giorgi, F., & Mearns, L. O. (2003). Probability of regional climate change based on the Reliability
20 Ensemble Averaging (REA) method. *Geophysical Research Letters*, 30(12). doi:
21 10.1029/2003GL017130
- 22 Gitonga, Z. M., De Groote, H., Kassie, M., & Tefera, T. (2013). Impact of metal silos on households'
23 maize storage, storage losses and food security: An application of a propensity score matching. *Food*
24 *Policy*, 43, 44–55.
- 25 Global Commerce Initiative. (2009). *Information sharing report*. Armonk, NY: IBM. Retrieved from
26 http://ecr-all.org/files/Informationsharingreport_final_5_20LR.pdf
- 27 Global Exchange. (2015). *Coffee FAQ*. Retrieved May 10, 2015, from
28 <http://www.globalexchange.org/fairtrade/coffee/faq>
- 29 Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. R., . . . Toulmin, C.
30 (2010). Food security: The challenge of feeding 9 billion people. *Science*, 327, 812–818.
- 31 Godfray, H. C. J., & Garnett, T. (2014). Food security and sustainable intensification. *Philosophical*
32 *Transactions of the Royal Society B*, 369(1639), 20120273. doi: 10.1098/rstb.2012.0273
- 33 Golden, C. D., Fernald, L. C. H., Brashares, J. S., Rasolofoniaina, B. J. R., & Kremen, C. (2011). Benefits
34 of wildlife consumption to child nutrition in a biodiversity hotspot. *Proceedings of the National*
35 *Academy of Sciences*, 108(49), 19653–19656. doi: 10.1073/pnas.1112586108
- 36 Gorstein, J., Sullivan, K., Yip, R., de Onis, M., Trowbridge, F. L., Fajans, P., & Clugston, G. A. (1994).
37 Issues in the assessment of nutritional status using anthropometry. *Bulletin of the World Health*
38 *Organization*, B72, 273–283.
- 39 Gourdji, S. M., Sibley, A. M., & Lobell, D. B. (2013). Global crop exposure to critical high temperatures
40 in the reproductive period: Historical trends and future projections. *Environmental Research*
41 *Letters*, 8(2), 024041. doi: 10.1088/1748-9326/8/2/024041
- 42 Grace, K., Brown, M. E., & McNally, A. (2014). Examining the link between food price and food
43 insecurity: A multi-level analysis of maize price and birthweight in Kenya. *Food Policy*, 46, 56–65.
44 doi: 10.1016/j.foodpol.2014.01.010

- 1 Grace, K., Davenport, F., Funk, C., & Lerner, A. (2013). Child malnutrition and climate conditions in
2 Kenya. *Applied Geography*, *11*, 164–177.
- 3 Grace, K., Husak, G., Harrison, L., Pedreros, D., & Michaelsen, J. (2012). Using high resolution satellite
4 imagery to estimate cropped area in Haiti and Guatemala. *Applied Geography*, *32*, 433–440.
- 5 Grassini, P., Eskridge, K. M., & Cassman, K. G. (2013). Distinguishing between yield advances and
6 yield plateaus in historical crop production trends. *Nature Communications*, *4*. doi:
7 10.1038/ncomms3918
- 8 Gregorich, E. G., Drury, C. F., & Baldock, J. A. (2001). Changes in soil carbon under long-term maize
9 in monoculture and legume-based rotation. *Canadian Journal of Soil Science*, *81*(1), 21–31. doi:
10 10.4141/S00-041
- 11 Gregory, P., Johnson, S. N., Newton, A. C., & Ingram, J. S. I. (2009). Integrating pests and pathogens
12 into the climate change/food security debate. *Journal of Experimental Botany*, *60*, 2827–2838.
- 13 Groopman, J. D., Kensler, T. W., & Wild, C. P. (2008). Protective interventions to prevent aflatoxin-
14 induced carcinogenesis in developing countries. *Annual Review of Public Health*, *29*, 187–203.
- 15 Grosh, M., del Ninno, C., Tesliuc, E., & Ouerghi, A. (2008). *For protection and promotion: The design
16 and implementation of effective safety nets*. Washington, DC: World Bank.
- 17 GTIS. (2015). *Global trade atlas*. Retrieved April 23, 2015, from <https://www.gtis.com/gta/>
- 18 Gundersen, C., Kreider, B., & Pepper, J. (2011). The economics of food insecurity in the United
19 States. *Applied Economic Perspectives and Policy*, *33*(3), 281–303. doi: 10.1093/aep/prr022
- 20 Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., & Meybeck, A. (2011). *Global food losses
21 and food waste: Extent, causes and prevention*. Rome, Italy: FAO. Retrieved from
22 <http://www.fao.org/docrep/014/mb060e/mb060e.pdf>
- 23 Haberl, H., Erb, K.-H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., . . . Fischer-Kowalski, M.
24 (2007). Quantifying and mapping the human appropriation of net primary production in Earth's terrestrial
25 ecosystems. *Proceedings of the National Academy of Sciences*, *104*, 12942–12947.
- 26 Haddad, F., Maffia, L. A., Mizubuti, E. S. G., & Teixeira, H. (2009). Biological control of coffee rust by
27 antagonistic bacteria under field conditions in Brazil. *Biological Control*, *49*(2), 114–119. doi:
28 10.1016/j.biocontrol.2009.02.004
- 29 Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., . . . Wisser, D. (2014). Global
30 water resources affected by human interventions and climate change. *Proceedings of the National
31 Academy of Sciences*, *111*(9), 3251–3256. doi: 10.1073/pnas.1222475110
- 32 Haggblade, S. (2013). Unscrambling Africa: Regional requirements for achieving food security.
33 *Development Policy Review*, *31*, 149–176. doi: 10.1111/dpr.12001
- 34 Haile, M. G., & Kalkhul, M. (2013, September). *Volatility in the international food markets:
35 Implications for global agricultural supply and for market and price policy*. Paper presented at the
36 53rd Annual Conference of the German Society of Economic and Social Sciences in Agriculture,
37 Berlin, Germany.
- 38 Halford, N. G., Curtis, T. Y., Chen, Z., & Huang, J. (2015). Effects of abiotic stress and crop
39 management on cereal grain composition: Implications for food quality and safety. *Journal of
40 Experimental Botany*, *65*(5), 1145–1156. doi: 10.1093/jxb/eru473
- 41 Handa, S., & Mlay, G. (2006). Food consumption patterns, seasonality and market access in
42 Mozambique. *Development Southern Africa*, *23*(4), 541–560.
- 43 Hansen, J. W. (2002). Realizing the potential benefits of climate prediction to agriculture: Issues,
44 approaches, challenges. *Agricultural Systems*, *74*, 309–330.

- 1 Hanson, J. D., Baker, B. B., & Bourdon, R. M. (1993). Comparison of the effects of different climate
2 change scenarios on rangeland livestock production. *Agricultural Systems*, *41*, 487–502.
- 3 Harrison, L., Michaelsen, J., Funk, C., & Husak, G. (2011). Effects of temperature changes on maize
4 production in Mozambique. *Climate Research*, *46*, 211–222. doi: 10.3354/cr0097946.211-222
- 5 Harvell, C. D., Mitchell, C. E., Ward, J. R., Altizer, S., Dobson, A. P., Ostfeld, R. S., & Samuel, M. D.
6 (2002). Ecology—climate warming and disease risks for terrestrial and marine biota. *Science*,
7 *296*(5576), 2158–2162. doi: 10.1126/science.1063699
- 8 Hatfield, J., Takle, G., Grotjahn, R., Holden, P., Izaurrealde, R. C., Mader, T., . . . Liverman, D. (2014).
9 Agriculture. In J. M. Melillo, T. C. Richmond, & G. W. Yohe (Eds.), *Climate change impacts in the*
10 *United States: The third national climate assessment* (pp. 150–174). Washington, DC: U.S. Global
11 Change Research Program. doi: 10.7930/J02Z13FR
- 12 Hawkes, C., Turner, R., & Waage, J. (2012). *Current and planned research on agriculture for improved*
13 *nutrition: A mapping and gap analysis*. London, United Kingdom: Department for International
14 Development.
- 15 Hazell, P. B. R. (2013). Options for African agriculture in an era of high food and energy prices.
16 *Agricultural Economics*, *44*(s1), 19–27. doi: 10.1111/agec.12047
- 17 Headey, D. (2011). Rethinking the global food crisis: The role of trade shocks. *Food Policy*, *36*(2),
18 136–146. doi: 10.1016/j.foodpol.2010.10.003
- 19 Headey, D. D. (2013). The impact of the global food crisis on self-assessed food security. *World Bank*
20 *Economic Review*, *27*, 1–27.
- 21 Headey, D., & Fan, S. (2008). Anatomy of a crisis: The causes and consequences of surging food
22 prices. *Agricultural Economics*, *39*(s1), 375–391. doi: 10.1111/j.1574-0862.2008.00345.x
- 23 Hebebrand, C., & Wedding, K. (2010). *The role of markets and trade in food security: A report of the*
24 *CSIS Global Food Security Project*. Washington, DC: Center for Strategic and International Studies.
- 25 Helfer, S. (2013). Rust fungi and global change. *New Phytologist*, *201*(3), 770–780. doi:
26 10.1111/nph.12570
- 27 Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., . . . Obersteiner, M.
28 (2013). Biomass use, production, feed efficiencies, and greenhouse gas emissions from global
29 livestock systems. *Proceedings of the National Academy of Sciences*, *110*(52), 20888–20893. doi:
30 10.1073/pnas.1308149110
- 31 Herrero, M., & Thornton, P. K. (2013). Livestock and global change: Emerging issues for sustainable
32 food systems. *Proceedings of the National Academy of Sciences*, *110*(52), 20878–20881. doi:
33 10.1073/pnas.1321844111
- 34 Hertel, T. W., Burke, M. B., & Lobell, D. B. (2010). The poverty implications of climate-induced crop
35 yield changes by 2030. *Global Environmental Change*, *20*, 577–585.
- 36 Hertel, T. W., & Lobell, D. B. (2014). Agricultural adaptation to climate change in rich and poor
37 countries: Current modeling practice and potential for empirical contributions. *Energy Economics*.
38 Advance online publication. doi: 10.1016/j.eneco.2014.04.014
- 39 Hicke, J. A., & Jenkins, J. C. (2008). Mapping lodgepole pine stand structure susceptibility to
40 mountain pine beetle attack across the western United States. *Forest Ecology and Management*, *255*,
41 1536–1547.
- 42 Hillbruner, C., & Egan, R. (2008). Seasonality, household food security, and nutritional status in
43 Dinajpur, Bangladesh. *Food and Nutrition Bulletin*, *29*(3), 221–231.

- 1 Hillbruner, C., & Moloney, G. (2012). When early warning is not enough: Lessons learned from the
2 2011 Somalia famine. *Global Food Security*, 1(1), 20–28. doi: 10.1016/j.gfs.2012.08.001
- 3 HLPE. (2014). *Sustainable fisheries and aquaculture for food security and nutrition* (A report by the
4 High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food
5 Security). Rome, Italy: FAO. doi: <http://www.fao.org/3/a-i3844e.pdf>
- 6 Hnatkovska, V., & Loayza, N. (2005). Volatility and growth. In J. Aizenman & B. Pinto (Eds.),
7 *Managing economic volatility and crises: A practitioner's guide* (pp. 65–100). Cambridge, United
8 Kingdom: Cambridge University Press.
- 9 Hoekstra, A. Y., & Chapagain, A. K. (2008). *Globalization of water: Sharing the planet's fresh water*
10 *resources*. Oxford, United Kingdom: Blackwell.
- 11 Hoerling, M., Eischeid, J., Kumar, A., Leung, R., Mariotti, A., Mo, K., . . . Seager, R. (2014). Causes and
12 predictability of the 2012 Great Plains drought. *Bulletin of the American Meteorological Society*, 95,
13 269–282.
- 14 Hoffmann, I. (2010). Climate change in context: Implications for livestock production and diversity.
15 In N. E. Odongo, M. Garcia, & G. J. Vilojen (Eds.), *Sustainable improvement of animal production and*
16 *health* (pp. 33–44). Rome, Italy: FAO.
- 17 Hornbeck, R., & Keskin, P. (2014). The historically evolving impact of the Ogallala aquifer:
18 Agricultural adaptation to groundwater and drought. *American Economic Journal: Applied*
19 *Economics*, 6, 190–219.
- 20 Hostetler, S. W., Alder, J. R., & Allan, A. M. (2011). *Dynamically downscaled climate simulations over*
21 *North America: Methods, evaluation and supporting documentation for users* (Open-File Report
22 2011–1238). Reston, VA: U.S. Department of the Interior and U.S. Geological Survey.
- 23 Hsu, H.-H., & Gale, F. (2001). *China: Agriculture in transition* (Agriculture and Trade Report No.
24 WRS-012). Washington, DC: USDA ERS.
- 25 Huang, P. M., Li, Y., & Sumner, M. E. (Eds.). (2011). *Handbook of soil sciences: Resource management*
26 *and environmental impacts* (2nd ed.). Boca Raton, FL: CRC Press.
- 27 Husak, G. J., Funk, C. C., Michaelsen, J., Magadzire, T., & Goldsberry, K. P. (2013). Developing seasonal
28 rainfall scenarios for food security early warning. *Theoretical and Applied Climatology*, 111, 1–12.
29 doi: 10.1007/s00704-013-0838-8
- 30 IAASTD. (2008). *International Assessment of Agricultural Knowledge, Science and Technology for*
31 *Development*. London, United Kingdom: Island Press.
- 32 IAASTD. (2009). *Agriculture at a crossroads: International Assessment of Agricultural Knowledge,*
33 *Science and Technology for Development* (Synthesis Report). Washington, DC: Island Press.
- 34 Ibnouf, F. O. (2009). The role of women in providing and improving household food security in
35 Sudan: Implications for reducing hunger and malnutrition. *Journal of International Women's Studies*,
36 10, 144–167.
- 37 IFAD. (2001). *Rural poverty report 2001: The challenge of ending rural poverty*. Rome, Italy.
- 38 IFAD. (2011). *Rural poverty report: New realities, new challenge, new opportunities for tomorrow's*
39 *generation*. Rome, Italy.
- 40 IHS. (2014, August 5). *IHS acquires Global Trade Information Services, world's leading provider of*
41 *international merchandise trade data* (Press release). Retrieved from [http://press.ihs.com/press-](http://press.ihs.com/press-release/corporate-financial/ihs-acquires-global-trade-information-services-worlds-leading-prov)
42 [release/corporate-financial/ihs-acquires-global-trade-information-services-worlds-leading-prov](http://press.ihs.com/press-release/corporate-financial/ihs-acquires-global-trade-information-services-worlds-leading-prov)
- 43 IICA. (2013). *La crisis del café en Mesoamérica: Causas y respuesta apropiadas*. Retrieved from
44 <http://www.iica.int/Esp/prensa/BoletinRoya/2013/N01/Roya-MA.pdf>

- 1 Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the Asian
2 water towers. *Science*, 328, 1382–1385.
- 3 Ingram, J. (2011). A food systems approach to researching food security and its interactions with
4 global environmental change. *Food Security*, 3(4), 417–431.
- 5 Ingram, J. S. I., Wright, H. L., Foster, L., Aldred, T., Barling, D., Benton, T. G., . . . Sutherland, W. J.
6 (2013). Priority research questions for the UK food system. *Food Security*, 5(5), 617–636. doi:
7 10.1007/s12571-013-0294-4
- 8 International Monetary Fund. (2013). *World economic outlook 2013*. Washington, DC.
- 9 IPCC. (2007a). *Climate change 2007: Working group I: The physical science basis*. Rome, Italy.
- 10 IPCC. (2007b). *Climate change 2007: Working group II: Impacts, adaptation and vulnerability*.
11 Washington, DC.
- 12 IPCC. (2007c). *The effects of climate change on agriculture, land resources, water resources and*
13 *biodiversity*. Washington, DC.
- 14 IPCC. (2012). *Managing the risks of extreme events and disasters to advance climate change*
15 *adaptation (SREX): A special report of working groups I and II of the Intergovernmental Panel on*
16 *Climate Change*. Cambridge, United Kingdom: Cambridge University Press.
- 17 IPCC. (2013). *Climate change 2013: The physical science basis. Contribution of working group I to the*
18 *fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge, United
19 Kingdom: Cambridge University Press.
- 20 IPCC. (2014a). *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and*
21 *sectoral aspects. Contribution of working group II to the fifth assessment report of the*
22 *Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University
23 Press.
- 24 IPCC. (2014b). Summary for policymakers. In *Climate change 2014: Impacts, adaptation, and*
25 *vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fifth*
26 *assessment report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom:
27 Cambridge University Press.
- 28 Irey, M., Gottwald, T. R., Graham, J. H., Riley, T. D., & Carlton, G. (2006). Post-hurricane analysis of
29 citrus canker spread and progress towards the development of a predictive model to estimate
30 disease spread due to catastrophic weather events. *Plant Health Progress*. doi: 10.1094/PHP-2006-
31 0822-01-RS
- 32 Irz, X., Lin, L., Thirtle, C., & Wiggins, S. (2001). Agricultural productivity growth and poverty
33 alleviation. *Development Policy Review*, 19, 449–466.
- 34 Issahaku, H. (2012). An analysis of the constraints in the tomato value chain. *International Journal*
35 *of Business and Management of Tomorrow*, 2(10), 1–8.
- 36 Jacobsen, S.-E., Sørensen, M., Pedersen, S. M., & Weiner, J. (2013). Feeding the world: Genetically
37 modified crops versus agricultural biodiversity. *Agronomy for Sustainable Development*, 33(4), 651–
38 662. doi: 10.1007/s13593-013-0138-9
- 39 Jacxsens, L., Luning, P. A., van der Vorst, J. G. A. J., Devlieghere, F., Leemans, R., & Uyttendaele, M.
40 (2010). Simulation modelling and risk assessment as tools to identify the impact of climate change
41 on microbiological food safety: The case study of fresh produce supply chain. *Food Research*
42 *International*, 43(7), 1925–1935. doi: 10.1016/j.foodres.2009.07.009

- 1 Jafry, T. (2012). Global trade and climate change challenges: A brief overview of impacts on food
2 security and gender issues. *International Journal of Climate Change Strategies and Management*,
3 4(4), 442–451. doi: 10.1108/17568691211277755
- 4 James, S. J., & James, C. (2010). The food cold-chain and climate change. *Food Research International*,
5 43, 1944–1956.
- 6 James, W. P. T., Jackson-Leach, R., Ni Mhurchu, C., Kalamara, E., Shayeghi, M., Rigby, N. J., . . . Rodgers,
7 A. (2004). Overweight and obesity (high body mass index). In M. Ezzati, A. D. Lopez, A. Rodgers, & C.
8 J. L. Murray (Eds.), *Comparative quantification of health risks: Vol. 1* (pp. 497–596). Geneva,
9 Switzerland: WHO.
- 10 Jayne, T. S., Yamano, T., Weber, M., Tschirley, D., Benfica, R., Chapoto, A., & Zulu, B. (2003).
11 Smallholder income and land distribution in Africa: Implications for poverty reduction strategies.
12 *Food Policy*, 28, 253–275.
- 13 Jiménez Cisneros, B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., . . . Mwakalila, S. S.
14 (2014). Freshwater resources. In *Climate change 2014: Impacts, adaptation, and vulnerability. Part*
15 *A: Global and sectoral aspects. Contribution of working group II to the fifth assessment report of the*
16 *Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University
17 Press.
- 18 Johnson, K. B., & Brown, M. E. (2014). Environmental risk factors and child nutritional status and
19 survival in a context of climate variability and change. *Applied Geography*, 54, 209–221. doi:
20 10.1016/j.apgeog.2014.08.007
- 21 Jones, P. G., & Thornton, P. K. (2013). Generating downscaled weather data from a suite of climate
22 models for agricultural modelling applications. *Agricultural Systems*, 114, 1–5.
- 23 Jones-Smith, J. C., Gordon-Larsen, P., Siddiqi, A., & Popkin, B. M. (2011). Is the burden of overweight
24 shifting to the poor across the globe? Time trends among women in 39 low-and middle-income
25 countries (1991–2008). *International Journal of Obesity*, 36(8), 1114–1120.
- 26 Jonkeren, O., Rietveld, P., van Ommeren, J., & te Linde, A. (2014). Climate change and economic
27 consequences for inland waterway transport in Europe. *Regional Environmental Change*, 14(3),
28 953–965. doi: 10.1007/s10113-013-0441-7
- 29 Jyoti, D. F., Frongillo, E. A., & Jones, S. J. (2005). Food insecurity affects school children’s academic
30 performance, weight gain, and social skills. *Journal of Nutrition*, 135(12), 2831–2839.
- 31 Kader, A. A. (2005). Increasing food availability by reducing postharvest losses of fresh
32 produce. *Acta Horticulturae*, 682, 2169–2175. doi: 10.17660/ActaHortic.2005.682.296
- 33 Kadzere, C. T., Murphy, M. R., Silanikove, N., & Maltz, E. (2002). Heat stress in lactating dairy cows: A
34 review. *Livestock Production Science*, 77(1), 59–91. doi: 10.1016/S0301-6226(01)00330-X
- 35 Kafalenos, R. S., Leonard, K. J., Beagan, D. M., Burkett, V. R., Keim, B. D., Meyers, A., . . . Savonis, M. J.
36 (2008). What are the implications of climate change and variability for Gulf Coast transportation? In
37 M. J. Savonis, V. R. Burkett, & J. R. Potter (Eds.), *Impacts of climate change and variability on*
38 *transportation systems and infrastructure: Gulf Coast study, phase I* (pp. 4-1 to 4-63). Washington,
39 DC: U.S. Climate Change Science Program and U.S. Department of Transportation.
- 40 Kandlikar, M., & Risbey, J. (2000). Agricultural impacts of climate change: If adaptation is the
41 answer, what is the question? *Climatic Change*, 45, 529–539.
- 42 Kane, S., & Yohe, G. (2000). Societal adaptation to climate variability and change: An introduction.
43 *Climatic Change*, 45, 1–4.
- 44 Kaplinsky, R. (2004). *Competitions policy and the global coffee and cocoa value chains*. Sussex, United
45 Kingdom: Institute of Development Studies.

- 1 Kastner, T., Rivas, M. J. I., Koch, W., & Nonhebel, S. (2012). Global changes in diets and the
2 consequences for land requirements for food. *Proceedings of the National Academy of Sciences*,
3 *109*(18), 6868–6872. doi: 10.1073/pnas.1117054109
- 4 Kates, R. W. (2000). Cautionary tales: Adaptation and the global poor. *Climatic Change*, *45*, 5–17.
- 5 Kau, A. L., Ahern, P. P., Griffin, N. W., Goodman, A. L., & Gordon, J. I. (2011). Human nutrition, the gut
6 microbiome and the immune system. *Nature*, *474*(7351), 327–336. doi: 10.1038/nature10213
- 7 Kearney, J. (2010). Food consumption trends and drivers. *Philosophical Transactions of the Royal
8 Society B*, *365*, 2793–2807.
- 9 Keeney, D. R., & Hatfield, J. L. (2008). *The nitrogen cycle, historical perspective, and current and
10 potential future concerns* (Paper 262). Lincoln, NE: USDA Agricultural Research Service and
11 University of Nebraska. Retrieved from
12 <http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1258&context=usdaarsfacpub>
- 13 Kennedy, G., Nantel, G., & Shetty, P. (2006). *The double burden of malnutrition: Case studies from six
14 developing countries*. Rome, Italy: Nutrition Planning, Assessment and Evaluation Service and the
15 FAO.
- 16 Kerby, J. T., Wilmers, C. C., & Post, E. (2012). Climate change, phenology and the nature of
17 consumer–resource interactions: Advancing the match/mismatch hypothesis. In T. Ohgushi, O. J.
18 Schmitz, & R. D. Holt (Eds.), *Trait-mediated indirect interactions: Ecological and evolutionary
19 perspectives* (pp. 508–525). Cambridge, United Kingdom: Cambridge University Press.
- 20 Key, N., Sneeringer, S., & Marquardt, D. (2014). *Climate change, heat stress, and U.S. dairy production*
21 (Economic Research Report No. 175). Washington, DC: USDA ERS. doi: 10.2139/ssrn.2506668
- 22 Kharin, V. V., & Zwiers, F. W. (2000). Changes in the extremes in an ensemble of transient climate
23 simulations with a coupled atmosphere–ocean GCM. *Journal of Climate*, *13*, 3760–3788.
24 doi: [http://dx.doi.org/10.1175/1520-0442\(2000\)013<3760:CITEIA>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(2000)013<3760:CITEIA>2.0.CO;2)
- 25 Kharin, V. V., Zwiers, F. W., Zhang, X., & Hegerl, G. C. (2007). Changes in temperature and
26 precipitation extremes in the IPCC ensemble of global coupled model simulations. *Journal of
27 Climate*, *20*(8), 1419–1444.
- 28 Kinsey, B., Burger, K., & Gunning, J. W. (1998). Coping with drought in Zimbabwe: Survey vidence on
29 responses of rural households to risk. *World Development*, *26*, 89–110.
- 30 Kirschbaum, M. U. F. (2004). Soil respiration under prolonged soil warming: Are rate reductions
31 caused by acclimation or substrate loss? *Global Change Biology*, *10*(11), 1870–1877.
32 doi: 10.1111/j.1365-2486.2004.00852.x
- 33 Klein, J. A., Harte, J., & Zhao, X.-Q. (2007). Experimental warming, not grazing, decreases rangeland
34 quality on the Tibetan plateau. *Ecological Applications*, *17*, 541–557. doi: [org/10.1890/05-0685](http://dx.doi.org/10.1890/05-0685)
- 35 Kneafsey, M., Dowler, E., Lambie-Mumford, H., Inman, A., & Collier, R. (2013). Consumers and food
36 security: Uncertain or empowered? *Journal of Rural Studies*, *29*. doi: 10.1016/j.jrurstud.2012.05.005
- 37 Knox, J., Hess, T., Daccache, A., & Wheeler, T. (2012). Climate change impacts on crop productivity in
38 Africa and South Asia. *Environmental Research Letters*, *7*, 034032. doi: 10.1088/1748-
39 9326/7/3/034032
- 40 Knudsen, M. T., Halberg, N., Olesen, J. E., Byrne, J., Iyer, V., & Toly, N. (2005). Global trends in
41 agriculture and food systems. In N. Halberg, H. Alroe, & M. Knudsen (Eds.), *Global development of
42 organic agriculture: Challenges and promises* (pp. xxx–xxx). City, United Kingdom: CABI.
- 43 Knutson, T. R., Zeng, F., & Wittenberg, A. T. (2013). The extreme March–May 2012 warm anomaly
44 over the eastern United States: Global context and multimodel trend analysis. (In “Explaining

- 1 extreme events of 2012 from a climate perspective".) *Bulletin of the American Meteorological*
2 *Society*, 94(9), S13–S17.
- 3 Koetse, M. J., & Rietveld, P. (2009). The impact of climate change and weather on transport: An
4 overview of empirical findings. *Transportation Research Part D: Transport and Environment*, 14(3),
5 205–221. doi: 10.1016/j.trd.2008.12.004
- 6 Konar, M., Dalin, C., Hanasaki, N., Rinaldo, A., & Rodriguez-Iturbe, I. (2012). Temporal dynamics of
7 blue and green virtual water trade networks. *Water Resources Research*, 48(7). doi:
8 10.1029/2012WR011959
- 9 Konar, M., Hussein, Z., Hanasaki, N., Mauzerall, D. L., & Rodriguez-Iturbe, I. (2013). Virtual water
10 trade flows and savings under climate change. *Hydrological and Earth System Science*, 17, 3219–
11 3224.
- 12 Körner, C., & Basler, D. (2010). Phenology under global warming. *Science*, 327, 1461–1462.
- 13 Kotzé, D. A. (2003). Role of women in the household economy, food production and food security:
14 Policy guidelines. *Outlook on Agriculture*, 32(2), 111–121. doi: 10.5367/000000003101294352
- 15 Krishnamurthy, P. K., Lewis, K., & Choularton, R. J. (2014). A methodological framework for rapidly
16 assessing the impacts of climate risk on national-level food security through a vulnerability index.
17 *Global Environment Change*, 25, 121–132. doi: 10.1016/j.gloenvcha.2013.11.004
- 18 Kurlansky, M. (2012). *Birdseye: The adventures of a curious man*. New York, NY: Anchor.
- 19 Kurukulasuriya, P., & Mendelsohn, R. (2008). A Ricardian analysis of the impact of climate change
20 on African cropland. *African Journal of Agricultural and Resource Economics*, 2, 1–23.
- 21 Kutz, S. J., Jenkins, E. J., Veitch, A. M., Ducrocq, J., Polley, L., Elkin, B., & Lair, S. (2009). The Arctic as a
22 model for anticipating, preventing, and mitigating climate change impacts on host–parasite
23 interactions. *Veterinary Parasitology*, 163, 217–228.
- 24 Lake, I. R., Hooper, L., Abdelhamid, A., Bentham, G., Boxall, A. B. A., Draper, A., . . . Waldron, K. W.
25 (2012). Climate change and food security: Health impacts in developed countries. *Environmental*
26 *Health Perspectives*, 120, 1520–1526.
- 27 Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the
28 looming land scarcity. *Proceedings of the National Academy of Sciences*, 108(9), 3465–3472. doi:
29 10.1073/pnas.1100480108
- 30 Lasco, R. D., Delfino, R. J. P., & Espaldon, M. L. O. (2014). Agroforestry systems: Helping smallholders
31 adapt to climate risks while mitigating climate change. *Climate Change*, 5(6), 825–833. doi:
32 10.1002/wcc.301
- 33 Lautze, S., Bella, W., Alinovi, L., & Russo, L. (2012). Early warning, late response (again): The 2011
34 famine in Somalia. *Global Food Security*, 1, 43–49.
- 35 LeComte, D. (2014). U.S. weather highlights 2013: Endless winter, tornadoes, flash floods, more
36 winter. *Weatherwise*, 67(3), 12–19. doi: 10.1080/00431672.2014.899799
- 37 Lee, J., Gereffi, G., & Beauvais, J. (2012). Global value chains and agrifood standards: Challenges and
38 possibilities for smallholders in developing countries. *Proceedings of the National Academy of*
39 *Sciences*, 109, 12326–12331.
- 40 Le Houerou, H. N. (2002). Man-made deserts: Desertization processes and threats. *Arid Land*
41 *Research and Management*, 16, 1–36.
- 42 Leichenko, R. (2011). Climate change and urban resilience. *Current Opinion in Environmental*
43 *Sustainability*, 3, 164–168.

- 1 Lemos, M. C., Agrawal, A., Eakin, H., Nelson, D. R., Engle, N. L., & Johns, O. (2013). Building adaptive
2 capacity to climate change in less developed countries. In G. R. Asrar & J. W. Hurrell (Eds.), *Climate*
3 *science for serving society* (p. 484). Heidelberg, Germany: Springer Verlag.
- 4 Levy, K., Hubbard, A. E., & Eisenberg, J. N. S. (2009). Seasonality of rotavirus disease in the tropics: A
5 systematic review and meta-analysis. *International Journal of Epidemiology*, 38(6), 1487–1496. doi:
6 10.1093/ije/dyn260
- 7 Lin, B. B. (2011). Resilience in agriculture through crop diversification: Adaptive management for
8 environmental change. *BioScience*, 61(3), 183–193. doi: 10.1525/bio.2011.61.3.4
- 9 Linderholm, H. W. (2006). Growing season changes in the last century. *Agricultural and Forest*
10 *Meteorology*, 137, 1–14.
- 11 Linnemann, A. R., & Dijkstra, D. S. (2002). Toward sustainable production of protein-rich foods:
12 Appraisal of eight crops for Western Europe. PART I. Analysis of the primary links of the production
13 chain. *Critical Reviews in Food Science and Nutrition*, 42(4), 377–401. doi:
14 10.1080/20024091054193
- 15 Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., . . . Torquebiau, E. F.
16 (2014). Climate-smart agriculture for food security. *Nature Climate Change*, 4, 1068–1072.
- 17 Little, P. (2005). *Unofficial trade when states are weak: The case of cross-border commerce in the*
18 *Horn of Africa*. Helsinki, Finland: UNU-WIDER.
- 19 Lloyd, S. J., Kovats, R. S., & Chalabi, Z. (2011). Climate change, crop yields, and undernutrition:
20 Development of a model to quantify the impact of climate scenarios on child undernutrition.
21 *Environmental Health Perspectives*, 119, 1817–1823.
- 22 Lobell, D. B. (2013). ErrorAgriculture datasets and their effects on statistical crop models.
23 *Agricultural and Forest Meteorology*, 170, 58–66.
- 24 Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008).
25 Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319, 607–610.
- 26 Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production
27 since 1980. *Science*, 333, 616–620. doi: 10.1126/science.1204531
- 28 Lobell, D. B., Sibley, A., & Ortiz-Monasterio, J. I. (2012). Extreme heat effects on wheat senescence in
29 India. *Nature Climate Change*, 2(3), 186–189.
- 30 Lofgren, H., Harris, R. L., & Robinson, S. (2002). *A standard computable general equilibrium model in*
31 *GAMS*. Washington, DC: IFPRI.
- 32 Lohman, B. J., Stewart, S., Gundersen, C., Garasky, S., & Eisenmann, J. C. (2009). Adolescent
33 overweight and obesity: Links to food insecurity and individual, maternal, and family stressors.
34 *Journal of Adolescent Health*, 45(3), 230–237. doi: 10.1016/j.jadohealth.2009.01.003
- 35 Loladze, I. (2002). Rising atmospheric CO₂ and human nutrition: Toward globally imbalanced plant
36 stoichiometry? *Trends in Ecology and Evolution*, 17(10), 457–461. doi: dx.doi.org/10.1016/S0169-
37 5347(02)02587-9
- 38 Lott, F. C., Christidis, N., & Stott, P. A. (2013). Can the 2011 East African drought be attributed to
39 human-induced climate change? *Geophysical Research Letters*, 40(6), 1177–1181.
- 40 Love, G., Soares, A., & Püempel, H. (2010). Climate change, climate variability and transportation.
41 *Procedia Environmental Sciences*, 1, 130–145.
- 42 Ludwig, D. S. (2011). Technology, diet, and the burden of chronic disease. *Journal of American*
43 *Medical Association*, 305(13), 1352–1353. doi: 10.1001/jama.2011.380

- 1 Lutz, W., & Samir, K. (2010). Dimensions of global population projections: What do we know about
2 future population trends and structures? *Philosophical Transactions of the Royal Society B*, 365,
3 2779–2791.
- 4 Lybbert, T. J., Barrett, C. B., Desta, S., & Coppock, D. L. (2004). Stochastic wealth dynamics and risk
5 management among a poor population. *Economic Journal*, 114(498), 750–777.
- 6 Lybbert, T., & Sumner, D. A. (2012). Agricultural technologies for climate change in developing
7 countries: Policy options for innovation and technology diffusion. *Food Policy*, 37(1), 114–123.
- 8 Lynn, K., Daigle, J., Hoffman, J., Lake, F., Michelle, N., Ranco, D., . . . Williams, P. (2013). The impacts of
9 climate change on tribal traditional foods. *Climatic Change*, 120(3), 545–556. doi: 10.1007/s10584-
10 013-0736-1
- 11 Lynton-Evans, J. (1997). *Strategic grain reserves: Guidelines for their establishment, management
12 and operation* (FAO Agricultural Services Bulletin 126). Rome, Italy: FAO Agricultural Support
13 Systems Division.
- 14 MacDonald, G. K., Brauman, K. A., Sun, S., Carlson, K. M., Cassidy, E. S., Gerber, J. S., & West, P. C.
15 (2015). Rethinking agricultural trade relationships in an era of globalization. *BioScience*, 65(3). doi:
16 10.1093/biosci/biu225
- 17 MacDonald, J. M., Korb, P., & Hoppe, R. A. (2013). *Farm size and the organization of U.S. crop farming*
18 (Economic Research Report No. 152). Washington, DC: USDA ERS.
- 19 Magan, N., Hope, R., Cairns, V., & Aldred, D. (2003). Post-harvest fungal ecology: Impact of fungal
20 growth and mycotoxin accumulation in stored grain. *European Journal of Plant Pathology*, 109(7),
21 723–730. doi: 10.1023/A:1026082425177
- 22 Majid, N. (2004). *Reaching millenium goals: How well does agricultural productivity growth reduce
23 poverty?* (Employment Strategy Paper 2004, No. 12). Geneva, Switzerland: International Labor
24 Organization.
- 25 Malcolm, S., Marshall, E., Aillery, M., Heisey, P., Livingston, M., & Day-Rubenstein, K. (2012).
26 *Agricultural adaptation to a changing climate: Economic and environmental implications vary by U.S.
27 region* (Economic Research Report No. 136). Washington, DC: USDA.
- 28 Mankiw, N. G. (2011). *Principles of microeconomics* (6th ed.). Mason, OH: South-Western Cengage
29 Learning.
- 30 Marques, A., Nunes, M. L., Moore, S. K., Strom, M. S. (2010). Climate change and seafood safety:
31 Human health implications. *Food Research International*, 43(7), 1766–1779. doi:
32 10.1016/j.foodres.2010.02.010
- 33 Marshall, M. T., Husak, G. J., Michaelsen, J., Funk, C., Pedreros, D., & Adoum, A. (2011). Testing a high-
34 resolution satellite interpretation technique for crop area monitoring in developing countries.
35 *International Journal of Remote Sensing*, 32, 7997–8012. doi: 10.1080/01431161.2010.532168
- 36 Martin, K. S., & Ferris, A. M. (2007). Food insecurity and gender are risk factors for obesity. *Journal
37 of Nutrition Education and Behavior*, 39(1), 31–36. doi: 10.1016/j.jneb.2006.08.021
- 38 Martínez, R., & Fernández, A. (2008). *The cost of hunger: Social and economic impact of child
39 undernutrition in Central America and the Dominican Republic*. Santiago, Chile: UN. Retrieved July
40 26, 2014, from
41 http://documents.wfp.org/stellent/groups/public/documents/liaison_offices/wfp175334.pdf
- 42 Mashayekh, Y., Jaramillo, P., Samaras, C., Hendrickson, C. T., Blackhurst, M., MacLean, H. L., &
43 Matthews, H. S. (2012). Potentials for sustainable transportation in cities to alleviate climate change
44 impacts. *Environmental Science and Technology*, 46, 2529–2537.

- 1 Masip, G., Sabalza, M., Pérez-Massot, E., Banakar, R., Cebrian, D., Twyman, R. M., . . . Christou, P.
2 (2013). Paradoxical EU agricultural policies on genetically engineered crops. *Trends in Plant*
3 *Science*, 18(6), 312–324. doi: 10.1016/j.tplants.2013.03.004
- 4 Masters, W. A., Djurfeldt, A. A., Haan, C. D., Hazell, P., Jayne, T., Jirström, M., & Reardon, T. (2013).
5 Urbanization and farm size in Asia and Africa: Implications for food security and agricultural
6 research. *Global Food Security*, 2(3), 156–165.
- 7 Mathers, C., Stevens, G., & Mascarenhas, M. (2009). *Global health risks: Mortality and burden of*
8 *disease attributable to selected major risks*. Geneva, Switzerland: WHO.
- 9 Maurer, E. P., & Hidalgo, H. G. (2008). Utility of daily vs. monthly large-scale climate data: An
10 intercomparison of two statistical downscaling methods. *Hydrology and Earth System Sciences*, 12,
11 551–563.
- 12 Maurer, E. P., Wood, A. W., Adam, J. C., Lettenmaier, D. P., & Nijssen, B. (2002). A long-term
13 hydrologically based data set of land surface fluxes and states for the conterminous United States.
14 *Journal of Climate*, 15(22), 3237–3251. doi: [http://dx.doi.org/10.1175/1520-](http://dx.doi.org/10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2)
15 [0442\(2002\)015<3237:ALTHBD>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2)
- 16 Maxwell, D. G. (1996). Measuring food insecurity: The frequency and severity of coping strategies.
17 *Food Policy*, 21, 291–303.
- 18 Maxwell, D., & Fitzpatrick, M. (2012). The 2011 Somalia famine: Context, causes, and complications.
19 *Global Food Security*, 1, 5–12.
- 20 Maxwell, S., & Smith, M. (1992). Household food security: A conceptual review. In S. Maxell & T.
21 Frankenberger (Eds.), *Household food security: Concepts, indicators, measurements* (pp. 1–72). New
22 York, NY: UN International Children’s Emergency Fund and IFAD.
- 23 Maze, T. H., Agarwal, M., & Burchett, G. (2006). Whether weather matters to traffic demand, traffic
24 safety, and traffic operations and flow. *Transportation Research Record*, 1948, 170–176.
- 25 McCarl, B. A., Attavanich, W., Musumba, M., Mu, J., & Aisabokhae, R. (2014). Land use and climate
26 change. In J. Duke & J. J. Wu (Eds.), *Oxford handbook of land economics* (pp. xxx–xxx). Oxford, United
27 Kingdom: Oxford University Press.
- 28 McDonalds. (2014). *Corporate social responsibility and sustainability report: 2012–2013*. Retrieved
29 from
30 [http://www.aboutmcdonalds.com/content/dam/AboutMcDonalds/2.0/pdfs/2012_2013_csr_repor](http://www.aboutmcdonalds.com/content/dam/AboutMcDonalds/2.0/pdfs/2012_2013_csr_report.pdf)
31 [t.pdf](http://www.aboutmcdonalds.com/content/dam/AboutMcDonalds/2.0/pdfs/2012_2013_csr_report.pdf)
- 32 McGowan, J. A., Cayan, D. R., & Dorman, L. M. (1998). Climate-ocean variability and ecosystem
33 response in the Northeast Pacific. *Science*, 281, 210–217.
- 34 McGuirk, M., Shuford, S., Peterson, T. C., & Pisano, P. (2009). Weather and climate change
35 implications for surface transportation in the USA. *WMO Bulletin*, 58, 84.
- 36 McKay, S., Gaudier, E., Campbell, D. I., Prentice, A. M., & Albers, R. (2010). Environmental
37 enteropathy: New targets for nutritional interventions. *International Health*, 2(3), 172–180. doi:
38 10.1016/j.inhe.2010.07.006
- 39 Mearns, L. O., Sain, S., Leung, L. R., Bukovsky, M. S., McGinnis, S., Biner, S., . . . Sloan, L. (2013).
40 Climate change projections of the North American Regional Climate Change Assessment Program
41 (NARCCAP). *Climatic Change*, 120(4), 965–975.
- 42 Meehl, G. A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J. F. B., . . . Taylor, K. E. (2007).
43 The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bulletin of the*
44 *American Meteorological Society*, 88(9), 1383–1394.

- 1 Meehl, G. A., Tebaldi, C., Walton, G., Easterling, D., & McDaniel, L. (2009). Relative increase of record
2 high maximum temperatures compared to record low minimum temperatures in the U.S.
3 *Geophysical Research Letters*, 36(23). doi: 10.1029/2009GL040736
- 4 Meléndez Arjona, M., & Uribe, M. J. (2012). *International product fragmentation and the insertion of*
5 *Latin America and the Caribbean in global production networks: Colombian case studies*. Washington,
6 DC: Inter-American Development Bank.
- 7 Melillo, J. M., McGuire, A. D., Kicklighter, D. W., Moore, B., Vorosmarty, C. J., & Schloss, A. L. (1993).
8 Global climate change and terrestrial net primary production. *Nature*, 363, 234–240. doi:
9 10.1038/363234a0
- 10 Melillo, J. M., Richmond, T. C., & Yohe, G. W. (Eds.). (2014). *Climate change impacts in the United*
11 *States: The third national climate assessment*. Washington, DC: U.S. Global Change Research Program.
12 doi: 10.7930/J0Z31WJ2
- 13 Mendelsohn, R., & Dinar, A. (2009). *Climate change and agriculture*. Washington, DC: World Bank.
- 14 Menkhaus, K. (2012). No access: Critical bottlenecks in the 2011 Somali famine. *Global Food*
15 *Security*, 1(1), 29–35. doi: 10.1016/j.gfs.2012.07.004
- 16 Menzel, A., Jakobi, G., Ahas, R., Scheifinger, H., & Estrella, N. (2003). Variations of the climatological
17 growing season (1951–2000) in Germany compared with other countries. *International Journal of*
18 *Climatology*, 23(7), 793–812.
- 19 Mérel, P., & Howitt, R. (2014). Theory and application of positive mathematical programming in
20 agriculture and the environment. *Annual Review of Resource Economics*, 6, 451–470. doi:
21 10.1146/annurev-resource-100913-012447
- 22 Mertz, O., Zoromé, M., Maiga, A., Diouf, A., Ouattara, I., Barbier, B., . . . Diallo, D. (2010). Climate
23 factors play a limited role for past adaptation strategies in West Africa. *Ecology and Society*, 15, 1–
24 15.
- 25 Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Scenarios. Findings of*
26 *the Scenarios Working Group*. Washington, DC: Island Press.
- 27 Millerd, F. (2005). The economic impact of climate change on Canadian commercial navigation on
28 the Great Lakes. *Canadian Water Resources Journal*, 30(4), 269–280.
- 29 Millerd, F. (2011). The potential impact of climate change on Great Lakes international shipping.
30 *Climatic Change*, 104, 629–652.
- 31 Milner-Gulland, E., & Bennett, E. (2003). Wild meat: The big picture. *Trends in Ecology & Evolution*,
32 18, 351–357.
- 33 Minot, N. (2012). *Food price volatility in Africa: Has it really increased?* (Discussion Paper No.
34 01239). Washington, DC: IFPRI.
- 35 Miraglia, M., Marvin, H. J. P., Kleter, G. A., Battilani, P., Brera, C., Coni, E., . . . Vespermann, A. (2009).
36 Climate change and food safety: An emerging issue with special focus on Europe. *Food and Chemical*
37 *Toxicology*, 47(5), 1009–1021. doi: 10.1016/j.fct.2009.02.005
- 38 Misselhorn, A., Aggarwal, P., Ericksen, P., Gregory, P., Horn-Phathanothai, L., Ingram, J., & Wiebe, K.
39 (2012). A vision for attaining food security. *Current Opinion in Environmental Sustainability*, 4, 7–17.
- 40 Mittal, S. (2007). Strengthening backward and forward linkages in horticulture: Some successful
41 initiatives. *Agricultural Economic Research Review*, 20, 457–469.
- 42 Monteiro, C. A., Levy, R. B., Claro, R. M., Castro, I. R. R. D., & Cannon, G. (2011). Increasing
43 consumption of ultra-processed foods and likely impact on human health: Evidence from Brazil.
44 *Public Health Nutrition*, 14(01), 5–13. doi: 10.1017/S1368980010003241

- 1 Montgomery, D. R. (2007). Soil erosion and agricultural sustainability. *Proceedings of the National*
2 *Academy of Sciences*, 104, 13268–13272.
- 3 Moretti, C. L., Mattos, L. M., Calbo, A. G., & Sargent, S. A. (2010). Climate changes and potential
4 impacts on postharvest quality of fruit and vegetable crops: A review. *Food Research International*,
5 43, 1824–1832.
- 6 Morton, J. F. (2007). The impact of climate change on smallholder and subsistence agriculture.
7 *Proceedings of the National Academy of Sciences*, 104, 19680–19685.
- 8 Moseley, W. G. (2003). Environmental degradation and ‘poor’ smallholders in the West African
9 Sudano-Sahel: Global discourses and local realities. In W. G. Moseley (Ed.), *African environment and*
10 *development: Rhetoric, programs, realities* (pp. 41–62). New York, NY: Ashgate.
- 11 Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., . . . Wilbanks,
12 T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature*,
13 463, 747–756.
- 14 Mowery, D., & Rosenberg, N. (1998). *Paths of innovation: Technological change in 20th century*
15 *America*. Cambridge, United Kingdom: Cambridge University Press.
- 16 Müller, C., Elliott, J., & Levermann, A. (2014). Food security: Fertilizing hidden hunger. *Nature*
17 *Climate Change*, 4, 540–541. doi:10.1038/nclimate2290
- 18 Murphy, A. G., Hartell, J., Cárdenas, V., & Skees, J. R. (2012). *Risk management instruments for food*
19 *price volatility and weather risk in Latin America and the Caribbean: The use of risk management*
20 *instruments*. Washington, DC: Inter-American Development Bank.
- 21 Murray, K. B., Muro, F. D., Finn, A., & Leszczyc, P. P. (2010). The effect of weather on consumer
22 spending. *Journal of Retailing and Consumer Services*, 17(6), 512–520.
- 23 Musante, A. R., Pekins, P. J., & Scarpitti, D. L. (2010). Characteristics and dynamics of a regional
24 moose *Alces alces* population in the northeastern United States. *Wildlife Biology*, 16, 185–204.
- 25 Myers, S. S., Golden, C. D., Ricketts, T., Turner, W. R., Redford, K. H., Gaffikin, L., & Osofsky, S. A.
26 (2013). Human health and ecosystem alteration: A critical review. *Proceedings of the National*
27 *Academy of Sciences*, 110(47), 18753–18760. doi: 10.1073/pnas.1218656110
- 28 Myers, S. S., Zanolatti, A., Kloog, I., Huybers, P., Leakey, A. D. B., Bloom, A. J., . . . Usui, Y.
29 (2014). Increasing CO₂ threatens human nutrition. *Nature*, 510, 139–142. doi:
30 10.1038/nature13179
- 31 Mysak, L. A. (1986). El-Nino, interannual variability and fisheries in the Northeast Pacific Ocean.
32 *Canadian Journal of Fisheries and Aquatic Sciences*, 43, 464–497.
- 33 Nagayets, O. (2005). *Small farms: Current status and key trends* (Research Workshop on the Future
34 of Small Farms). Wye, United Kingdom: IFPRI, Overseas Development Institute, and Imperial
35 College.
- 36 Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., . . . Dadi, Z. (Eds.) (2000).
37 *Special report on emissions scenarios: A special report of working group III of the Intergovernmental*
38 *Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press.
- 39 Nardone, A., Ronchi, B., Lacetera, N., Ranieri, M. S., & Bernabucci, U. (2010). Effects of climate
40 changes on animal production and sustainability of livestock systems. *Livestock Science*, 130(1–3),
41 57–69. doi: 10.1016/j.livsci.2010.02.011
- 42 National Research Council. (2007). *Understanding multiple environmental stresses: Report of a*
43 *workshop*. Washington, DC: National Academy Press.

- 1 Naylor, R., Steinfeld, H., Falcon, W., Galloway, J., Smil, V., Bradford, E., . . . Mooney, H. (2005). Losing
2 the links between livestock and land. *Science*, *310*, 1621–1622.
- 3 Nearing, M. A., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., . . . van Oost, K. (2005).
4 Modeling response of soil erosion and runoff to changes in precipitation and cover. *Catena*, *61*(2–3),
5 131–154. doi: 10.1016/j.catena.2005.03.007
- 6 Nelson, G. C., Rosegrant, M. W., Koo, J., Robertson, R., Sulser, T., Zhu, T., . . . Lee, D. (2009). *Climate*
7 *change: Impact on agriculture and costs of adaptation*. Washington, DC: IFPRI. doi:
8 10.2499/0896295354
- 9 Nelson, G. C., Rosegrant, M. W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., . . . You, L. (2010).
10 *Food security, farming and climate change to 2050: Scenarios, results, policy options*. Washington, DC:
11 IFPRI. doi: 10.2499/9780896291867
- 12 Nelson, G. C., Valin, H., Sands, R. D., Havlik, P., Ahammad, H., Deryng, D., . . . Willenbockel, D. (2014).
13 Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the*
14 *National Academy of Sciences*, *111*(9), 3274–3279. doi: 10.1073/pnas.1222465110
- 15 Nelson, G. C., van der Mensbrugge, D., Ahammad, H., Blanc, E., Calvin, K., Hasegawa, T., . . .
16 Willenbockel, D. (2014). Agriculture and climate change in global scenarios: Why don't the models
17 agree. *Agricultural Economics*, *45*, 1–17.
- 18 Nemry, F., & Demirel, H. (2012). *Impacts of climate change on transport: A focus on road and rail*
19 *transport infrastructures*. Sevilla, Spain: European Commission Joint Research Centre.
- 20 Neven, D., Odera, M., Reardon, T., & Wang, H. (2009). Kenyan supermarkets, emerging middle-class
21 horticultural farmers, and employment impacts on the rural poor. *World Development*, *37*, 1802–
22 1811.
- 23 Ng, M., Fleming, T., Robinson, M., Thomson, B., Graetz, N., Margono, C., . . . Gakidou, E. (2014). Global,
24 regional, and national prevalence of overweight and obesity in children and adults during 1980–
25 2013: A systematic analysis for the Global Burden of Disease Study 2013. *Lancet*, *384*(9945), 766–
26 781.
- 27 Nicholls, R. J., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Corfee-Morlot, J., . . . Muir-Wood, R.
28 (2008). *Ranking port cities with high exposure and vulnerability to climate extremes: Exposure*
29 *estimates* (OECD Environment Working Papers, No. 1). Paris, France: OECD. doi:
30 <http://dx.doi.org/10.1787/011766488208>
- 31 Nielsen, J. O., & Vigh, H. (2012). Adaptive lives: Navigating the global food crisis in a changing
32 climate. *Global Environmental Change*, *22*(3), 659–669. doi: 10.1016/j.gloenvcha.2012.03.010
- 33 Niles, D., & Roff, R. J. (2008). Shifting agrifood systems: The contemporary geography of food and
34 agriculture—An introduction. *GeoJournal*, *73*, 1–10.
- 35 Nin-Pratt, A., Johnson, M., Magalhaes, E., You, L., Diao, X., & Chamberlin, J. (2011). *Yield gaps and*
36 *potential agricultural growth in West and Central Africa* (Research Monograph 170). Washington,
37 DC: IFPRI.
- 38 Nkendah, R. (2010, December). *The informal cross-border trade of agricultural commodities between*
39 *Cameroon and its CEMAC's neighbours*. Paper for the NSF/AERC/IGC Conference, Mombasa, Kenya.
40 Retrieved from <http://www.theigc.org/wp-content/uploads/2014/08/nkendah.pdf>
- 41 Nukenine, E. N. (2010). Stored product protection in Africa: Past, present and future. *Julius-Kühn-*
42 *Archiv*, *425*, 26–41. doi: 10.5073/jka.2010.425.177
- 43 OECD. (2013). *Global food security: Challenges for the food and agricultural system*. Paris, France.
- 44 O'Gorman, P. A., & Muller, C. J. (2010). How closely do changes in surface and column water vapor

1 follow Clausius-Clapeyron scaling in climate change simulations? *Environmental Research Letters*,
2 5(2), 025207. doi: 10.1088/1748-9326/5/2/025207

3 Ogotu, J. O., Piepho, H.-P., & Dublin, H. T. (2014). Reproductive seasonality in African ungulates in
4 relation to rainfall. *Wildlife Research*, 41(4), 323–342. doi: 10.1071/WR13211

5 Ojima, D., Canadell, J. G., Conant, R., Negra, C., & Tscharkert, P. (2013). Ecosystem sustainability
6 through strategies of integrated carbon and land-use management. In D. G. Brown, D. T. Robinson,
7 N. H. F. French, & B. C. Reed (Eds.), *Land use and the carbon cycle: Advances in integrated science,
8 management, and policy* (pp. 523–538). Cambridge, United Kingdom: Cambridge University Press.

9 Ojima, D. S., Field, C., Leadley, P., Salad, O., Messem, D., Petersen, J. E., . . . Wright, M.
10 (2009). Mitigation strategies: Biofuel development considerations to minimize impacts on the socio-
11 environmental system. In R. W. Howarth & S. Bringer (Eds.), *Biofuels: Environmental consequences
12 and interactions with changing land use* (pp. 293–308). Ithaca, NY: Cornell University.

13 Olesena, J. E., Trnkab, M., Kersebaumc, K. C., Skjelvågd, A. O., Seguine, B., Peltonen-Sainiof, P., . . .
14 Micaloi, F. (2011). Impacts and adaptation of European crop production systems to climate change.
15 *European Journal of Agronomy*, 34, 96–112.

16 Omamo, S. W. (1998). Transport costs and smallholder cropping choices: An application to Siaya
17 District, Kenya. *American Journal of Agricultural Economics*, 80(1), 116–123. doi: 10.2307/3180274

18 O'Neill, B. C., Kriegler, E., Kristie, E. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., . . . Solecki, W.
19 (2015). The roads ahead: Narratives for shared socioeconomic pathways describing world futures
20 in the 21st century. *Global Environmental Change*. doi: org/10.1016/j.gloenvcha.2015.01.004

21 O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., . . . van Vuuren, D. P. (2014).
22 A new scenario framework for climate change research: The concept of shared socio-economic
23 pathways. *Climatic Change*, 122, 387–400.

24 O'Reilly, J. (2012). Rail innovation keeps ag moving, despite drought. *Inbound Logistics*. Retrieved
25 from <http://www.inboundlogistics.com/cms/article/trends-september-2012/>

26 Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems.
27 *Science*, 325(5939), 419–422. doi: 10.1126/science.1172133

28 Ottersen, G., Planque, B., Belgrano, A., Post, E., Reid, P. C., & Stenseth, N. C. (2001). Ecological effects
29 of the North Atlantic oscillation. *Oecologia*, 128, 1–14.

30 Otto, F. E. L., Massey, N., van Oldenborgh, G. J., Jones, R. G., & Allen, M. R. (2012). Reconciling two
31 approaches to attribution of the 2010 Russian heat wave. *Geophysical Research Letters*, 39, L04702.
32 doi: 10.1029/2011GL050422

33 Paarlberg, R. (2013). *Food politics* (2nd ed.). Oxford, United Kingdom: Oxford University Press.

34 Pagell, R. A., & Halperin, M. (1999). *International business information: How to find it, how to use it*
35 (2nd ed.). Chicago, IL: Oryx Press.

36 Paggi, M. S., Parr Rosson, C., III, Adcock, F. J., & Hanselka, D. (2012). National and regional impacts of
37 U.S. agricultural exports. *Choices*. Retrieved from
38 <http://www.choicesmagazine.org/magazine/article.php?article=169>

39 Parfitt, J., Barthel, M., & Macnaughton, S. (2010). Food waste within food supply chains:
40 Quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B*,
41 365, 3065–3081.

42 Parida, A. K., & Das, A. B. (2005). Salt tolerance and salinity effects on plants: A review.
43 *Ecotoxicology and Environmental Safety*, 60, 324–349.

- 1 Parry, M. L., Rosenzweig, C., Iglesias, A., Livermore, M., & Fischer, G. (2004). Effects of climate
2 change on global food production under SRES emissions and socio-economic scenarios. *Global*
3 *Environmental Change*, 14, 53–67. doi: 10.1016/j.gloenvcha.2003.10.008
- 4 Parry, M., Rosenzweig, C., & Livermore, M. (2005). Climate change, global food supply and risk of
5 hunger. *Philosophical Transactions of the Royal Society B*, 360, 2125–2138.
- 6 Paterson, R. R. M., & Lima, N. (2011). Further mycotoxin effects from climate change. *Food Research*
7 *International*, 44(9), 2555–2566. doi: 10.1016/j.foodres.2011.05.038
- 8 Patz, J. A., Daszak, P., Tabor, G. M., Aguirre, A. A., Pearl, M., Epstein, J., . . . Bradley, D. J. (2004).
9 Unhealthy landscapes: Policy recommendations on land use change and infectious disease
10 emergence. *Environmental Health Perspectives*, 10(1289), 1–32.
- 11 Pérez de León, A., Teel, P., Auclair, A., Messenger, M., Guerrero, F., Schuster, G., & Miller, R. (2012).
12 Integrated strategy for sustainable cattle fever tick eradication in USA is required to mitigate the
13 impact of global change. *Frontiers of Physiology*, 3, 195. doi: 10.3389/fphys.2012.00195
- 14 Perry, A. L., Low, P. J., Ellis, J. R., & Reynolds, J. D. (2005). Climate change and distribution shifts in
15 marine fishes. *Science*, 308, 1912–1915.
- 16 Petrolia, D. R. (2008). The economics of harvesting and transporting corn stover for conversion to
17 fuel ethanol: A case study for Minnesota. *Biomass and Bioenergy*, 32(7), 603–612.
- 18 Pingali, P. (2007). Westernization of Asian diets and the transformation of food systems:
19 Implications for research and policy. *Food Policy*, 32, 218–298.
- 20 Pingali, P. L. (2012). Green revolution: Impacts, limits, and the path ahead. *Proceedings of the*
21 *National Academy of Sciences*, 109, 12302–12308. doi: 10.1073/pnas.0912953109
- 22 Pinstrup-Andersen, P. (2009). Food security: Definition and measurement. *Food Security*, 1, 5–7.
- 23 Poku, K. (2002). *Small-scale palm oil processing in Africa* (FAO Agricultural Services Bulletin 148).
24 Rome, Italy: FAO.
- 25 Popkin, B. M. (1998). The nutrition transition and its health implications in lower-income countries.
26 *Public Health Nutrition*, 1(1), 5–21. doi: 10.1079/PHN19980004
- 27 Popkin, B. M. (1999). Urbanization, lifestyle changes and the nutrition transition. *World*
28 *Development*, 27(11), 1905–1916. doi: 10.1016/S0305-750X(99)00094-7
- 29 Popkin, B. M. (2006). Global nutrition dynamics: The world is shifting rapidly toward a diet linked
30 with noncommunicable diseases. *American Journal of Clinical Nutrition*, 84(2), 289–298.
- 31 Porkka, M., Kumm, M., Siebert, S., & Varis, O. (2013). From food insufficiency towards trade
32 dependency: A historical analysis of global food availability. *PLOS One*, 8(12), e82714. doi:
33 10.1371/journal.pone.0082714
- 34 Porter, J. R., Xie, L., Challinor, A., Cochrane, K., Howden, M., Iqbal, M. M., . . . Travasso, M. I. (2014).
35 Food security and food production systems. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D.
36 Mastrandrea, T. E. Bilir, . . . L. L. White (Eds.), *Climate change 2014: Impacts, adaptation, and*
37 *vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fifth*
38 *assessment report of the Intergovernmental Panel on Climate Change* (pp. 485–533). Cambridge,
39 United Kingdom: Cambridge University Press.
- 40 Post, E., & Forchhammer, M. C. (2008). Climate change reduces reproductive success of an Arctic
41 herbivore through trophic mismatch. *Philosophical Transactions of the Royal Society B*, 363, 2369–
42 2375.
- 43 Power, A. G. (2010). Ecosystem services and agriculture: Tradeoffs and synergies. *Philosophical*
44 *Transactions of the Royal Society B*, 365, 2959–2971. doi: 10.1098/rstb.2010.0143

- 1 Presidential Documents. (2014). Climate-resilient international development (Executive Order
2 13677). *Federal Register*, 79(187), 58231–58236. Retrieved from
3 <http://www.gpo.gov/fdsys/pkg/FR-2014-09-26/pdf/2014-23228.pdf>
- 4 Prince, S. D., Geores, M. E., & Boburg, J. (1999). Coping strategies in the Sahel and Horn of Africa: A
5 conceptual model based on cultural behavior and satellite sensor data. In S. Morain (Ed.), *GIS*
6 *solutions in natural resource management: Balancing the technical-political equation* (pp. 235–250).
7 Santa Fe, NM: OnWord Press.
- 8 Qiang, W., Liu, A., Cheng, S., Kastner, T., & Xie, G. (2013). Agricultural trade and virtual land use: The
9 case of China's crop trade. *Land Use Policy*, 33, 141–150.
- 10 Quisumbing, A. R., Brown, L. R., Feldstein, H. S., Haddad, L., & Pena, C. (1995). *Women: The key to*
11 *food security*. Washington, DC: IFPRI.
- 12 Racherla, P. N., Shindell, D. T., & Faluvegi, G. S. (2012). The added value to global model projections
13 of climate change by dynamical downscaling: A case study over the continental U.S. using the GISS-
14 ModelE2 and WRF models. *Journal of Geophysical Research Atmospheres*, 117(D20). doi:
15 10.1029/2012JD018091
- 16 Rahmstorf, S., & Coumou, D. (2011). Increase of extreme events in a warming world. *Proceedings of*
17 *the National Academy of Sciences USA*, 108, 17905–17909. doi: 10.1073/pnas.1101766108
- 18 Raleigh, C. (2010). Political marginalization, climate change, and conflict in African Sahel states.
19 *International Studies Review*, 12(1), 69–86. doi: 10.1111/j.1468-2486.2009.00913.x
- 20 Ramakrishnan, U., & Semba, R. D. (2008). Iron deficiency and anemia. In R. D. Semba & M. W. Bloem
21 (Eds.), *Nutrition and health in developing countries* (2nd ed.) (pp. 479–505). Totowa, NJ: Humana
22 Press.
- 23 Ramirez-Villegas, J., & Challinor, A. (2012). Assessing relevant climate data for agricultural
24 applications. *Agricultural and Forest Meteorology*, 161, 26–45.
- 25 Ravallion, M., Chen, M., & Sangraula, P. (2007). *New evidence on the urbanization of global poverty*
26 (World Bank Policy Research Working Paper 4199). Washington, DC: World Bank.
- 27 Rawlani, A. K., & Sovacool, B. K. (2011). Building responsiveness to climate change through
28 community based adaptation in Bangladesh. *Mitigation and Adaptation Strategies for Global Change*,
29 16, 845–863.
- 30 Ray, D. K., Mueller, N. D., West, P. C., & Foley, J. A. (2013). Yield trends are insufficient to double
31 global crop production by 2050. *PLOS ONE*, 8(6), e66428.
- 32 Ray, D. K., Ramankutty, N., Mueller, N. D., West, P. C., & Foley, J. A. (2012). Recent patterns of crop
33 yield growth and stagnation. *Nature Communications*, 3, 1293. doi: 10.1038/ncomms2296
- 34 Reardon, T., Timmer, C. P., Barrett, C. B., & Berdegue, J. (2003). The rise of supermarkets in Africa,
35 Asia, and Latin America. *American Journal of Agricultural Economics*, 85, 1140–1146. doi:
36 10.1111/j.0092-5853.2003.00520.x
- 37 Reardon, T., Timmer, P., & Minten, B. (2012). Supermarket revolution in Asia and emerging
38 development strategies to include small farmers. *Proceedings of the National Academy of Sciences*,
39 109, 12332–12337.
- 40 Regmi, A., & Meade, B. (2013). Demand side drivers of global food security. *Global Food Security*, 2,
41 166–171.
- 42 Reilly, J., Tubiello, F., McCarl, B., Abler, D., Darwin, R., Fuglie, K., . . . Rosenzweig, C. (2003). U.S.
43 agriculture and climate change: New results. *Climatic Change*, 57, 43–67.

- 1 Renna, M., Lussiana, C., Malfatto, V., Mimosi, A., & Battaglini, L. M. (2010). Effect of exposure to heat
2 stress conditions on milk yield and quality of dairy cows grazing on Alpine pasture. In *Building*
3 *sustainable rural futures: The added value of systems approaches in times of change and uncertainty,*
4 *9th European IFSA symposium* (pp. 1338–1348). Vienna, Austria: University of Natural Resources
5 and Applied Life Sciences.
- 6 Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., . . . Rafaj, P. (2011). RCP 8.5—A scenario of
7 comparatively high greenhouse gas emissions. *Climatic Change*, *109*(1–2), 33–57. doi:
8 10.1007/s10584-011-0149-y
- 9 Richardson, A. J., & Schoeman, D. S. (2004). Climate impact on plankton ecosystems in the Northeast
10 Atlantic. *Science*, *305*, 1609–1612.
- 11 Risbey, J., Kandlikar, M., Dowlatabadi, H., & Graetz, D. (1999). Scale, context, and decision making in
12 agricultural adaptation to climate variability and change. *Mitigation Adaptation Strategies Global*
13 *Change*, *4*, 137–165.
- 14 Roberts, P. (2008). *The end of food*. New York, NY: Houghton Mifflin.
- 15 Robeson, S. M. (2002). Increasing growing-season length in Illinois during the 20th century.
16 *Climatic Change*, *52*(1–2), 219–238.
- 17 Robinet, C., & Roques, A. (2010). Direct impacts of recent climate warming on insect populations.
18 *Integrative Zoology*, *5*, 132–142.
- 19 Rodrigue, J.-P. (2013). *The geography of transport systems* (3rd ed.). New York, NY: Routledge.
- 20 Roessig, J., Woodley, C., Cech, J., Jr., & Hansen, L. (2004). Effects of global climate change on marine
21 and estuarine fishes and fisheries. *Reviews in Fish Biology and Fisheries*, *14*(2), 251–275.
- 22 Romero-Lankao, P., & Dodman, D. (2011). Cities in transition: Transforming urban centers from
23 hotbeds of GHG emissions and vulnerability to seedbeds of sustainability and resilience:
24 Introduction and editorial overview. *Current Opinion in Environmental Sustainability*, *3*, 113–120.
- 25 Rosegrant, M. W., & IMPACT Development Team. (2012). *International model for policy analysis of*
26 *agricultural commodities and trade (IMPACT) model description*. Washington, DC: IFPRI.
- 27 Rosen, S., Shapouri, S., Meade, B., Trueblood, M., Liefert, W., & Valdes, C. (2004). *Food security*
28 *assessment, GFA-15* (Food Assistance and Nutrition Research Report No. GFA-15). Washington, DC:
29 USDA ERS.
- 30 Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Muller, C., Arneth, A., . . . Jones, J. W. (2014).
31 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model
32 intercomparison. *Proceedings of the National Academy of Sciences*, *111*(9), 3268–3273. doi:
33 10.1073/pnas.1222463110
- 34 Rosenzweig, C., & Hillel, D. (Eds.). (2015). *Handbook of climate change and agroecosystems: The*
35 *Agricultural Model Intercomparison and Improvement Project integrated crop and economic*
36 *assessments, Parts 1 and 2*. London, United Kingdom: Imperial College Press.
- 37 Rosenzweig, C., & Iglesias, A. (Eds.). (1994). *Implications of climate change for international*
38 *agriculture: Crop modeling study*. Washington, DC: U.S. Environmental Protection Agency.
- 39 Rosenzweig, C., Iglesias, A., Yang, X. B., Epstein, P. R., & Chivian, E. (2001). Climate change and
40 extreme weather events: Implications for food production, plant diseases and pests. *Global Change*
41 *and Human Health*, *2*, 90–104.
- 42 Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P., . . . Winter, J. M.
43 (2013). The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and

- 1 pilot studies. *Agricultural and Forest Meteorology*, 170, 166–182. doi:
2 10.1016/j.agrformet.2012.09.011
- 3 Rosenzweig, C., & Parry, M. L. (1994). Potential impact of climate change on world food supply.
4 *Nature*, 367, 133–138.
- 5 Rosset, P. (2008). Food sovereignty and the contemporary food crisis. *Development Anthropology*
6 *Network*, 51, 460–463.
- 7 Rossi, V., Ravanetti, A., Patteri, E., & Giosuè, S. (2001). Influence of temperature and humidity on the
8 infection of wheat spikes by some fungi causing *Fusarium* head blight. *Journal of Plant Pathology*,
9 83(3), 189–198. doi: 10.4454/jpp.v83i3.1128
- 10 Rothman, D. S., Romero-Lankao, P., Schweizer, V. L., & Bee, B. A. (2013). Challenges to adaptation: A
11 fundamental concept for a new generation of socio-economic scenarios. *Climatic Change*, 122(3),
12 495–507. doi: 10.1007/s10584-013-0907-0
- 13 Rötter, R., & van de Geijn, S. C. (1999). Climate change effects on plant growth, crop yield and
14 livestock. *Climatic Change*, 43(4), 651–681. doi: 10.1023/A:1005541132734
- 15 Roza, Y., Escobar, C., Gaitán, Á., & Cristancho, M. (2012). Aggressiveness and genetic diversity of
16 *Hemileia vastatrix* during an epidemic in Colombia. *Journal of Phytopathology*, 160(11–12), 732–
17 740. doi: 10.1111/jph.12024
- 18 Rudorff, C. M., Melack, J. M., & Bates, P. D. (2014). Flooding dynamics on the lower Amazon
19 floodplain: Seasonal and interannual hydrological variability. *Water Resources Research*, 50(1),
20 635–649. doi: 10.1002/2013WR014714
- 21 Rulli, M. C., Savioli, A., & D’Odorico, P. (2013). Global land and water grabbing. *Proceedings of the*
22 *National Academy of Sciences*, 110(3), 892–897.
- 23 Sanders, T. H., Blankenship, P. D., Cole, R. J., & Hill, R. A. (1984). Effect of soil temperature and
24 drought on peanut pod and stem temperatures relative to *Aspergillus flavus* invasion and aflatoxin
25 contamination. *Mycopathologia*, 86(1), 51–54. doi: 10.1007/BF00437229
- 26 SATCAFE. (2015). *Central America coffee rust information system*. Retrieved from
27 http://en.centralamericadata.com/en/article/home/Coffee_Rust_Information_System
- 28 Satterthwaite, D., McGranahan, G., & Tacoli, C. (2010). Urbanization and its implications for food and
29 farming. *Philosophical Transactions of the Royal Society B*, 365, 2809–2820.
- 30 Saxena, V. K., & Krishnaswamy, N. (2012). Molecular mechanisms of livestock adaptation. In V.
31 Sejian, S. M. K. Naqvi, T. Ezeji, J. Lakritz, & R. Lal (Eds.), *Environmental stress and amelioration in*
32 *livestock production* (pp. 299–315). Berlin, Germany: Springer-Verlag. doi: 10.1007/978-3-642-
33 29205-7_12
- 34 Schiavone, A. (2010). *Trade and climate change implications for food security in mainland Southeast*
35 *Asia* (Policy Brief). Trade Knowledge Network.
- 36 Schlenker, W., & Lobell, D. B. (2010). Robust negative impact of climate change on African
37 agriculture. *Environmental Research Letters*, 5, 1–9. doi: 10.1088/1748-9326/5/1/014010
- 38 Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to
39 U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences*, 106, 15594–
40 15598.
- 41 Schmidhuber, J., & Tubiello, F. N. (2007). Global food security under climate change. *Proceedings of*
42 *the National Academy of Sciences*, 104, 19703–19708.
- 43 Schmitt, S. G., & Hurburgh, C. (1989). Distribution and measurement of aflatoxin in 1983 Iowa corn.
44 *Cereal Chemistry*, 165–168.

- 1 Schneider, S., Semenov, S., Patwardhan, A., Burton, I., Magadza, C., Oppenheimer, M., . . . Hanson, C.
2 (Eds.). (2007). *Assessing key vulnerabilities and the risk from climate change. Climate change 2007:*
3 *Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment*
4 *report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge
5 University Press.
- 6 Schreiner, M. (2012). Estimating consumption-based poverty in the Ethiopia demographic and
7 health survey. *Ethiopian Journal of Economics*, 21(1), 73–106. Retrieved from
8 <http://www.ajol.info/index.php/eje/article/view/91568>
- 9 Schweikert, A., Chinowsky, P., Kwiatkowski, K., & Espinet, X. (2014). The infrastructure planning
10 support system: Analyzing the impact of climate change on road infrastructure and development.
11 *Transport Policy*, 35, 146–153.
- 12 Schweizer, V., & O'Neill, B. (2014). Systematic construction of global socioeconomic pathways using
13 internally consistent element combinations. *Climatic Change*, 122, 431–445.
- 14 Scoones, I. (2008). Mobilizing against GM crops in India, South Africa and Brazil. *Journal of Agrarian*
15 *Change*, 8(2-3), 315–344. doi: 10.1111/j.1471-0366.2008.00172.x
- 16 Seligman, H. K., Bindman, A. B., Vittinghoff, E., Kanaya, A. M., & Kushel, M. B. (2007). Food insecurity
17 is associated with diabetes mellitus: Results from the National Health Examination and Nutrition
18 Examination Survey (NHANES) 1999–2002. *Journal of General Internal Medicine*, 22(7), 1018–1023.
- 19 Seligman, H. K., Laraia, B. A., & Kushel, M. B. (2009). Food insecurity is associated with chronic
20 disease among low-income NHANES participants. *Journal of Nutrition*, 140(2), 304–
21 310. doi: 10.3945/jn.109.112573
- 22 Semba, R. D., & Delange, F. (2008). Iodine deficiency disorders. In R. D. Semba & M. W. Bloem (Eds.),
23 *Nutrition and health in developing countries* (2nd ed.) (pp. 507–529). Totowa, NJ: Humana Press.
- 24 Senay, G. B., & Verdin, J. (2003). Characterization of yield reduction in Ethiopia using a GIS-based
25 crop water balance model. *Canadian Journal of Remote Sensing*, 29(6), 687–692.
- 26 Seré, C., & Steinfeld, H. (1996). *World livestock production systems: Current status, issues and trends*
27 (Animal Production and Health Paper 127). Rome, Italy: FAO.
- 28 Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and
29 direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences*,
30 109, 16083–16088.
- 31 Sexton, J. P., McIntyre, P. J., Angert, A. L., & Rice, K. J. (2009). Evolution and ecology of species range
32 limits. *Annual Review of Ecology, Evolution, and Systematics*, 40, 415–436. doi:
33 10.1146/annurev.ecolsys.110308.120317
- 34 Sheffield, J., & Wood, E. (2012). *Drought: Past problems and future scenarios*. New York, NY:
35 Routledge.
- 36 Shepherd, A. W. (2012). Grain storage in Africa: Learning from past experiences. *Food Chain*, 2, 149–
37 163.
- 38 Shepherd, A., Mitchell, T., Lewis, K., Lenhardt, A., Jones, L., Scott, L., & Muir-Wood, R. (2013). *The*
39 *geography of poverty, disasters and climate extremes in 2030*. London, United Kingdom: Overseas
40 Development Institute.
- 41 Shively, G., Sununtnasuk, C., & Brown, M. E. (2015). Environmental variability and child growth in
42 Nepal. *Health Place*, 35, 37–51. doi: 10.1016/j.healthplace.2015.06.008
- 43 Shockley, M., & Dossey, A. T. (2014). Insects for human consumption. In J. Morales-Ramos, G. Rojas,
44 & D. I. Shapiro-Ilan (Eds.), *Mass production of beneficial organisms: Invertebrates and*

- 1 *entomopathogens* (pp. 617–652). London, United Kingdom: Academic Press. doi: 10.1016/B978-0-
2 12-391453-8.00018-2
- 3 Sillmann, J., Kharin, V. V., Zhang, X., Zwiers, F. W., & Bronaugh, D. (2013). Climate extremes indices
4 in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *Journal of Geophysical*
5 *Research: Atmospheres*, 118(6), 2473–2493. doi: 10.1002/jgrd.50188
- 6 Silva, M. D. C., Varzea, V., Guerra-Guimaraes, L., Azinheira, H. G., Fernandez, D., Petitot, A. S., . . .
7 Nicole, M. (2006). Coffee resistance to the main diseases: Leaf rust and coffee berry disease.
8 *Brazilian Journal of Plant Physiology*, 18(1), 119–147. doi.org/10.1590/S1677-
9 04202006000100010
- 10 Simelton, E., Fraser, E. D. G., Termansen, M., Benton, T. G., Gosling, S. N., South, A., . . . Forster, P. M.
11 (2012). The socioeconomics of food crop production and climate change vulnerability: A global
12 scale quantitative analysis of how grain crops are sensitive to drought. *Food Security*, 4(2), 163–
13 179. doi: 10.1007/s12571-012-0173-4
- 14 Simon, D., & Thirion, M.-C. (2013). *Rainfed food crops in West and Central Africa: Points for analysis*
15 *and proposals for action*. Paris, France: Agence Française de Développement.
- 16 Sinclair, T. R. (1992). Mineral-nutrition and plant-growth response to climate change. *Journal of*
17 *Experimental Botany*, 43, 1141–1146.
- 18 Slack, K. S., & Yoo, J. (2005). Food hardship and child behavior problems among low-income
19 children. *Social Service Review*, 79(3), 511–536.
- 20 Slayton, T. (2009). *Rice crisis forensics: How Asian governments carelessly set the world rice market*
21 *on fire* (Working Paper 163). Washington, DC: Center for Global Development.
- 22 Smil, V. (2000). *Feeding the world: A challenge for the twenty-first century*. Cambridge, MA: MIT
23 Press.
- 24 Smith, L. C., Alderman, H., & Aduayom, D. (2006). *Food insecurity in sub-Saharan Africa: New*
25 *estimates from household expenditure surveys*. Washington, DC: IFPRI.
- 26 Smith, L. C., El Obeid, A. E., & Jensen, H. H. (2000). The geography and causes of food insecurity in
27 developing countries. *Agricultural Economics*, 22, 199–215.
- 28 Smucker's. (2012). *2012 corporate responsibility report*. Orrville, OH: J. M. Smucker. Retrieved from
29 http://public.thecorporatelibrary.net/Sustain/sr_2012_13667.pdf
- 30 Snyder, R. L., Spano, D., Duce, P., & Cesaraccio, C. (2001). Temperature data for phenological models.
31 *International Journal of Biometeorology*, 45, 178–183.
- 32 Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., . . . Miller, H. L. (Eds.). (2007).
33 *Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on*
34 *Climate Change*. Cambridge, United Kingdom: Cambridge University Press.
- 35 Sonka, S. T., & Lamb, P. J. (1987). On climate change and economic analysis. *Climatic Change*, 11,
36 291–311.
- 37 SPARS. (2014). *Strategic plans for agricultural and rural statistics: Guidelines*. Retrieved from
38 <http://www.gsars.org/wp-content/uploads/2014/07/SPARS-final-3007.pdf>
- 39 Stathers, T., Lamboll, R., & Mvumi, B. M. (2013). Postharvest agriculture in changing climates: Its
40 importance to African smallholder farmers. *Food Security Journal*, 5, 361–392.
- 41 Stecke, K. E., & Kumar, S. (2009). Sources of supply chain disruptions, factors that breed
42 vulnerability, and mitigating strategies. *Journal of Marketing Channels*, 16(3), 193–226. doi:
43 10.1080/10466690902932551

- 1 Stocker, T., Qin, D., Plattner, G.-K., Tignor, M., Allen, S., Boschung, J., . . . Midgley, P. (Eds.). (2013).
2 *Summary for policymakers. Climate change 2013: The physical science basis. Contribution of working*
3 *group I to the fifth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge,
4 United Kingdom: Cambridge University Press.
- 5 Stoner, A. M. K., Hayhoe, K., Yang, X., & Wuebbles, D. J. (2013). An asynchronous regional regression
6 model for statistical downscaling of daily climate variables. *International Journal of Climatology*,
7 33(11), 2473–2494. doi: 10.1002/joc.3603
- 8 St-Pierre, N. R., Cobanov, B., & Schnitkey, G. (2003). Economic losses from heat stress by U.S.
9 livestock industries. *Journal of Dairy Science*, 86(Suppl.), E52–E77.
- 10 Su, W. (2015). *China's big grain reserves come with equally big problems.* Retrieved from
11 [http://www.marketwatch.com/story/chinas-big-grain-reserves-come-with-equally-big-problems-](http://www.marketwatch.com/story/chinas-big-grain-reserves-come-with-equally-big-problems-2015-04-20)
12 [2015-04-20](http://www.marketwatch.com/story/chinas-big-grain-reserves-come-with-equally-big-problems-2015-04-20)
- 13 Sutherst, R. W. (2001). The vulnerability of animal and human health to parasites under global
14 change. *International Journal for Parasitology*, 31(9), 933–948. doi: 10.1016/S0020-
15 7519(01)00203-X.
- 16 Swinnen, J. (2007). *Global supply chains, standards and the poor: How the globalization of food*
17 *systems and standards affects rural development and poverty.* Oxon, United Kingdom: CAB
18 International.
- 19 Swinnen, J., & Squicciarini, P. (2012). Mixed messages on prices and food security. *Science*, 335,
20 405–406.
- 21 Takle, E. S., Gustafson, D., Beachy, R., Nelson, G. C., Mason-D'Croz, D., & Palazzo, A. (2013). U.S. food
22 security and climate change: Agricultural futures. *Economics: The Open-Access, Open-Assessment E-*
23 *Journal*, 7(2013–34), 1–41. Retrieved from [http://dx.doi.org/10.5018/economics-ejournal.ja.2013-](http://dx.doi.org/10.5018/economics-ejournal.ja.2013-34)
24 [34](http://dx.doi.org/10.5018/economics-ejournal.ja.2013-34)
- 25 Tam, C. C., Rodrigues, L. C., O'Brien, S. J., & Hajat, S. (2006). Temperature dependence of reported
26 campylobacter infection in England, 1989–1999. *Epidemiology & Infection*, 134(1), 119–125.
- 27 TANGO. (2015). *SHOUHARDO II Final Quantitative Performance Evaluation: SHOUHARDO II Multi-*
28 *Year Assistance Program (MYAP).* Tucson, AZ.
- 29 Tao, F. L., Yokozawa, M., Xu, Y. L., Hayashi, Y., & Zhang, Z. (2006). Climate changes and trends in
30 phenology and yields of field crops in China, 1981–2000. *Agricultural and Forest Meteorology*, 138,
31 82–92.
- 32 Tao, F., Zhang, Z., Zhang, S., Zhu, Z., & Shi, W. (2012). Response of crop yields to climate trends since
33 1980 in China. *Climate Research*, 54, 233–247.
- 34 Tatsumi, K., Yamashiki, Y., Valmir da Silva, R., Takara, K., Matsuoka, Y., Takahashi, K., . . . Kawahara,
35 N. (2011). Estimation of potential changes in cereals production under climate change scenarios.
36 *Hydrological Processes*, 25(17), 2715–2725. doi: 10.1002/hyp.8012
- 37 Taub, D. R., & Wang, X. (2008). Why are nitrogen concentrations in plant tissues lower under
38 elevated CO₂? A critical examination of the hypotheses. *Journal of Integrative Plant Biology*, 50(11),
39 1365–1374. doi: 10.1111/j.1744-7909.2008.00754.x
- 40 Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). A summary of the CMIP5 experiment design.
41 *Bulletin of the American Meteorological Society*, 93, 485–498.
- 42 Tebaldi, C., & Arblaster, J. (2014). Pattern scaling: Its strengths and limitations, and an update on
43 the latest model simulations. *Climatic Change*, 122(3), 459–471.

- 1 Tebaldi, C., Hayhoe, K., Arblaster, J. M., & Meehl, G. A. (2006). Going to the extremes: An
2 intercomparison of model-simulated historical and future changes in extreme events. *Climatic*
3 *Change*, *79*, 185–211.
- 4 Teixeira, E. I., Fischer, G., van Velthuis, H., Walter, C., & Ewert, F. (2013). Global hot-spots of heat
5 stress on agricultural crops due to climate change. *Agricultural and Forest Meteorology*, *170*, 206–
6 215. doi: 10.1016/j.agrformet.2011.09.002
- 7 Tester, M., & Langridge, P. (2010). Breeding technologies to increase crop protection in a changing
8 world. *Science*, *327*, 818–822. doi: org/10.1126/science.1183700
- 9 Thirtle, C., Lin, L., & Piesse, J. (2003). The impact of research-led agricultural productivity growth on
10 poverty reduction in Africa, Asia and Latin America. *World Development*, *31*, 1959–1975.
- 11 Thompson, J. E. (2002). Cooling horticultural commodities. In A. A. Kader (Ed.), *Postharvest*
12 *technology of horticultural crops* (pp. 97–112). Oakland: University of California Agriculture and
13 Natural Resources.
- 14 Thomson, L. J., Macfadyen, S., & Hoffmann, A. A. (2010). Predicting the effects of climate change on
15 natural enemies of agricultural pests. *Biological Control*, *52*(3), 296–306. doi:
16 10.1016/j.biocontrol.2009.01.022
- 17 Thornton, P. E., Lamarque, J.-F., Rosenbloom, N. A., & Mahowald, N. M. (2007). Influence of carbon-
18 nitrogen cycle coupling on land model response to CO₂ fertilization and climate variability. *Global*
19 *Biogeochemical Cycles*, *21*(4). doi: 10.1029/2006GB002868
- 20 Thornton, P. K. (2010). Livestock production: Recent trends, future prospects. *Philosophical*
21 *Transactions of the Royal Society B*, *365*, 2853–2867. doi: 10.1098/rstb.2010.0134
- 22 Thornton, P. K., Jones, P. G., Ericksen, P. J., & Challinor, A. J. (2011). Agriculture and food systems in
23 Sub-Saharan Africa in a 4 C+ world. *Philosophical Transactions of the Royal Society A: Mathematical,*
24 *Physical and Engineering Sciences*, *369*(1934), 117–136.
- 25 Thornton, P. K., van de Steeg, J., Notenbaert, A., & Herrero, M. (2009). The impacts of climate change
26 on livestock and livestock systems in developing countries: A review of what we know and what we
27 need to know. *Agricultural Systems*, *101*, 113–127. doi: 10.1016/j.agsy.2009.05.002
- 28 Tilman, D., Balze, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable
29 intensification of agriculture. *Proceedings of the National Academy of Sciences*, *108*(50), 20260–
30 20264. doi: 10.1073/pnas.1116437108
- 31 Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability
32 and intensive production practices. *Nature*, *418*, 671–677.
- 33 Tirado, M. C., Clarke, R., Jaykus, L. A., McQuatters-Gollop, A., & Frank, J. M. (2010). Climate change
34 and food safety: A review. *Food Research International*, *43*(7), 1745–1765. doi:
35 10.1016/j.foodres.2010.07.003
- 36 Tiwari, S., Jacoby, H. G., & Skoufias, E. (2013). *Monsoon babies: Rainfall shocks and child nutrition in*
37 *Nepal* (Policy Research Working Paper 6395). Washington, DC: World Bank.
- 38 Tolliver, D. (2012). *An assessment of county and local road infrastructure needs in North Dakota*.
39 Fargo: Upper Great Plains Transportation Institute, North Dakota State University.
- 40 Toussaint-Samat, M. (1992). *History of food* (A. Bell, Trans.). Malden, MA: Blackwell.
- 41 Trenberth, K. (2011). Changes in precipitation with climate change. *Climate Research*, *47*, 123–138.
- 42 Trenberth, K. E., Dai, A., van der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R., & Sheffield, J.
43 (2014). Global warming and changes in drought. *Nature Climate Change*, *4*(1), 17–22.

1 Trostle, R. (2008). *Global agricultural supply and demand: Factors contributing to the recent increase*
2 *in food commodity prices* (WRS-0801). Washington, DC: USDA ERS.

3 Tschakert, P., Huber-Sannwald, E., Ojima, D., Raupach, M., & Schienke, E. (2008). Holistic, adaptive
4 management of the terrestrial carbon cycle at local and regional scales. *Global Environmental Change*,
5 *18*(1), 128–141. doi: 10.1016/j.gloenvcha.2007.07.001

6 Tubiello, F. N., Soussana, J. F., & Howden, S. M. (2007). Crop and pasture response to climate change.
7 *Proceedings of the National Academy of Sciences*, *104*(50), 19686–19690. doi:
8 10.1073/pnas.0701728104

9 Turnpenny, J. R., Parsons, D. J., Armstrong, A. C., Clark, J. A., Cooper, K., & Matthews, A. M. (2001).
10 Integrated models of livestock systems for climate change studies: Intensive systems. *Global Change*
11 *Biology*, *7*, 163–170.

12 UN. (2012). *World population prospects: The 2012 revisions*. Rome, Italy: UN Department of
13 Economic and Social Affairs, Population Division.

14 UN. (2014). *Open working group proposal for sustainable development goals* (UN Document
15 A/68/970). Retrieved from <http://undocs.org/A/68/970>

16 UNEP. (2007). *Global environment outlook 4: Environment for development*. Nairobi, Kenya: UN
17 Environment Programme.

18 UN Human Rights. (1974). *Universal declaration on the eradication of hunger and malnutrition*.
19 Retrieved from
20 <http://www.ohchr.org/EN/ProfessionalInterest/Pages/EradicationOfHungerAndMalnutrition.aspx>

21 UNISDR. (2004). *Living with risk: A global review of disaster reduction initiatives*. Rome, Italy: UN.

22 UN Standing Committee on Nutrition. (2010). *6th report on the world nutrition situation: Progress in*
23 *nutrition*. Geneva, Switzerland: WHO.

24 USAID. (2011). *Enhancing resilience in the Horn of Africa: An evidence-based workshop on strategies*
25 *for success, December 13–14, 2011* (USAID Workshop Proceedings). Washington, DC.

26 USBLs. (2014). *Labor force statistics from the current population survey*. Retrieved September 25,
27 2014, from
28 [http://data.bls.gov/timeseries/LNU04000000?years_option=all_years&periods_option=specific_pe](http://data.bls.gov/timeseries/LNU04000000?years_option=all_years&periods_option=specific_periods&periods=Annual+Data)
29 [riods&periods=Annual+Data](http://data.bls.gov/timeseries/LNU04000000?years_option=all_years&periods_option=specific_periods&periods=Annual+Data)

30 USDA. (2014). *USDA agricultural projections to 2023* (Long-term Projections Report OCE-2014-1).
31 Washington, DC: USDA, Office of the Chief Economist, World Agricultural Outlook Board.

32 USDA. (2015). *Production, supply, and distribution (PSD) online database*. Retrieved April 23, 2015,
33 from <http://apps.fas.usda.gov/psdonline/>

34 USDA ERS. (1996–2013). *Household food insecurity in the U.S.* Retrieved from
35 [http://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-](http://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-us.aspx#.VCR1UmddWjE)
36 [us.aspx#.VCR1UmddWjE](http://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-us.aspx#.VCR1UmddWjE)

37 USDA ERS. (2012). *U.S. agricultural trade/export share of production*. Retrieved from
38 [http://www.ers.usda.gov/topics/international-markets-trade/us-agricultural-trade/export-share-](http://www.ers.usda.gov/topics/international-markets-trade/us-agricultural-trade/export-share-of-production.aspx)
39 [of-production.aspx](http://www.ers.usda.gov/topics/international-markets-trade/us-agricultural-trade/export-share-of-production.aspx)

40 USDA ERS. (2013a). *Global food security*. Retrieved from
41 <http://www.ers.usda.gov/topics/international-markets-trade/global-food-security.aspx>

42 USDA ERS. (2013b). *U.S. drought 2012: Farm and food impacts*. Retrieved from
43 <http://www.ers.usda.gov/topics/in-the-news/us-drought-2012-farm-and-food-impacts.aspx>

1 USDA ERS. (2014a). *Foreign agricultural trade of the U.S.* Retrieved August 26, 2014, from
2 <http://www.ers.usda.gov/data-products/foreign-agricultural-trade-of-the-united-states->
3 [fatus\)/calendar-year.aspx#.U_zUI_n-OSo](http://www.ers.usda.gov/data-products/foreign-agricultural-trade-of-the-united-states-(fatus)/calendar-year.aspx#.U_zUI_n-OSo)

4 USDA ERS. (2014b). *Nutrients spreadsheet of food availability (per capita) data system.* Retrieved
5 March 31, 2015, from [http://www.ers.usda.gov/data-products/food-availability-\(per-capita\)-data-](http://www.ers.usda.gov/data-products/food-availability-(per-capita)-data-)
6 [system/.aspx](http://www.ers.usda.gov/data-products/food-availability-(per-capita)-data-system/.aspx)

7 USDA ERS. (2015a). *Corn trade.* Retrieved from
8 <http://www.ers.usda.gov/topics/crops/corn/trade.aspx>

9 USDA ERS. (2015b). *Effects of trade on the U.S. economy.* Retrieved from
10 <http://www.ers.usda.gov/data-products/agricultural-trade-multipliers/effects-of-trade-on-the-us->
11 [economy.aspx](http://www.ers.usda.gov/data-products/agricultural-trade-multipliers/effects-of-trade-on-the-us-economy.aspx)

12 USDA FAS. (2015a). *Coffee: World markets and trade 2105/16 forecast overview.* Retrieved from
13 <http://apps.fas.usda.gov/psdonline/circulars/coffee.pdf>

14 USDA FAS. (2015b). *Global agricultural trade system.* Retrieved May 26, 2015, from
15 <http://apps.fas.usda.gov/gats/default.aspx>

16 USDA FAS. (2015c). *Guatemala coffee annual: Production slightly recovering from coffee leaf rust.*
17 Retrieved from
18 http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Coffee%20Annual_Guatemala%20City_
19 [Guatemala_5-11-2015.pdf](http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Coffee%20Annual_Guatemala%20City_Guatemala_5-11-2015.pdf)

20 USDA NASS. (1997–2013). *Agricultural statistics.* Retrieved from
21 http://www.nass.usda.gov/Publications/Ag_Statistics/

22 USDA NASS. (2009). *Crop production 2008 summary.* Washington, DC.

23 USDA NASS. (2013). *Crop production 2012 summary.* Washington, DC.

24 USDA NASS. (2014). *Crop production 2013 summary.* Washington, DC.

25 U.S. EPA. (2013). *Major crops grown in the United States.* Retrieved from
26 <http://www.epa.gov/agriculture/ag101/cropmajor.html>

27 USTR. (2015). *Americas.* Retrieved May 10, 2015, from <https://ustr.gov/countries->
28 [regions/americas/](https://ustr.gov/countries-regions/americas/)

29 Valdivia, R. O., Antle, J. M., Rosenzweig, C., Ruane, A. C., Vervoort, J., Ashfaq, M., . . . Singh, H. (2015).
30 Representative agricultural pathways and scenarios for regional integrated assessment of climate
31 change impact, vulnerability and adaptation. In C. Rosenzweig & D. Hillel (Eds.), *Handbook of*
32 *climate change and agroecosystems: The Agricultural Model Intercomparison and Improvement*
33 *Project integrated crop and economic assessments, Part 1.* London, United Kingdom: Imperial College
34 Press.

35 Valdivia, R. O., Antle, J. M., & Stoorvogel, J. J. (2012). Coupling the Tradeoff Analysis Model with a
36 market equilibrium model to analyze economic and environmental outcomes of agricultural
37 production systems. *Agricultural Systems*, 110, 17–29.

38 Valin, H., Sands, R. D., van der Mensbrugge, D., Nelson, G. C., Ahammad, H., Blanc, E., . . .
39 Willenbockel, D. (2014). The future of food demand: Understanding differences in global economic
40 models. *Agricultural Economics*, 45, 51–67. doi: 10.1111/agec.12089

41 van de Geijn, S. C., & van Veen, J. A. (1993). Implications of increased carbon dioxide levels for
42 carbon input and turnover in soils. *CO₂ and Biosphere: Advances in Vegetation Science*, 14, 283–
43 292. doi: 10.1007/978-94-011-1797-5_19

- 1 Vandermeer, J. H., & Perfecto, I. (2012). Syndromes of production in agriculture: Prospects for
2 social-ecological regime change. *Ecology and Society*, 17(4), 39. [http://dx.doi.org/10.5751/ES-](http://dx.doi.org/10.5751/ES-04813-170439)
3 04813-170439
- 4 van der Mensbrugge, D. (2013). *The ENVironmental Impact and Sustainability Applied General*
5 *Equilibrium (ENVISAGE) Model: Version 8.0* (Technical Report). Rome, Italy: FAO.
- 6 van Tongeren, F., van Meijl, H., & Surry, Y. (2001). Global models applied to agricultural and trade
7 policies: A review and assessment. *Agricultural Economics*, 26, 149–172.
- 8 van Vuuren, D. P., Stehfest, E., den Elzen, M. G. J., Kram, T., van Vliet, J., Deetman, S., . . . van Ruijven, B.
9 (2011). RCP 2.6: Exploring the possibility to keep global mean temperature increase below 2°C.
10 *Climatic Change*, 109(1–2), 95–116. doi: 10.1007/s10584-011-0152-3
- 11 van Wijk, M., Rufino, M., Enahoro, D., Parsons, D., Silvestri, S., Valdivia, R., & Herrero, M. (2014).
12 Farm household models to analyse food security in a changing climate: A review. *Global Food*
13 *Security*, 3, 77–84.
- 14 Velázquez, F. R., Garcia-Lozano, H., Rodriguez, E., Cervanted, Y., Gómez, A., Melo, M., . . . Kuri, P.
15 (2004). Diarrhea morbidity and mortality in Mexican children: Impact of rotavirus disease.
16 *Pediatric Infectious Disease Journal*, 23(10 Supp.), S149–155.
- 17 Verdin, J., & Klaver, R. (2002). Grid cell based crop water accounting for the famine early warning
18 system. *Hydrological Processes*, 16, 1617–1630.
- 19 Verghese, K., Lewis, H., Lockrey, S., & Williams, H. (2013). *The role of packaging in minimizing food*
20 *waste in the supply chain of the future*. Melbourne, Australia: RMIT University.
- 21 Vermeulen, S. J., Aggarwal, P. K., Ainslie, A., Angelone, C., Campbell, B. M., Challinor, A. J., . . .
22 Wollenberg, E. (2012). Options for support to agriculture and food security under climate change.
23 *Environmental Science & Policy*, 15, 136–144.
- 24 Vermeulen, S. J., Campbell, B. M., & Ingram, J. S. I. (2012). Climate change and food systems. *Annual*
25 *Review of Environment and Resources*, 37, 195–222.
- 26 Vermeulen, S. J., Challinor, A. J., Thornton, P. K., Campbell, B. M., Eriyagama, N., Vervoort, J. M., . . .
27 Smith, D. R. (2013). Addressing uncertainty in adaptation planning for agriculture. *Proceedings of*
28 *the National Academy of Sciences*, 110(21), 8359–8362.
- 29 von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., . . . van Meijl, H. (2014).
30 Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global
31 Economic Model Intercomparison. *Agricultural Economics*, 45, 3–20.
- 32 Wagacha, J. M., & Muthomi, J. W. (2008). Mycotoxin problem in Africa: Current status, implications
33 to food safety and health and possible management strategies. *International Journal of Food*
34 *Microbiology*, 124(1), 1–12. doi: 10.1016/j.ijfoodmicro.2008.01.008
- 35 Wallach, D., Mearns, L. O., Rivington, M., Antle, J. M., & Ruane, A. C. (2015). Uncertainty in
36 agricultural impact assessment. In C. Rosenzweig & D. Hillel (Eds.), *Handbook of climate change and*
37 *agroecosystems: The Agricultural Model Intercomparison and Improvement Project integrated crop*
38 *and economic assessments, Part 1* (pp. 223–260). London, United Kingdom: Imperial College Press.
- 39 Walthall, C. L., Hatfield, J., Backlund, P., Lengnick, L., Marshall, E., Walsh, M., . . . Ziska, L. H. (2012).
40 *Climate change and agriculture in the United States: Effects and adaptation* (USDA Technical Bulletin
41 1935). Washington, DC: USDA.
- 42 Walther, G. R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., . . . Bairlein, F. (2002).
43 Ecological responses to recent climate change. *Nature*, 416, 389–395.

- 1 Walther, G. R., Roques, A., Hulme, P. E., Sykes, M. T., Pysek, P., Kuhn, I., . . . Bugmann, H. (2009). Alien
2 species in a warmer world: Risks and opportunities. *Trends in Ecology and Evolution*, *24*, 686–693.
- 3 Wang, S. L., Heisey, P., Huffman, W., & Fuglie, K. (2013). Public R&D, private R&D and U.S.
4 agricultural productivity growth: Dynamic and long-run relationships. *American Journal of*
5 *Agricultural Economics*, *95*(5), 1287–1293. doi: 10.1093/ajae/aat032
- 6 Wang, Y., & Lobstein, T. I. M. (2006). Worldwide trends in childhood overweight and
7 obesity. *International Journal of Pediatric Obesity*, *1*(1), 11–25.
- 8 Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., & Schewe, J. (2014). The Inter-
9 Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework. *Proceedings of the*
10 *National Academy of Sciences*, *111*(9), 3228–3232. doi: 10.1073/pnas.1312330110
- 11 Wassmann, R., Jagadish, S. V. K., Heuer, S., Ismail, A., Redona, E., Serraj, R., . . . Sumfleth, K. (2009).
12 Climate change affecting rice production: The physiological and agronomic basis for possible
13 adaptation strategies. *Advances in Agronomy*, *101*, 59–122.
- 14 Watts, M. (1983). *Silent violence: Food, famine and peasantry in northern Nigeria*. Berkeley:
15 University of California Press.
- 16 Webb, P. (2010). Medium- to long-run implications of high food prices for global nutrition. *Journal*
17 *of Nutrition*, *140*(1), 143S–147S.
- 18 Weber, C. L., & Matthews, H. S. (2008). Food-miles and the relative climate impacts of food choices
19 in the United States. *Environmental Science and Technology*, *42*, 3508–3513.
- 20 Wesche, S. D., & Chan, H. M. (2010). Adapting to the impacts of climate change on food security
21 among Inuit in the Western Canadian Arctic. *EcoHealth*, *7*(3), 361–373. doi: 10.1007/s10393-010-
22 0344-8
- 23 Wespestad, V. G., Fritz, L. W., Ingraham, W. J., & Megrey, B. A. (2000). On relationships between
24 cannibalism, climate variability, physical transport, and recruitment success of Bering Sea walleye
25 pollock (*Theragra chalcogramma*). *Ices Journal of Marine Science*, *57*, 272–278.
- 26 Wessels, K. J., Prince, S. D., Frost, P. E., & van Zyl, D. (2004). Assessing the effects of human-induced
27 land degradation in the former homelands of northern South Africa with a 1 km AVHRR NDVI time-
28 series. *Remote Sensing of Environment*, *91*, 47–67.
- 29 West, J. W. (2003). Effects of heat-stress on production in dairy cattle. *Journal of Dairy Science*, *86*,
30 2131–2144.
- 31 West, K. P., Jr., & Darnton-Hill, I. (2008). Vitamin A deficiency. In R. D. Semba, M. W. Bloem, & P. Piot
32 (Eds.), *Nutrition and health in developing countries* (2nd ed.) (pp. 377-433). Totowa, NJ: Humana
33 Press.
- 34 West, P. C., Gerber, J. S., Engstrom, P. M., Mueller, N. D., Brauman, K. A., Carlson, K. M., . . . Siebert, S.
35 (2014). Leverage points for improving global food security and the environment. *Science*, *345*, 325–
36 328.
- 37 WFP. (2012). *Nutrition at the World Food Programme: Programming for nutrition-specific*
38 *interventions*. Rome, Italy.
- 39 WFP. (2013a). *The cost of hunger in Egypt: Implications of child undernutrition on the social and*
40 *economic development of Egypt*. Retrieved July 26, 2014, from
41 <http://documents.wfp.org/stellent/groups/public/documents/ena/wfp257981.pdf>
- 42 WFP. (2013b). *WFP distributes food to families affected by the coffee rust in Central America*.
43 Retrieved from [https://www.wfp.org/news/news-release/wfp-distributes-food-families-affected-](https://www.wfp.org/news/news-release/wfp-distributes-food-families-affected-coffee-rust-central-america)
44 [coffee-rust-central-america](https://www.wfp.org/news/news-release/wfp-distributes-food-families-affected-coffee-rust-central-america)

- 1 Wheeler, T., & von Braun, J. (2013). Climate change impacts on global food security. *Science*,
2 341(6145), 508–513. doi: 10.1126/science.1239402
- 3 Whitaker, R. C., Phillips, S. M., & Orzol, S. M. (2006). Food insecurity and the risks of depression and
4 anxiety in mothers and behavior problems in their preschool-aged children. *Pediatrics*, 118(3),
5 e859–e868. doi: 10.1542/peds.2006-0239
- 6 White, N., Sutherst, R. W., Hall, N., & Whish-Wilson, P. (2003). The vulnerability of the Australian
7 beef industry to impacts of the cattle tick (*Boophilus microplus*) under climate change. *Climatic*
8 *Change*, 61, 157–190.
- 9 WHO. (2003a). *Diet, nutrition and the prevention of chronic diseases*. Geneva, Switzerland.
- 10 WHO. (2003b). *General principles of food hygiene* (CAC/RCP 1-169). Geneva, Switzerland: WHO and
11 FAO.
- 12 Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., van der Mensbrugge, D., Biewald, A., . . .
13 Willenbockel, D. (2015). Climate change impacts on agriculture in 2050 under a range of plausible
14 socioeconomic and emissions scenarios. *Environmental Research Letters*, 10, 085010. doi:
15 10.1088/1748-9326/10/8/085010
- 16 Wilby, R. L., Wigley, T. M. L., Conway, D., Jones, P. D., Hewitson, B. C., Main, J., & Wilks, D. S. (1998).
17 Statistical downscaling of general circulation model output: A comparison of methods. *Water*
18 *Resources Research*, 34(11), 2995–3008. doi: 10.1029/98WR02577
- 19 Williams, J. H., Grubb, J. A., Davis, J. W., Wang, J. -S., & Jolly, P. E. (2010). HIV and hepatocellular and
20 esophageal carcinomas related to consumption of mycotoxin-prone foods in sub-Saharan Africa.
21 *American Journal of Clinical Nutrition*, 92, 154–160.
- 22 Williams, J. H., Phillips, T. D., Jolly, P. E., Stiles, J. K., Jolly, C. M., & Aggarwal, D. (2004). Human
23 aflatoxicosis in developing countries: A review of toxicology, exposure, potential health
24 consequences, and interventions. *American Journal of Clinical Nutrition*, 80(5), 1106–1122.
- 25 Williams, K. A. (2005). An overview of the U.S. National Plant Germplasm System's exploration
26 program. *HortScience*, 40(2), 297–301.
- 27 Wood, A. W., Maurer, E. P., Kumar, A., & Lettenmaier, D. P. (2002). Long-range experimental
28 hydrologic forecasting for the eastern United States. *Journal of Geophysical Research: Atmospheres*,
29 107(D20), ACL 6-1–ACL 6-15, 27. doi: 10.1029/2001JD000659
- 30 World Bank. (2008a). *Rising food prices: Policy options and World Bank response*. Washington, DC.
- 31 World Bank. (2008b). *World development report 2008: Agriculture for development*. Washington, DC.
- 32 World Bank. (2012a). *Severe droughts drive food prices higher, threatening the poor*. Washington,
33 DC.
- 34 World Bank. (2012b). *Using public foodgrain stocks to enhance food security* (Agricultural and Rural
35 Development, Economic and Sector Work). Washington, DC.
- 36 World Bank. (2013). *Fish to 2030: Prospects for fisheries and aquaculture*. Washington, DC.
- 37 World Bank. (2014). *World development indicators 2014*. Washington, DC.
- 38 World Databank. (2015a). *Agriculture value added parameter*. Retrieved May 10, 2015, from
39 <http://databank.worldbank.org/data/home.aspx>
- 40 World Databank. (2015b). *Employment in agriculture parameter*. Retrieved May 10, 2015, from
41 <http://databank.worldbank.org/data/home.aspx>
- 42 Wu, D. S., & Olson, D. L. (2008). Supply chain risk, simulation and vendor selection. *International*
43 *Journal of Production Economics*, 114, 646–655.

1 Wu, F., Bhatnagar, D., Bui-Klimke, T., Carbone, I., Hellmich, R., Munkvold, G., . . . Takle, E. (2011).
2 Climate change impacts on mycotoxin risks in U.S. maize. *World Mycotoxin Journal*, 4(1), 79–93.

3 Wu, J. J., Adams, R. M., Kling, C. L., & Tanaka, K. (2004). From microlevel decisions to landscape
4 changes: An assessment of agricultural conservation policies. *American Journal of Agricultural*
5 *Economics*, 86(1), 26–41.

6 Wuebbles, D., Meehl, G., Hayhoe, K., Karl, T. R., Kunkel, K., Santer, B., . . . Sun, L. Q. (2014). CMIP5
7 climate model analyses: Climate extremes in the United States. *Bulletin of the American*
8 *Meteorological Society*, 95(4), 571–583.

9 Xu, Z., Hennessy, D. A., Sardana, K., & Moschini, G. (2013). The realized yield effect of genetically
10 engineered crops: U.S. maize and soybean. *Crop Science*, 53, 735–745.

11 Yates, D., Gangopadhyay, S., Rajagopalan, B., & Strzepek, K. (2003). A technique for generating
12 regional climate scenarios using a nearest-neighbor algorithm. *Water Resources Research*, 39(7),
13 1199. doi: 10.1029/2002WR001769

14 Young, E. M. (2013). *Food and development*. London, United Kingdom: Routledge Press.

15 Yu, T., & Fuller, S. W. (2005). The measurement of grain barge demand on inland waterways: A
16 study of the Mississippi River. *Journal of the Transportation Research Forum*, 44(1), 27–39.

17 Zant, W. (2013). How is the liberalization of food markets progressing? Market integration and
18 transaction costs in subsistence economies. *World Bank Economic Review*, 27, 28–54.

19 Zhang, W., Ricketts, T. H., Kremen, C., Carney, K., & Swinton, S. M. (2007). Ecosystem services and
20 dis-services to agriculture. *Ecological Economics*, 64, 253–260.

21 Zhang, W., & Wilhelm, W. E. (2011). OR/MS decision support models for the specialty crops
22 industry: A literature review. *Annals of Operations Research*, 190(1), 131–148.

23 Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Klein Tank, A., Peterson, T. C., . . . Zwiers, F. W. (2011).
24 Indices for monitoring changes in extremes based on daily temperature and precipitation data.
25 *Climate Change*, 2(6), 851–870.

26 Zhao, J., & Goodwin, B. K. (2011). *Volatility spillovers in agricultural commodity markets: An*
27 *application involving implied volatilities from options markets*. Paper prepared for presentation at
28 the Agricultural & Applied Economics Association's 2011 AAEA & NAREA Joint Annual Meeting,
29 Pittsburgh, PA. Retrieved from
30 [http://ageconsearch.umn.edu/bitstream/103636/2/AAEA%20Paper%202011,%20Zhao%20J_2.p](http://ageconsearch.umn.edu/bitstream/103636/2/AAEA%20Paper%202011,%20Zhao%20J_2.pdf)
31 [df](http://ageconsearch.umn.edu/bitstream/103636/2/AAEA%20Paper%202011,%20Zhao%20J_2.pdf)

32 Zhu, T., Ringler, C., Iqbal, M. M., Sulser, T. B., & Goheer, M. A. (2013). Climate change impacts and
33 adaptation options for water and food in Pakistan: Scenario analysis using an integrated global
34 water and food projections model. *Water International*, 38, 651–669.

35 Zilberman, D., Liu, X., Roland-Holst, D., & Sunding, D. (2004). The economics of climate change in
36 agriculture. *Mitigation and Adaptation Strategies for Global Change*, 9, 365–382.

37 Zwiers, F. W., Alexander, L. V., Hegerl, G. C., Knutson, T. R., Kossin, J. P., Naveau, P., . . . Zhang, X. B.
38 (2013). Climate extremes: Challenges in estimating and understanding recent changes in the
39 frequency and intensity of extreme climate and weather events. In G. R. Asrar & J. W. Hurrell (Eds.),
40 *Climate science for serving society: Research, modeling and prediction priorities* (pp. 339–389).
41 Dordrecht, Netherlands: Springer. doi: 10.1007/978-94-007-6692-1_13

42