

Chapter 2

Climate Change Impacts on Agriculture: Challenges, Opportunities, and AgMIP Frameworks for Foresight

Alex C. Ruane
Cynthia Rosenzweig

2.1 Introduction

Agricultural systems are currently undergoing rapid shifts owing to socioeconomic development, technological change, population growth, economic opportunity, evolving demand for commodities, and the need for sustainability amid global environmental change. It is not sufficient to maintain current harvest levels; rather, there is a need to rapidly increase production in light of a population growing to nearly 10 billion by mid-century and to more than 11 billion by 2100 (FAO, 2016; UN, 2016; Popkin *et al.*, 2012). Current and future agricultural systems are additionally burdened by human-caused climate change, the result of accumulating greenhouse gas and aerosol emissions, ecological

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destruction, and land use changes that have altered the chemical composition of Earth's atmosphere and trapped energy in the Earth system (IPCC, 2013; Porter *et al.*, 2014). This increased energy has already raised average surface temperatures by $\sim 1^{\circ}\text{C}$ (GISTEMP Team, 2017; Hansen *et al.*, 2010), leading early on to the term "global warming," but this phenomenon is now more accurately referred to as "climate change" because it also modifies atmospheric circulation, adjusts regional and seasonal precipitation patterns, and shifts the distribution and characteristics of extreme events (Bindoff *et al.*, 2013; Collins *et al.*, 2013).

Food and health systems face increasing risk owing to progressive climate change now manifesting itself as more frequent, severe extreme weather events—heat waves, droughts, and floods (IPCC, 2013). Often without warning, weather-related shocks can have catastrophic and reverberating impacts on the increasingly exposed global food system—through production, processing, distribution, retail, disposal, and waste. Simultaneously, malnutrition and ill health are arising from lack of access to nutritious food, exacerbated in crises such as food price spikes or shortages. For some countries, particularly import-dependent low-income countries, weather shocks and price spikes can lead to social unrest, famine, and migration.

Although previous actions have already guaranteed a human fingerprint on Earth's climate system, the extent to which the climate will change in coming years will depend on future emissions, land use, and technological innovations. Furthermore, the extent to which climate changes will affect agricultural systems and dependent populations will be determined by our ability to anticipate risks, diagnose vulnerabilities, and develop mitigation and adaptation strategies that lessen agricultural sector damages.

Climate change impacts on agriculture must be understood in the context of the intertwined systems that affect food security and agricultural trade, including biological, socioeconomic, and political processes. Rapid gains in socioeconomic development around the world may give the mistaken impression that climate change is not detrimental, but in many of these regions climate change impacts act as an additional burden holding back the pace of development. In addition to the biological impact

of changing climate conditions on farms, future agricultural production will be affected by economic and policy incentives across a wide variety of stakeholders and actors both locally and interacting through global markets (Valdivia *et al.*, 2015). Figure 2.1 illustrates how the current and future state of these systems dictate the extent of vulnerability to physical climate risks, which for agriculture in any given location are determined by a combination of the following:

1. *Societal pathway* – the net future impact of policies and actions that determine total global greenhouse gas emissions, aerosol emissions, and land use changes, in addition to the development and implementation of adaptation technologies (Moss *et al.*, 2010; O’Neill *et al.*, 2015).
2. *Mean climate changes* – the amount by which mean climate change variables (e.g., temperature, precipitation, sunlight, winds, relative humidity) are altered by the global climate change signal (Flato *et al.*, 2013).
3. *Changes to climate extremes* – the extent to which extreme climate events (e.g., droughts, floods, heat waves, frosts, tropical cyclones, hail) alter their magnitude, frequency, duration, and geographic extent (Seneviratne *et al.*, 2012).
4. *Patterns of local agro-climate exposure compared with global signal* – the ways in which geographical characteristics (e.g., latitude, mountains, coastlines, land cover) and growing season exposure lead to local climate changes affecting agriculture in a manner that is distinct from the overall global and long-term climate signals (Ruane and McDermid, 2017).

This chapter provides foresight into the ways in which climate change will shape future agricultural systems, seeking to anticipate new challenges and opportunities so that new technological and policy strategies may be developed for a more resilient and productive future. The chapter focuses primarily on foresight into major crops (maize, wheat, rice, and soy), which together account for about 43% of global dietary calories; soybean is the primary oilseed for human and livestock consumption (FAO, 2013). These areas of emphasis reflect the focus of the scientific literature but fall short of meeting the diverse needs of

agricultural sector planners. Priority areas for continuing foresight development include the creation of models for more crop species (notably perennials, fruits and vegetables, oil crops, and tropical cereals) and plantation crops (such as coffee, tea, cacao, and wine grapes, where yield quality may be more important than yield quantity). Tools capable of simulating more complex systems would also allow testing of creative interventions for intercropping, crop rotations, mixed crop-livestock systems, and aquaculture.

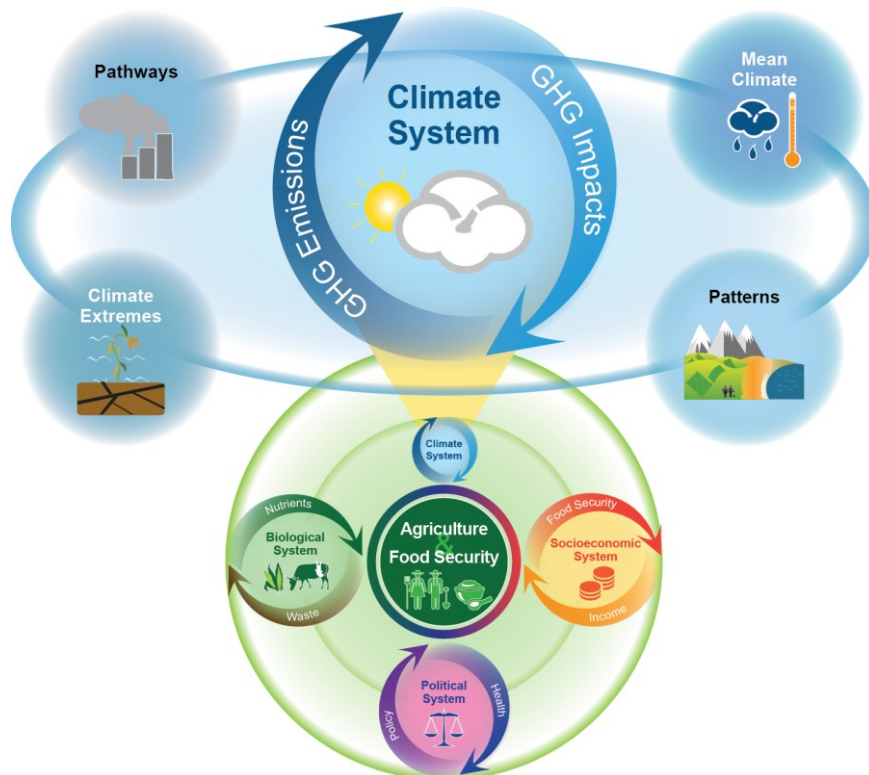


Figure 2.1. Climate is one of the complex and interacting systems comprising agriculture and food security, and its effects on any given farming system will be distinguished by society's pathway of emissions and land use, shifts in mean climate, changing climate extremes, and regional patterns owing to geography and exposure resulting from farm management. Figure adapted from Rosenzweig and Hillel (2017).

Climate changes will also affect elements of the agriculture and food system beyond the farm, including economic risks to elements of the value chain such as storage facilities, processing plants, and transportation, as well as political risks should governmental policies shift toward or away from environmental sustainability (Figure 2.1). Other chapters in this volume specifically address the context in which future agricultural systems will be impacted by climate change, evaluating trends in socioeconomic conditions, demand for agricultural products, characteristics of future food systems, resource sustainability, and agricultural technology trends, among other topics.

The most prominent recent assessment of the scientific literature on climate change and food security was conducted by the IPCC (Porter *et al.*, 2014), with additional notable assessments about vulnerability and opportunities provided by the CGIAR (Beddington *et al.*, 2012), the United States Department of Agriculture (Brown *et al.*, 2015), and the United Nations Food and Agriculture Organization (FAO, 2016).

Here we provide an overview of climate trends affecting agriculture (section 2.2), projected risks from future agro-climatic changes (section 2.3), the nature of differing impacts among regions and farming systems (section 2.4), and a foresight framework that identifies vulnerabilities and prioritizes adaptation strategies using major developments within the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig *et al.*, 2013) (section 2.5).

2.2 Agro-climatic Trends and System Responses

The signal of ongoing climate change trends affecting agriculture is difficult to isolate amid significant changes in technological adoption and socioeconomic development. These include trends and step changes stemming from the introduction of hybrid and dwarf varieties, proliferation of mechanical equipment, application of herbicides and pesticides, installation of water resources infrastructure, and increased interconnection of markets, as well as social conflicts that punctuate the historical production record. In many regions, climate is not the primary limiting factor for production—in the developing world, for example, farm

nitrogen levels, labor shortages, or lack of pest, disease, and weed controls often cap yields. Additionally, heterogeneity in farming systems and gaps in surveys and reported agricultural information make observing direct climate impacts at large scales difficult.

2.2.1 Observed changes to agricultural climates

Rising mean temperatures are the most direct and observable signal of climate change for agricultural regions around the world, with many regions showing robust trends that are distinct from the signal of natural variability (Hartmann *et al.*, 2013). Figure 2.2a presents more recent trends in annual temperature changes from the GISTEMP dataset (GISTEMP Team, 2017; Hansen *et al.*, 2010), comparing the 1980–2010 period against the previous 30 years (1951–1980). Surface warming is amplified at high latitudes owing primarily to feedback associated with melting of snow and ice, as well as at higher elevations and in arid regions where excess energy is more efficiently transferred into near-surface heat. Many of these most rapidly warming areas have little agricultural production at present. Growing seasons for maize, wheat, rice, and soy (Fig. 2.2b–e) have been exposed to slightly different climate changes than the annual average; tending to avoid the larger increases in winter and dry season temperatures while taking advantage of a higher portion of annual rainfall coming during the wet season (Ruane *et al.*, 2018a). Increases in daily minimum (nighttime) temperature appear to be outpacing the warming of daily maximum temperature, resulting in an uncertain reduction in diurnal temperature range (Hartmann *et al.*, 2013) that may lead to nighttime crop respiration stresses.

Observed precipitation trends in any given location are often quite difficult to separate from what is often considerable natural variability. Large-scale trends noted by the IPCC (Hartmann *et al.*, 2013), however, have largely exacerbated historical patterns by making wet areas wetter and dry areas drier (Trenberth, 2011). Higher temperatures are expected to enhance the overall water cycle, but thus far increases in atmospheric moisture have tracked increases in saturation limits, resulting in nearly constant relative humidities (Hartmann *et al.*, 2013). Changes in photosynthetically active radiation (PAR) are also uncertain, as climate

shifts affect different types of clouds in unique ways, as well as the circulation patterns that steer them.

Extreme events (e.g., heat waves, cold snaps, droughts, floods, severe storms), by definition, are rare, and therefore it is difficult to assess robust trends with limited observational records. Gauging the severity of a 1-in-100-year event, for example, is challenging in regions where the consistent historical record is around 100 years long or shorter, particularly when the underlying distribution of extreme events is also responding to long-term climate trends.

The IPCC recently undertook a review of observed changes in extreme events (Seneviratne *et al.*, 2012), and both models and observations provide more robust signals for temperature extremes (e.g., increases in warm days) than for hydrologic extremes (e.g., heavy precipitation events became more frequent in many regions even as other regions displayed the opposite trends) (Hartmann *et al.*, 2013). Even in cases with clear increases in the frequency of extreme events, it may be difficult to determine whether this is a result of a shift in the overall distribution or an additional fundamental shift in the shape of the distribution (Hansen *et al.*, 2012).

There are no clear observational trends in major modes of climate variability such as the El Niño/Southern Oscillation, the North Atlantic Oscillation, or the Pacific Decadal Oscillation (Hartmann *et al.*, 2013).

2.2.2 *Direct climate impacts on agricultural systems*

Direct impacts of climate, including atmospheric carbon dioxide (CO₂) concentrations, on agricultural systems include effects on plant development, grain productivity, and mortality. Table 2.1 summarizes the main drivers and mechanisms of climate impact on cropping systems, which were reviewed by Bongaarts (1994), Rosenzweig *et al.* (2001), Boote *et al.* (2010), Kimball (2010), and Porter *et al.* (2014). Notably, direct climate impacts include both damage and benefits as well as opportunities for farm-level adaptations. In assessing vulnerabilities and opportunities of farming systems, it is also important to recognize that C3 plants (e.g., wheat, rice, soy, potato, and peanut) generally react more

strongly than C4 plants (e.g., maize, sugarcane, sorghum) to both increases in temperature and CO₂.

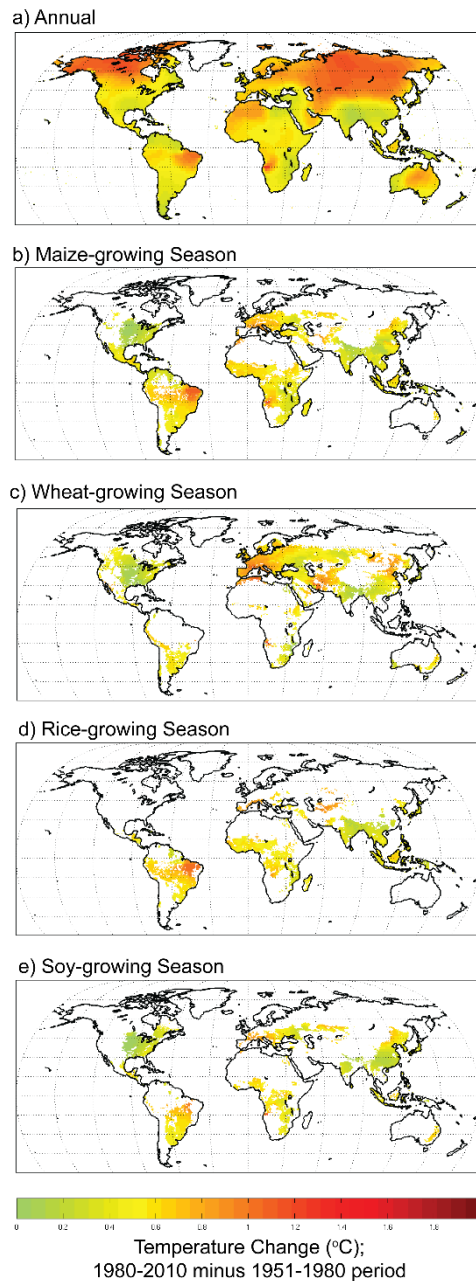


Figure 2.2. Recent (a) annual, (b) maize, (c) wheat, (d) rice, and (e) soy growing season observed mean temperature changes (GISTEMP Team, 2017; Hansen et al., 2010). Growing seasons for each $\frac{1}{2} \times \frac{1}{2}$ degree gridbox were drawn from the AgMIP Global Gridded Crop Model Intercomparison (Elliott *et al.*, 2015), and grid boxes that harvested less than 10 ha of a given crop species were omitted to focus on regions with substantial production (You *et al.*, 2014).

Characteristics of direct climate impacts have been investigated using a variety of chamber and field experiment approaches, although published studies have focused more on mid-latitude and high-input cereals while direct impacts on tropical cropping systems, perennials, fruits, and vegetables have persistent uncertainties (Porter *et al.*, 2014; Long *et al.*, 2006; Tubiello *et al.*, 2007a,b; Ainsworth *et al.*, 2008; Boote *et al.*, 2010). Interactions between soils and climate changes are crucial, as the full benefits of higher CO₂ cannot be achieved by farms experiencing nitrogen stress.

Panel regressions and other statistical methods have also identified statistically significant climate signals within reported yields (Lobell and Burke, 2008; Schlenker and Roberts, 2009), with resulting models suggesting that climate changes have already led to decreases in wheat and maize production since 1980 (Lobell *et al.*, 2011).

Table 2.1. Overview of main drivers and mechanisms for direct climate change impacts on cropping systems. Further detail provided by Bongaarts (1994), Rosenzweig *et al.* (2001), Boote *et al.* (2010), Kimball (2010), Porter *et al.* (2014), and Myers *et al.* (2017).

Climate driver	Biophysical mechanism	Overview of direct impact on agriculture
Increased mean temperatures	Accelerated maturity	Warmer temperatures cause plants to develop at an accelerated pace, leading to an earlier maturity before sufficient biomass has been gained and therefore reducing overall yields.
Increased mean temperatures	Shifts in suitable growing seasons	Warmer temperatures generally extend the growing season in areas that are currently limited by cold temperatures while restricting growing seasons in regions limited by high temperatures.
Extreme temperatures	Heat stress, leaf loss, and mortality	Extremely hot temperatures cause plants to reduce photosynthetic activity, with prolonged exposure leading to leaf loss and potentially full crop failure (Asseng <i>et al.</i> , 2015).
Heat wave during flowering stage	Pollen sterility	The impacts of heat waves depend on a plant's developmental stage; heat waves during flowering (anthesis) can cause pollen to be sterile leading to reproductive failure and low grain numbers.
Elevated CO ₂	Enhanced primary productivity	Higher CO ₂ concentrations benefit photosynthesis, resulting in higher productivity (Rosenzweig <i>et al.</i> , 2014).
Elevated CO ₂	More efficient water use	Plants in high-CO ₂ environments have more efficient stomatal gas exchanges, which reduce transpiration and improve water retention (Deryng <i>et al.</i> , 2016).
Elevated CO ₂	Reduction in nutritional content	Yield from crops in CO ₂ -rich conditions contains a lower percentage of key nutrients including protein, iron, and zinc (Müller <i>et al.</i> , 2014; Myers <i>et al.</i> , 2014; Medek <i>et al.</i> , 2017).
dDecreased precipitation	Increase in water stress and mortality	Excessive transpiration demand causes plants to reduce gas exchanges for photosynthesis, conserving water at the expense of primary

		production. Plant water loss can lead to wilting and mortality.
Increased precipitation	Reduction in water stress	Areas that regularly experience drought conditions likely stand to benefit should mean precipitation increase.
More severe storms	Plant damage	High winds and hail can knock down, break, or uproot crops, leading to potentially severe losses.

2.2.3 Indirect mechanisms for agro-climatological impacts

Climate change impacts on other biophysical systems are likely to have indirect impacts on agricultural systems. These include the following:

- Sea-level rise: Glacial melting and thermal expansion of the oceans could lead to sea-level rise of up to a meter or more by 2100 (Church *et al.*, 2013), potentially inundating low-lying coastal regions with saltwater in a process exacerbated by extreme storms. Mega-deltas (e.g., the Ganges-Brahmaputra in Bangladesh, Nile in Egypt, or Mekong/Red in Vietnam) are particularly vulnerable and contain some of the world's most productive breadbaskets as well as high densities of smallholder farmers.
- Inland flooding: Inland freshwater flooding may also be exacerbated by mean precipitation increases, more severe storms, and a higher proportion of precipitation falling as rain rather than snow (Dettinger and Cayan, 1995). Higher rainfall totals could also increase the occurrence of waterlogging and field conditions that are too wet for the use of heavy farm equipment.
- Water resources: Water resources for irrigation are projected to face increased stress owing to long-term reductions in mountain snowpack that reduce the natural reservoir capacity of a river basin for irrigation; this effect could be particularly challenging for semi-arid areas irrigated by surface water in snow-fed river systems (Döll, 2002; Mote *et al.*, 2005).
- Pests: Shifting climate zones will also affect agro-ecological zones (Fischer *et al.*, 2002) and alter the potential extent and

timing of damaging agricultural pests, diseases, and weeds (Ziska and Runion, 2006; Rosenzweig and Tubiello, 2007).

Direct and indirect agro-climatic effects can be long-term and widespread (e.g., elevated temperatures, CO₂ effects, water resources supply) or temporally and regionally acute (e.g., drought, heat wave, coastal and inland flooding, pests). Climate change may also indirectly affect agriculture and food systems through economic and political disruption. Prominent examples include a consistent and extended decline in sea ice that would allow for transportation of agricultural commodities through the Northwest Passage, more frequent disruption of major trading ports due to sea-level rise and more intense hurricanes, and the potential for social unrest and migration following extended agricultural droughts.

2.2.4 *Agricultural system influences on the climate system*

The agricultural sector is not only vulnerable to weather and climate hazards, but also a major contributor to the greenhouse gas emissions and land use changes that drive climate change (IPCC, 2014). Historical deforestation was motivated in large part by demand for more lands for crops and grazing, and agricultural systems are a net greenhouse gas emissions source owing to exchanges with carbon and nitrogen stocks in soils and fertilizers as well as methane from paddy rice and livestock enteric fermentation. Together the agricultural sector accounts for just under a quarter of total greenhouse gas emissions (Smith *et al.*, 2014), resulting in a mandate for a substantial agricultural system role in overall societal mitigation. Socioeconomic and biophysical pathways evaluated by the chapters in this foresight volume will also determine the total and relative contribution of agricultural sector emissions and land use changes that alter the future climate system.

2.3 Projected Climate Changes for Agricultural Regions

Projections show that climate change in agricultural regions will be characterized by slow, long-term changes in mean conditions punctuated by acute extreme events.

Figure 2.3 presents end-of-century mean temperature changes according to the median of 29 global climate model (GCM) ensemble drawn from the Coupled Model Intercomparison Project Phase 5 (Taylor *et al.*, 2012; Ruane and McDermid, 2017), and Figure 2.4 shows corresponding projected changes in mean precipitation. Warming across the GCM ensemble is clear, while the direction of precipitation shows strong regional variation but is more uncertain overall. The magnitude of regional changes depends strongly on future pathways of socioeconomic development, land use change, and greenhouse gas emissions (Moss *et al.*, 2010; O'Neill *et al.*, 2014), with projections for the higher-emissions pathway doubling the extent of climate changes projected for the lower-emissions pathway in many regions. Patterns of these mean changes are similar to the recent climatic trends shown in Figure 2.1, with the largest warming projected over high latitudes and during winter months and an exacerbation of wet and dry regions, particularly around major monsoon circulations (Trenberth, 2011). These climate changes are driven by substantial increases in CO₂ concentrations (with positive direct effects on agricultural systems), which would rise from about 400 parts per million (ppm) today to 532ppm or 801 ppm by 2085 under the lower- or higher-emissions pathway, respectively (Ruane *et al.*, 2015).

Climate model projections of changes in the characteristics of extreme events are less certain than the mean changes, but shifts toward more heat waves, dry spells, and extreme precipitation events (when storms do occur) are strongly supported by theory and emerge from ensemble model analyses even as uncertainty in individual models and regions remains substantial (Flato *et al.*, 2013; Pendergrass and Hartmann, 2014). Analysis of the paleoclimate record and climate model projections also indicates an increasing probability of regional “mega-droughts” with magnitudes and durations unlike anything observed in modern times (Cook *et al.*, 2015).

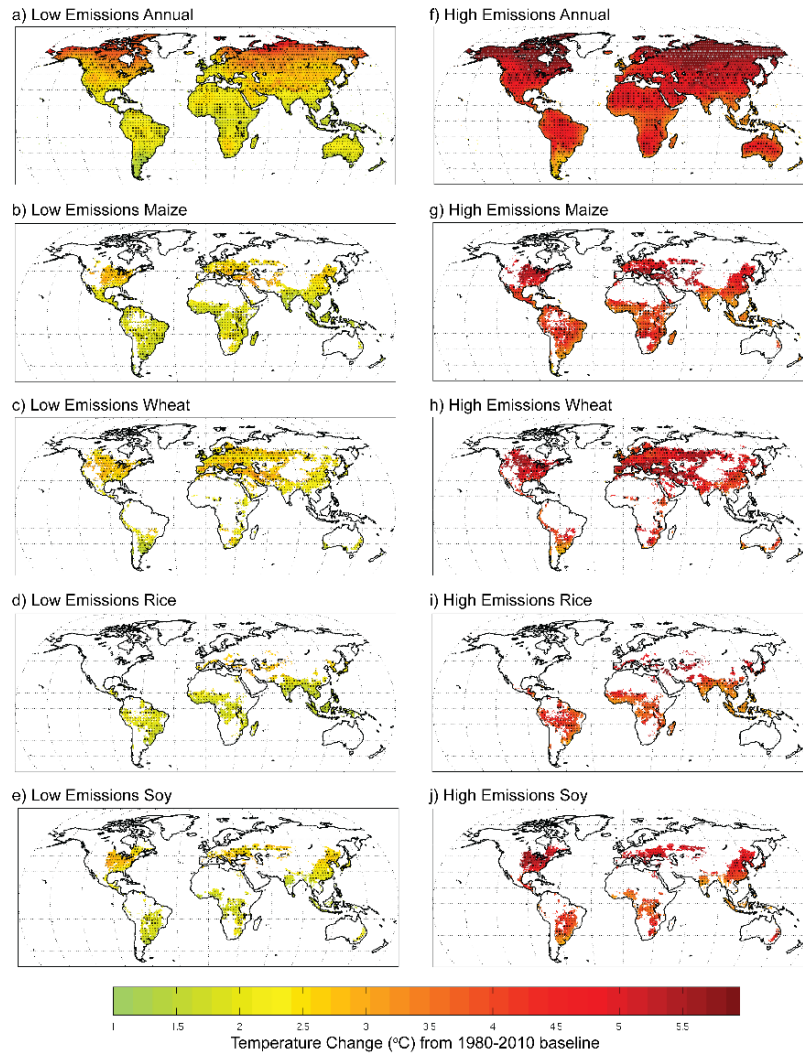


Figure 2.3. (a,f) Annual, (b,g) maize, (c,h) wheat, (d,i) rice, and (e,j) soy growing season projected mean temperature changes for the end of the 21st century (2070–2099) compared with the 1980–2010 baseline period. Projections are for (a–e) a low-emissions pathway and (f–j) a high-emissions pathway (RCP4.5 and RCP8.5 in Moss *et al.*, 2010). Growing seasons and cropped areas are defined as in Figure 2.2, and hatching indicates regions where at 70% or more of the GCM projections indicate the same direction of change.

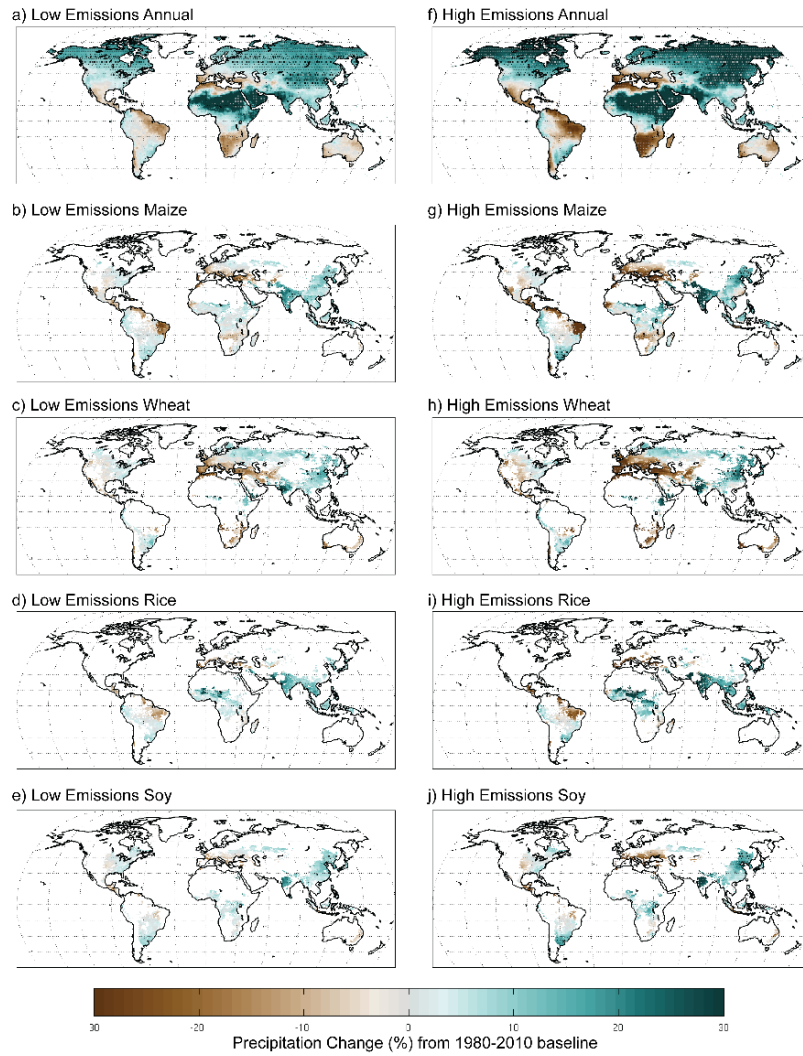


Figure 2.4. (a,f) Annual, (b,g) maize, (c,h) wheat, (d,i) rice, and (e,j) soy growing season projected mean precipitation changes for the end of the 21st century (2070–2099) compared with the 1980–2010 baseline period. Emissions pathways, cropped area, and growing seasons are as in Figure 2.3, and hatching indicates regions where at 70% or more GCM projections indicate the same direction of change.

2.4 Ramifications of Climate Change on the Agricultural Sector

Climate change threatens agricultural production, which in turn is expected to alter the geographic extent of major farm systems, shift trade flows, and drive major investment in adaptation and mitigation within the agricultural sector.

Figure 2.5 displays an example of the changes in projected rainfed maize yields under the higher-emissions scenario simulated by a global gridded crop model (Elliott *et al.*, 2014). Regional yield impacts can be substantial even in early decades, although their magnitudes and exact projected location is subject to uncertainty from climate and crop models as well as internal climate variability (Wallach *et al.*, 2015). The long-term yield impacts of climate change more clearly emerge from variability in the middle and end of the 21st century, with considerable variation across region, and with maize and wheat systems generally more vulnerable than rice and soy (Rosenzweig *et al.*, 2014).

As a C4 crop, maize stands to benefit less from elevated CO₂ concentrations, while wheat struggles to meet vernalization requirements as temperatures rise (Bassu *et al.*, 2014; Asseng *et al.*, 2013). All crops show more pessimistic yield changes at lower latitudes and in semi-arid regions where agriculture is already limited by high temperatures and water stress. Yield changes are more optimistic at high latitudes where cold temperatures are most limiting, although the potential for poleward expansion is hindered by shallow soils with poor drainage as well as vast forests that are important in efforts to mitigate climate change risk.

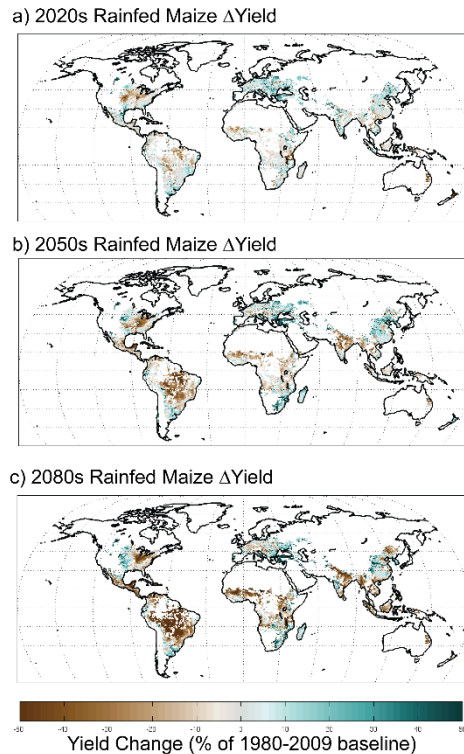


Figure 2.5. Projected rainfed maize yield changes, compared with the 1980–2009 period, under the higher-emissions scenario in the (a) 2020s, (b) 2050s, and (c) 2080s. Projections driven by climate scenarios drawn from the UK HadGEM2-ES climate model (Rosenzweig *et al.*, 2014). Grid cells with 10 ha of maize area or less were omitted as in Figure 2.3.

Agricultural vulnerabilities to climate change are quite robust across methods (Zhao *et al.*, 2017), having also been identified in meta-analyses of crop model projections (Easterling *et al.*, 2007; Challinor *et al.*, 2014) as well as statistical model applications (Schlenker and Roberts, 2009). Agro-climatic risk is also sensitive to scale, as yield changes can show large

differences over small geographic scales owing to emerging storm tracks, mountains, coastlines, and land cover (Porter *et al.*, 2014). Yield impacts may also contrast strongly across different growing seasons (e.g., short and long rains in tropical climates; Zubair *et al.*, 2015; Ruane *et al.*, 2012) and management systems (Ruane *et al.*, 2013), and even areas with average rainfall increases may see a higher risk of drought (Trenberth, 2011).

Direct climate impacts are also expected to affect aquaculture, wild fisheries, and livestock, although most investigations of livestock impacts have focused on productivity changes of their grain feedstock (Porter *et al.*, 2014).

Climate-induced changes in regional yields will have repercussions throughout the agricultural sector and heighten pressure for adaptation (Figure 2.6; Wiebe *et al.*, 2015). Agricultural prices will rise in light of

production shortfalls, leading to an expansion of agricultural area in order to meet food and fiber demands. Agricultural regions will face increased pressure where hot and dry conditions currently prevail, with potential movement toward wetter zones, high latitudes, and elevated regions following the movement of shifting agro-ecological zones. Coupled with the potential collapse of ground- and surface water resources in regions with substantial irrigation (e.g., in northern India and Pakistan; Rodell *et al.*, 2009), this could lead to the degradation of some breadbaskets even as others emerge. The impacts of price changes will be felt in different ways by vulnerable populations: farmers in regions that are not severely affected are likely to obtain better prices for agricultural commodities whereas urban populations will bear the brunt of higher costs. Changes in regional production may also affect competitive trade balances and alter the flow of market goods.

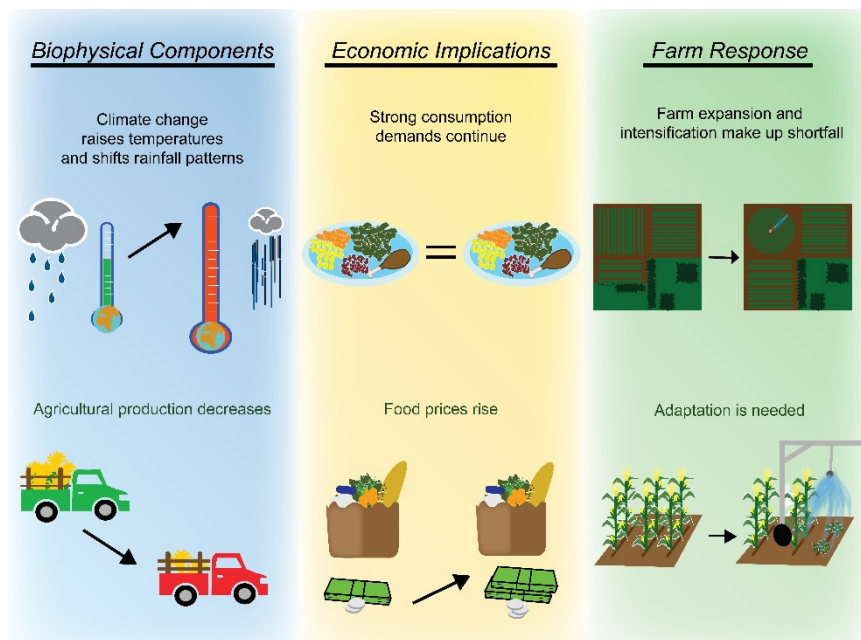


Figure 2.6. Overview of climate effects on the agricultural sector and their downstream ramifications based on results of a multi-model climate-crop-economic analysis performed by Wiebe *et al.* (2015). Climate change leads to biophysical impacts that affect economic

systems driven by strong consumer demand, leading to price, land use change, and farm system responses.

Changes in yields and prices will galvanize adaptation across the agricultural sector, with more transformational adaptations spurred by climate shocks or the accumulating impact of more frequent poor harvests (Yadav *et al.*, 2011; Rickards and Howden, 2012; Howden *et al.*, 2007; Rosenzweig and Tubiello, 2007). Proactive adaptation planning may be integrated into ongoing investment and rehabilitation cycles with an aim to build resilience. This can be accomplished through new breeding programs, irrigation infrastructure, management strategies, and farming systems, as well as enhanced diversification, shifts in growing seasons, pest, disease, and weed control, protection against extreme events, insurance programs, and stock building. The development and implementation of early-warning systems also stands to increase the efficiency of planning and response.

Efforts to mitigate climate change are also likely to acutely affect the future of global agriculture (IPCC, 2014). Efforts to replace fossil energy sources with biofuels and incentives for afforestation will both increase competition for land, potentially squeezing out the production of food for both subsistence and market trade. Policies and related technologies to control industrial pollution are also likely to reduce overall aerosol loading and surface ozone concentrations, with likely benefits for agricultural systems.

Mitigation in agriculture and food systems could come from a reduction in the intensity of emissions from agricultural lands (e.g., emissions/harvested crop weight) or from a reduction in demand for agricultural products (e.g., from dietary pathways with a lower emissions footprint). Many mitigation practices (such as reduced tillage) were originally developed as “best practices” for agriculture; sustainable management of carbon, nitrogen, and water stocks help raise production and build resilience against climate variability in addition to mitigating (or even reversing) greenhouse gas fluxes into the atmosphere (Rosenzweig and Tubiello, 2007). Corporations and development agencies are increasingly organizing efforts around “climate-smart agriculture” (CSA), a systematic approach to agricultural development intended to address the

dual challenges of food security and climate change from multiple entry points, from field management to national policy. CSA aims to guide public and private investments to (1) improve food security and agricultural productivity and (2) increase the resilience of farming systems to climate change by adaptation, while (3) capturing potential mitigation co-benefits. Dickie *et al.* (2014) review an array of mitigation strategies, although it is important that these be considered in the context of socioeconomic and political systems (FAO, 2009).

2.5 Agricultural Modeling for Climate Vulnerability Foresight

Providing agricultural system stakeholders and adaptation planners with foresight on climate change's cascading impacts requires an assessment of multiple scales, disciplines, and systems that interact in a complex manner (Figure 2.1). Responsive actions are likewise spurred by a diverse set of motivations and priorities, and all of this is occurring in a highly uncertain setting owing to data limitations, model differences, and dependence on socioeconomic decisions in the coming years. The Agricultural Model Intercomparison and Improvement Project (AgMIP), an international transdisciplinary community of modelers and practitioners, has developed a number of modeling frameworks that may be used to envision and plan for future challenges, allowing us to test policy and adaptation strategies in a virtual setting before more costly development, trial, and at-scale rollout (Rosenzweig *et al.*, 2013, 2015; Ruane *et al.*, 2017).

AgMIP has developed teams to investigate farm-level impacts, vulnerability, and adaptation using process-based crop models. AgMIP-Wheat (Asseng *et al.*, 2013, 2015; Martre *et al.*, 2015; Ruane *et al.*, 2016; Wang *et al.*, 2017), AgMIP-Maize (Bassu *et al.*, 2014; Durand *et al.*, 2017), AgMIP-Rice (Li *et al.*, 2015), AgMIP-Potato (Fleisher *et al.*, 2017), and AgMIP-Sugarcane (Marin *et al.*, 2015) have each investigated core responses to climate changes and provided benchmarks for model-based applications oriented around genetic and management improvements for resilience.

AgMIP's Global Gridded Crop Model Intercomparison (GGCMI; Elliott *et al.*, 2015; Müller *et al.*, 2017) takes these models to a global scale, elucidating regional differences and aggregate production changes. Additional activities in progress include focus on soils and crop rotation, water resources, livestock modeling, and pests and diseases.

AgMIP as a community is also developing frameworks to understand impacts and trade-offs in the wider socioeconomic system at local to global scales. The AgMIP Global Economics Team explores the ramifications of climate changes on production, land use, commodity markets, and vulnerable populations around the world (Nelson *et al.*, 2014; Wiebe *et al.*, 2015). Regional integrated assessment modeling adds a sharper perspective on heterogeneous populations even in a small region, allowing evaluation of costs, benefits, and trade-offs between the current systems and those associated with climate, adaptation, and policy shifts (Antle *et al.*, 2015). Socioeconomic foresight is aided by the development of representative agricultural pathways (RAPs) that can be used in integrated assessment modeling at global, regional, or local scales (Valdivia *et al.*, 2015). Table 2.2 shows an example of the types of information contained in RAPs produced for nine countries in South Asia and sub-Saharan Africa. These RAPs were produced through a stakeholder-driven exploration of current and future trends in sustainability, agricultural technologies, socioeconomic factors, policies, and agricultural extension that will determine the future systems that climate change will affect. RAPs are the primary mechanism for agricultural models to represent the types of foresight elements detailed in other chapters in this volume (e.g., on resource constraints, value chains, farm technologies, societal demand).

Table 2.2. Selected elements of RAPs for nine countries in South Asia and sub-Saharan Africa.

Driver type	RAP element
Sustainability	Soil degradation
	Water availability
Agricultural technologies	Resilience to pests and diseases
	Livestock productivity

	Resilience to extreme events
Socioeconomic	Farm size Household size Herd size Fertilizer prices Fertilizer use Use of improved crop varieties Labor availability Off-farm income
Policy	Subsidies (for farm inputs) Public investment in agriculture

Agricultural extension Information availability

Source: Adapted from Valdivia *et al.* (2015).

Note: RAPS = representative agricultural pathways. The RAPs were created under illustrative “green road” (sustainability-oriented) and “gray road” (economic development-oriented) pathways.

AgMIP recently launched a new initiative on coordinated global and regional assessments (CGRA), which link AgMIP activities to consistently incorporate biophysical and socioeconomic assessments across spatial scales while also seeking integrate nutrition and food security metrics (Figure 2.7; Rosenzweig *et al.*, 2016, 2018; Ruane *et al.*, 2018b). One of CGRA’s main aims is to facilitate an assessment of the ways in which climate shocks affect biological and social systems throughout the agricultural sector, as well as the likely behavioral responses of actors who may be in a position to intervene in or exacerbate the resulting challenges. The CGRA framework also allows for the tracking of various sources of uncertainty that may form bottlenecks in our ability to project future conditions (Ruane *et al.*, 2018b). Further integration of agricultural model projections with integrated assessment models will also shed light on how agricultural sector impacts (e.g., as discussed in other foresight topic chapters in this volume) affect other sectors and the overall interactions between society and the natural environment (Ruane *et al.*, 2017). In the longer run the CGRA framework

could become more comprehensive with the addition of elements such as livestock, fisheries, value chains, diet shifts, and nutrition.

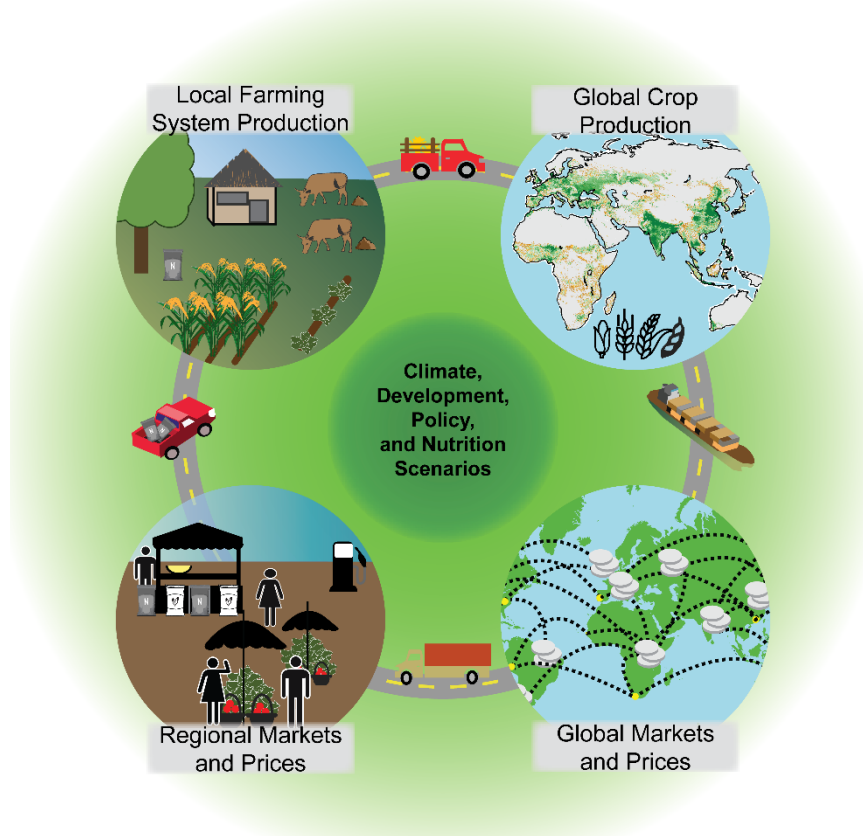


Figure 2.7. Schematic describing the core interactions captured by the AgMIP coordinated global and regional assessments (CGRAs). Careful simulation of regional farm system production allows insight into the individual elements of a global agricultural production system represented by global gridded crop models. Regional production drives global economic and agricultural trade models that simulate land use and prices for food and farm inputs with effects on regional markets, in turn driving decision-making and investment that can be modeled when simulating regional farming systems. The dynamic CGRA modeling framework connects across scales and disciplines to understand agriculture and food security under a number of scenarios and future pathways.

Persistent monitoring of long-term challenges and the use of foresight tools for planning are important elements of building a more productive and resilient future. By anticipating challenges, we can identify

vulnerabilities and opportunities with enough time for society to develop, disseminate, and implement promising strategies for mitigation and adaptation.

2.6 References

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