Chapter 4

CLIMATE CHANGE
Understanding Impacts on Agrifood Systems and Evaluating Policy Options

Mark W. Rosegrant, Elizabeth Bryan, Timothy S. Thomas, and Keith Wiebe

Mark W. Rosegrant is a research fellow emeritus, IFPRI; **Elizabeth Bryan** is a research fellow, Natural Resources and Resilience Unit, IFPRI; **Timothy S. Thomas** and **Keith Wiebe** are senior research fellows, Foresight and Policy Modeling Unit, IFPRI.

Key messages

- As climate change became a central focus of food policy research, research expanded from projecting global and national impacts on agriculture to assessing risks to households and individuals and options for policy responses, and from a focus on mitigation toward actions that support both mitigation and adaptation.
- Model-based projections broadly agree on the key agricultural impacts of climate change: declining productivity growth and nutrient density of crops and reduced food security, with the greatest impacts at lower latitudes and in low-income countries.
- Research focused on identifying and reducing risks for vulnerable populations, particularly small-scale producers and women, identifies “hot spots” and effective adaptation strategies.
- Farm-level adaptations show promise for protecting livelihoods and food security but have not been adopted at scale. Research explores the barriers to greater impact of these innovations.
- Climate-smart agriculture research emphasizes synergies among adaptation, mitigation, and productivity goals at the farm level, and shows that climate-smart practices can reduce hunger.
- Evidence on disparities in climate impacts between high- and low-income countries and within countries, where impacts are greater on marginalized peoples, supports policies for climate justice.

Looking to the future, policy research on climate and food systems should aim to:

- **Improve identification of hotspots and targeting of resources** by combining yield projections from crop models with information on the local importance of crops and local indicators of vulnerability, including social inequalities.
- **Increase capacity for modeling** the frequency and impact of extreme climate events and better incorporate feedback mechanisms, impacts on labor productivity, economic growth, and nutrition, to allow comparison of the effectiveness of potential policy responses.
- **Identify and help to prioritize scalable adaptation strategies** that can be effective both at large and local scales.
- **Identify effective mechanisms to address climate injustice** and ways to make climate governance more representative of vulnerable communities, including women and poor populations.
- **Combine climate modeling and household survey analysis** at the country level to provide policy-relevant foresight and evidence to decision-makers as countries undergo major socioeconomic and environmental changes in coming years.
- **Inform the design and implementation of climate interventions and policies** that better address broader development goals such as food security, nutrition, and health.

Climate change is a major challenge of our time, with global and far-reaching—though often uncertain—effects on and from agriculture and food systems. Rising temperatures and changing weather patterns are already increasing the risk of hunger, malnutrition, and food insecurity among the world's poorest and most vulnerable populations. Natural disasters such as droughts and flooding are becoming more frequent and intense, while climate change makes arable land and freshwater scarcer and agricultural productivity harder to increase (Parry et al. 2009). New or more damaging pests, pathogens, and weeds will challenge farmers. Agriculture is also a major contributor to greenhouse gas (GHG) emissions. Thus, policies and investments for the agrifood sector must support both the goals of reducing GHG emissions and sequestering carbon (Mbow et al. 2019; Smith et al. 2018) and increasing farmers' resilience through adaptation to climate change and income growth.

However, as it becomes less likely that the world will meet its 2015 Paris Agreement goal of keeping the global temperature increase below 1.5°C, the risks to agriculture and difficulty of adaptation are growing rapidly, especially in low-income countries.

Climate change has rapidly shifted from a peripheral concern to a central focus of food policy research. Early research was primarily model based, with a strong focus on projecting potential global and national impacts of climate change on agrifood systems and examining adaptation policies and priorities in low- and middle-income countries (LMICs) and GHG mitigation policies in wealthier countries. This research has now expanded to encompass a wider array of methods, with a strong focus on assessing the risks and vulnerabilities faced by diverse households and individuals and their options for responding to climate shocks and stressors.

This chapter reviews the evolution of research on climate change, food security, and food systems and reflects on IFPRI's major contributions to understanding climate change impacts and identifying promising policies and investments for mitigation and adaptation. Looking ahead, we explore promising new research directions, including advancing understanding of climate risks and vulnerabilities to support policy prioritization that will facilitate low-emission development pathways and avoid maladaptation—that is, actions that increase vulnerability to climate change or result in adverse outcomes or diminished welfare for some populations.

Evolution of research

Models to assess global, regional, and national impacts of climate change

Several types of models are used to assess the impacts of climate change on agricultural production, food prices, and food security, including econometric models and simulation models. These all show broad areas of agreement on the key impacts of climate change, although specific quantitative results can vary substantially.

Econometric models estimate the impact of climate change on crop yields based on an analysis of the relationship between historical precipitation and temperature, on the one hand, and crop yields or total production on the other hand. Some models extend this analysis to consider impact on total factor productivity (TFP). Econometric analysis of TFP provides a more comprehensive measure of impact than crop yields, as it captures interactions between changes in outputs and inputs, including not only land but also capital, labor, and technology, throughout the entire sector (see, for example, Lobell, Bänziger et al. 2011). Other research considers the impact of climate on land values or farm net revenues (such as Mendelsohn et al. 1994, 1996).

Simulation models include both process-based crop models and global economic models.[1] *Process-based crop models* model physiological processes of crop growth and incorporate environmental factors such as temperature, water, and light, as well as soil parameters, cultivar choices, and agronomic management practices, to estimate the impact of climate variables (and therefore climate change) and other factors on crop yields (Feng et al. 2023). Prominent crop models include DSSAT (Jones et al. 2003) and the APSIM series (Keating et al. 2003), both developed by universities and research organizations.

Global economic models that address climate change impacts, including partial and computable general equilibrium models (CGEs), combine economic models of the agriculture sector (or multiple sectors, in the case of CGEs) with crop models and climate system models known as general circulation models (GCMs).

GCMs are numerical models representing physical processes in the atmosphere, ocean, cryosphere, and land surface, and are used to simulate changes in temperature, precipitation, and other variables over time. They are the most advanced tools currently available for simulating the response of the global climate system to increasing GHG concentrations. Global economic models also employ different assumptions about Shared Socioeconomic Pathways (SSPs), which represent alternative futures for economic and population growth, with implied Representative Concentration Pathways (RCPs), which represent potential GHG emission levels in the atmosphere and the subsequent increase in solar energy that would be absorbed (radiative forcing).

Global economic models can capture the economic feedback effects generated by climate shocks and estimate their impacts, not only on production but also on food demand, prices, and thus food security. For example, IFPRI's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)[2] is a system of models that links information from climate models, crop simulation models, and water

---

[1] See De Salvo et al. (2013) and Feng et al. (2023) for detailed descriptions of these types of models.

[2] www.ifpri.org/project/ifpri-impact-model/

models with a core global, partial equilibrium, multimarket model focused on the agriculture sector (see Robinson et al. 2024). It links to the GLOBE CGE model to capture whole-economy impacts of climate change. IMPACT relies on GCMs produced by ISIMIP (Inter-Sectoral Impact Model Intercomparison Project) and based on CMIP (Coupled Model Intercomparison Project) data created to inform the reports of the International Panel on Climate Change (IPCC).

Finally, it is important to note that IMPACT and similar modeling systems consider the impacts of temperatures and precipitation that affect crop productivity, but generally do not yet account for climate variability, extreme events (droughts, floods, and heat waves), sea level rise, or shifting pest and disease patterns. As a result, the aggregate modeled impacts summarized in the next section are likely conservative.

Modeling results: Impact of climate change

Across all types of models, most analyses have focused on four major crops: maize, rice, soybeans, and wheat (although IMPACT includes a much larger set of crop and livestock commodities, including many that are important in LMICs). This reflects the importance of these crops, which provide half of total global calorie availability. The models show broad areas of agreement on the key impacts of climate change (De Salvo et al. 2013; Feng et al. 2023).

Table 4.1 summarizes the findings on the impact of climate change on crop yields, commodity prices, and TFP from modeling studies, concentrating on relatively comprehensive meta-analyses and reviews of research studies that summarize the results from many analyses, as well as two seminal individual papers on global historical yields and TFP effects that address impacts in LMICs (Lobell, Bänziger et al. 2011 and Ortiz-Bobea et al. 2021, respectively). The estimated impacts vary across models, due to differences in the models themselves and differences in assumptions on the severity of climate change, projections of economic and agricultural growth, and underlying parameters. For each cited paper in Table 4.1 that covers multiple studies, there are also differences across individual studies, resulting in a range of projections around the mean values shown.

Crop yields and total factor productivity

There is substantial agreement among these studies that climate change is already having an appreciable negative impact on crop yields and TFP, and that it will continue to affect these key outcomes negatively to 2050 and

TABLE 4.1 Impact of climate change on crop yields, prices, and agricultural total factor productivity (TFP), mean results

				Impacts of climate change				
				Without adaptation (%)			With adaptation (%)	
Type of model	Year	Global/Region	Crop	Yield	Price	TFP	Yield	Citation
Crop model	2050	Global	Maize, Rice, Soybeans, Wheat	−11 (mean) −6.2 (median)			−4.6 (mean) −1.6 (median)	Hasegawa et al. (2022) Meta-analysis, 202 studies
Crop model	Change from 1998 to 2084	Global	Maize	−24.1				Jägermeyr et al. (2021) Results from 12 crop models and 5 GCMs
			Soybeans	−2.1				
			Rice	1.7				
			Wheat	17.5				
Crop model	2050	Africa	Wheat	−17				Knox et al. (2012) Review of 52 studies
			Sorghum	−15				
			Millet	−10				
			Maize	−5				
		South Asia	Maize	−16				
			Sorghum	−11				
Econometric model * Percent of studies that find negative impacts of climate change on crop yields.	2050	Low latitudes		−86*				Huang and Sim (2016) Review of 130 studies
		Lower-middle latitudes		−71*				
		Higher-middle latitudes		−15*				
		Upper latitudes		0*				

Table 4.1 continued

				Impacts of climate change				
				Without adaptation (%)			With adaptation (%)	
Type of model	Year	Global/Region	Crop	Yield	Price	TFP	Yield	Citation
Crop models, econometric regression, and field-warming experiments	Future impact per each 1°C increase in mean global temperature	Global	Maize	–7.4				
			Wheat	–6.0				Zhao et al. (2017)
			Rice	–3.2				Multiple studies
			Soybean	–3.1				
Econometric model	1980 to 2008	Global	Maize	–3.8	18.9			Lobell, Bänziger, et al. (2011)[a]
			Wheat	–5.5	6.4			
Econometric model	1961 to 2020	Global				–21.0		Ortiz-Bobea et al. (2021)[b]
		Africa				–26 to –34		
		LAC				–26 to –34		
		North America				–15		
		Europe				–10		
Global economic model	2050	Global	Coarse grains (mainly maize)	–12.5	11.8			Nelson et al (2014)
			Wheat	–9.9	15.9			Mean results from 10 global economic models
			Rice	–9.3	13.9			

Note: (a) Other studies of this type include Miao, Khanna, and Huang (2015); Schlenker and Roberts (2009); Lobell, Schlender, and Costa-Roberts (2011); and Choi and Helmberger (1993). (b) Other studies of this type include Liang et al. (2017) and Xiang et al. (2022).

beyond. The reduced crop yields and TFP due to climate change raise crop prices and reduce food consumption, worsening food security (see below). The negative impacts tend to be greatest for maize, although not in all studies. Maize is highly sensitive to temperature fluctuations, especially during critical growth stages, and has a relatively high water requirement, making it vulnerable to drought conditions. The estimated mean global impacts of climate change on crop yields are generally in the range of −5 percent to −15 percent in 2050 compared to a no-climate change scenario. Although this may seem relatively small, these reductions can cost 5 to 10 years of crop yield growth for major commodities. As shown in Table 4.1, the impacts of climate change vary by region. Nearly all studies that assess regional differences find that losses are larger at lower latitudes, mainly in low-income countries that can least afford or adapt to these impacts.

Nutrient effects

Recent findings show that climate change also affects the nutrient content of crops. According to the IPCC, while increased atmospheric CO_2 relative to current levels is projected to boost crop yields (CO_2 fertilization), it is also expected to significantly decrease the nutritional value of crops, particularly by lowering protein and key micronutrient density (the available nutrient content per unit of grain or other commodity) in staple grains like wheat and rice (Mbow et al. 2019). For example, a meta-study by Myers et al. (2014) found that wheat grown at 546–586 ppm atmospheric CO_2, compared with wheat grown at ambient levels, has 5.9–12.7 percent less protein, 5.2–7.5 percent less iron, and 3.7–6.5 percent less zinc (Mbow et al. 2019). Projections from IMPACT of per capita availability of nutrients in 2050 show that technological advances, market responses, and CO_2 fertilization will all increase crop and livestock production and therefore global availability of dietary protein, iron, and zinc (Beach et al. 2019). However, these potential benefits are significantly offset by the adverse impacts of climate change on both agricultural productivity and nutrient density. A study that compared projections based on two different datasets found that both predict global dietary reductions in protein, iron, and zinc relative to levels associated with current CO_2 emission levels, although the size of the declines differ (−4.1 percent, −2.8 percent, and −2.5 percent, respectively, for one dataset; −2.9 percent, −3.6 percent, and −3.4 percent, respectively, for the other) (Beach et al. 2019). The combined effects of elevated atmospheric CO_2, climate change, and associated nutrient reductions are projected to slow growth in nutrient availability for protein, zinc, and iron (Beach et al. 2019). Low-income nations already facing high

BOX 4.1 Modeling to inform policies for improved food security and climate change adaptation in the Philippines

From 2014 to 2016, IFPRI and the CGIAR Research Programs on Climate Change, Agriculture, and Food Security (CCAFS) and Policies, Institutions, and Markets (PIM) partnered with the Philippines' National Economic and Development Authority (NEDA), the country's top socioeconomic planning body, to assess the impacts of climate change on agriculture and food security and to examine policies and investments for adaptation. NEDA conducts macroeconomic forecasting, policy analysis, and research, playing a crucial role in shaping policies and investments for the agriculture sector and the broader economy to address climate change challenges. The project engaged key NEDA officials early on, ensuring that outputs from analysis and modeled scenarios were relevant to policies, plans, and investments. The modeling identified investments that can improve food security under climate change as well as policies that worsened outcomes, including rice import quotas. These outputs informed the preparation of the Philippine Development Plan 2017–2022 and the 2019 Rice Tariffication Law. In 2016, training sessions were provided, focused on using IMPACT results to inform policies on investments, food security, and malnutrition. NEDA organized three sessions for 63 government staff (22 men, 41 women) to build regional capacity in modeling methodologies.

Source: CGIAR (2018).

rates of nutrient deficiencies are likely to bear the greatest burden. Regardless of the baseline scenario used to project future consumption patterns, rising atmospheric CO_2 levels will hinder progress in reducing global nutrient deficiencies. In fact, the nutrient impacts offset any benefits of CO_2 fertilization on the availability of protein, iron, and zinc (Beach et al. 2019). These findings are consistent with another study, which found that the nutrient densities of protein, iron, and zinc of major crops are likely to decline by 3–17 percent if the world reaches 550 ppm atmospheric CO_2, resulting in an additional 175 million people who are zinc-deficient and 122 million who are protein-deficient worldwide in 2050, if dietary patterns do not change (Smith and Meyers 2018).

Food security

Climate change also reduces food security. The climate-change-related reductions in agricultural yields described above will be tempered, but not fully offset, by expansion in crop areas as prices rise. The resulting net decline in agricultural production decreases food availability and further raises prices, leading to lower per capita incomes and greater hunger. By 2050, world commodity prices are projected to be 16–18 percent higher as a result of climate change, as compared with a no-climate-change scenario, making it more difficult for low-income consumers to afford healthy diets (Sulser et al. 2021). Estimates from IFPRI's IMPACT model show that climate change will slow global progress toward ending hunger, leaving 78 million more people (a 19 percent increase) chronically hungry by 2050 compared to a no-climate-change scenario (Sulser et al. 2021). More than half of this increase is expected to occur in sub-Saharan Africa.

Investments in climate adaptation

The IMPACT model was used to evaluate the costs of adapting to climate change through investments in agriculture (Sulser et al. 2021). Offsetting the projected 78 million-person increase in hunger requires an increase in annual funding for international agricultural research from US$1.62 billion to $2.77 billion between 2015 and 2050. Additional investments of $12.7 billion in water and $10.8 billion in infrastructure per year are also required, totaling $24.7 billion annually to address climate-driven hunger impacts. Other modeling studies suggest even higher costs for adaptation or mitigation to alleviate hunger; the diverse estimates reflect differences in study objectives, sectors covered, climate considerations, and methodologies (Fan et al. 2018; Mason-D'Croz et al. 2019; Rosegrant et al. 2022). For example, Germany's Center for Global Development (ZEF) and the Food and Agriculture Organization of the United Nations (FAO) estimate that between $39 billion and $50 billion per year are needed to end hunger by 2030 (ZEF and FAO 2020). However, another study suggests that an investment of $33 billion annually could not only end hunger but also double small-scale producer incomes by 2030 and keep agricultural GHG emissions aligned with the Paris Agreement targets (Laborde et al. 2020).

The impact of adaptation and mitigation investments could be enhanced, and the prospects for meeting global sustainability and development goals in 2030 increased by improvements in supporting policies and investments. These enabling conditions and specific policy approaches—including improved value chains, finance, extension, gender-responsive policies and investments, social protection, implementation of smart subsidies, and agroecological and landscape approaches—are discussed in other chapters of this report.

Assessing the vulnerability of households and individuals to climate change and options to respond

Another body of policy research examines household and individual vulnerability to climate change and explores mechanisms to increase the resilience of the poor, women, and other vulnerable populations in the face of short- and long-term climate change impacts (see also Chapters 6 and 13).

Shift toward adaptation

The impacts of climate change on agriculture are devastating for the livelihoods and well-being of small-scale producers in LMICs, who are reliant on natural resources and have limited capacity to adapt (Adger et al. 2003; Easterling et al. 2007; Morton 2007). While early efforts to address climate change emphasized the need for mitigation of GHG emissions, the IPCC's 2007 assessment report included a focus on adaptation. The report highlighted the inevitability of changes in climate that were "baked in" due to historic emissions and, thus, the urgent need for adaptation (IPCC 2007; Mertz et al. 2009; Solomon et al. 2009).

Agricultural adaptation is now a key priority in many low-income countries to protect the livelihoods and employment of large shares of the population and to reduce the risk of worsening food insecurity and hunger (Bizikova et al. 2015; UNEP 2024). In the 2010s, low-income countries began to engage in adaptation planning in a more coordinated way through the National Adaptation Plan process, recognizing that they were likely to experience the worst impacts of climate change. The process, which was established in 2010 and reinforced by the Paris Agreement in 2015 (Huq et al. 2004; Reid and Huq 2008), helped 171 countries (87 percent of parties to the UNFCCC) put adaptation plans in place by 2024, although the effectiveness of these plans is mixed and implementation often lags (UNEP 2024). Broadly speaking, key adaptation strategies emphasized in many of these plans include adjustment of planting dates, diversification of production, selection of resilient and/or stress tolerant crop varieties and animal species, improved irrigation and water management, adoption of precision agriculture and other resource conserving strategies, and expansion of climate information services.

Early policy research introduced several important concepts, including vulnerability, exposure, sensitivity, and adaptive capacity, that have guided the study and measurement of adaptation (Adger 2006; Bryan et al. 2000; Smit et al. 1999, 2001). This work identified human adaptation as a process of adjustment to long-term changes in climate (often in anticipation of these changes), as distinct from coping with short-term climate variability, in order to minimize risks and take advantage of opportunities (Smithers and Smit 1997), while recognizing that effectively coping with climate shocks in the short-term may facilitate adaptation to long-term climate changes (Burton 1997). It also described the complexity of adaptation processes, which require actions at multiple scales and by multiple actors, as well as the varied forms of adaptation responses, which can be spontaneous or planned, anticipatory or reactive, and incremental or transformative (Kates et al. 2012; Smit et al. 2001).

Identifying hot spots

As climate change has become a reality in many parts of the world, the critical role of smallholder farmers in LMICs in adapting to climate change has been widely recognized, given that smallholders (those with less than 2 ha of land) produce 30–34 percent of the global food supply (Ricciardi et al. 2018). Research focused on identifying and reducing risks, building resilience capacities, and coping and adaptation strategies for smallholders began to emerge in the early 2000s. Papers explored vulnerability to climate change and identified "hotspots" based on the level of exposure to climate change, sensitivity of agricultural production systems, communities, households, and individuals to its negative impacts, and adaptive capacity of farm households and regions (Deressa and Hassan 2009; Gbetibouo and Hassan 2005; Gbetibouo, Ringler, and Hassan 2010; Kurukulasuriya et al. 2006). More recent analyses of hotspots integrate gender, recognizing that entrenched inequalities limit women's adaptive capacity (Koo et al. 2022; Lecoutere et al. 2023).

Farm-level adaptation

Research also documented and classified autonomous farm-level adaptation to long-term climate change (that is, spontaneous actions taken by farmers) (Bryant et al. 2000; Smit 1996). This work looked at the types of strategies and innovations adopted by farmers, including new technologies (such as irrigation and new crop varieties) and management strategies (such as soil and water conservation measures, changing planting dates, or adjusting inputs to deal with climate-related challenges), and diversification on and off farm (Below et al. 2010; Jagnani et al. 2021).

Autonomous adaptation measures initiated at the farm level are important but largely incremental (as opposed to systematic and transformational). They are thus insufficient to address the challenges posed by climate change at scale without support from policies and investments to accelerate and deepen adaptation and ensure participation of many stakeholders (Adger et al. 2005; Burton and Lim 2005; Smit and Skinner 2002; Thornton et al. 2018). Research has explored the determinants of farm-level adaptation in order to identify both constraints and entry points for interventions to facilitate greater uptake (Bryan et al. 2009, 2013b; Deressa et al. 2009a; Hassan and Nhemachena 2008; Silvestri et al. 2012). The key determinants identified include access to credit and climate information, land tenure security, and wealth status. Knowledge of these can inform policies and programs for managing climate risks and facilitating agricultural sector adaptation. Examples include the development of climate information services (Ziervogel et al. 2010) and insurance and bundled financial products (see Chapter 10) (Kramer 2023; Ndegwa et al. 2020), as well as social protection programs (see Chapter 11) (Tenzing 2019). IFPRI made an important contribution to this household-level research with a focus on how smallholder farmers' perceptions of long-term climate change affect their adoption of adaptation strategies (Gbetibouo et al. 2010; Deressa et al. 2011; Maddison 2007).

Emergence of climate-smart agriculture

Research has emphasized the potential synergies between adaptation and mitigation goals and actions and encouraged more coordinated efforts to achieve both goals, as well as greater productivity (Ayers and Huq 2009; Rosenzweig and Tubiello 2007). While the early promise of carbon markets as an opportunity for low-income countries to be paid for contributing to mitigation goals in the agriculture sector has not produced the expected boon (Lipper and Zilberman 2018), this "win-win" option did increase interest in finding climate solutions that offer benefits for adaptation, mitigation, and smallholder farmer livelihoods (Bryan et al. 2010). In addition, the Paris Agreement requires countries to identify voluntary emissions reductions in the context of long-term low-emission development strategies, thus balancing mitigation and development goals (Waisman et al. 2019). This search for synergies led to the development of the climate-smart agriculture (CSA) framework, which facilitates evaluation of agricultural practices and climate change strategies across three goals—productivity (and profits), adaptation, and mitigation (FAO 2010; Lipper and Zilberman 2018). For example, in Kenya, a study identified several farm-level practices that support all three goals; these practices include integrated soil fertility management, improved livestock feeding, and irrigation and soil and water conservation in arid areas (Bryan et al. 2013a). Modeling-based approaches to assess the effectiveness of CSA practices have shown that widespread adoption of these practices at the global level can contribute to all three goals, while increasing food accessibility and reducing hunger (De Pinto, Cenacchi et al. 2020). However, CSA is not a one-size-fits-all solution. Priorities for CSA vary based on the policy context, agroecological conditions, and farming systems among other factors, and different stakeholders often have different preferences regarding CSA outcomes (Khatri-Chhetri et al. 2017; Mwongera et al. 2017). The CSA framework has also been criticized as a set of purely technical solutions that ignore power dynamics that lead to inequitable distribution of benefits (Rosén et al. 2017; Taylor 2017).

Climate justice

Climate justice discussions arose from recognition of the divide between high-income countries, which bear most of the responsibility for climate change, and those mostly low-income nations that are experiencing the worst impacts. Concerns initially focused on the imperative for wealthier countries to reduce GHG emissions and support adaptation investments (Hossain et al. 2021), leading to the establishment of a Loss and Damage Fund at COP27 in 2022 (although the fund is still grossly underfunded) (see also Chapter 18).

More recently, greater attention is being paid to the unequal impacts of climate change—and of climate interventions—within countries and communities due to gender and other social differences (Bryan et al. 2024; FAO 2024). Entrenched inequalities in agrifood systems influence the distribution of climate change impacts in ways that increase the vulnerability of already marginalized groups, such as smallholder producers and other value chain actors, the poor, women, and Indigenous Peoples. Many of those affected by structural inequalities, who lack access to resources and services, are also least able to adapt to climate change impacts (Bryan et al. 2024). Even within the same household, individuals have different needs, preferences, and capacities to respond effectively to climate shocks and stressors (Kristjanson et al. 2017). These differences are driven by gender as well as other social identities, such as ethnicity, caste, and class (Djoudi et al. 2016) (see Box 4.2). Ensuring that resources and services are targeted to the most vulnerable groups (that is, through social protection programs and climate information and financial services); facilitating group-based approaches; addressing structural inequalities, such as women's unequal access to land or restrictive social norms; and ensuring that all stakeholders participate in policy processes are some approaches to addressing inequalities through climate action (Bryan et al. 2024). Implementing these measures also requires policymakers, practitioners, and other stakeholders to have the capacity to design and implement equitable policies and programs.

BOX 4.2 Gender in climate change research

Women and men experience and respond to climate change impacts differently. Over the past decade, research by IFPRI and others has advanced our understanding of the linkages between gender and climate change, particularly gender and climate-smart agriculture (CSA) (Gardezi et al. 2021). This work has explored gendered differences in vulnerability (exposure, sensitivity, adaptive capacity) and adoption of climate change responses (and the ability to negotiate for preferred responses), as well as outcomes of climate change and response choices for well-being (Bryan et al. 2017; Kristjanson et al. 2017). Gender-differentiated impacts of climate change depend on many factors, including how climate change affects gendered asset dynamics, labor allocation, and control over income. Men and women tend to own different assets, in line with sociocultural norms, and draw on these assets in different ways in response to climate and other types of shocks (Quisumbing et al. 2018; Rakib and Matz 2016). Whose assets are affected can depend on a variety of factors, including the type of shock and the context. Extreme climate events also affect labor allocation in agrifood systems. These events cause both men's and women's labor contributions to decline, particularly under heat stress, but the declines are larger among men. This leads to a relative increase in women's agricultural labor burden under increasingly hazardous working conditions that have implications for their well-being (Lee et al. 2021; Nico and Azzarri 2024). In addition, *The Unjust Climate*, an FAO report to which IFPRI contributed, shows that women-headed households experience greater income losses as a result of extreme climate events, and women farmers suffer greater crop losses despite adopting climate-smart strategies at rates similar to men (FAO 2024). The report suggests that gender-responsive agricultural extension services are needed to enhance the effectiveness of women's adaptation efforts (see Chapter 8).

Our understanding of women's and men's differing experiences with climate shocks and stressors, access to climate information, and awareness and adoption of CSA practices is enhanced by collection and analysis of intrahousehold data (Bryan et al. 2021; Twyman et al. 2014). Findings from Bangladesh, Kenya, Senegal, and Uganda show that while both men and women are adjusting their farming practices in response to climate change, women tend to be less aware of CSA practices and less likely to adopt them. However, when women have access to climate information and are informed about CSA practices, they are just as likely or, in some cases, more likely to adopt these practices, particularly when they pertain to their livelihood roles. Research from India, Kenya, and Uganda also shows that targeting women with information, including through innovative approaches such as video-based extension, can be an effective way to increase their awareness and adoption of CSA practices (see Chapter 8) (Barooah et al. 2023; Kato et al. 2023; Ndegwa et al. 2023). However, other constraints, such as lack of access to labor or capital, can limit adoption of some practices despite awareness and interest.

Women's empowerment is also an important vehicle for increasing climate resilience and managing climate risks (Bryan et al. 2024; Huyer et al. 2021). For example, a study from Bangladesh shows that women's input into agricultural decisions and participation in groups increases crop diversification away from rice and toward more fruit and vegetable production, with positive implications for both climate resilience and dietary diversity (De Pinto, Seymour et al. 2020). Women also play key roles in maintaining food security and nutrition under climate change, including through their roles along nutrition-sensitive value chains (such as dairy products) (Kane et al. 2024) and in minimizing food safety risks, which are increasing with climate change (Brown 2018).

Looking forward: Improving understanding of climate risks and vulnerabilities

Better identification of hotspots

Some critical consequences of climate change's impacts on agriculture are not captured by the global averages from models, because they will be most damaging in specific locations ("hotspots") or during extreme events, (Jägermeyr et al. 2021; Rosegrant et al. 2024). In addition to reducing productivity, climate change can also amplify agriculture's environmental impacts, including GHG emissions, water use and scarcity, soil erosion, and biodiversity loss, increase nitrogen and phosphorus pollution as a result of increased fertilizer use, and cause more frequent and severe pest outbreaks, leading to higher pesticide use and pollution (Yang et al. 2024).

Crop modeling helps identify locations that are particularly vulnerable to higher yield losses for any given crop under climate change (Jalloh et al. 2013; Hachigonta et al. 2013; Nelson et al. 2010; Thomas 2024; Thomas et al. 2018; Waithaka et al. 2013). Combining these data with information on the local importance of the crop can systematically identify hotspots, a critical step to assist planners in pinpointing investments geographically for the development of climate-resilient cultivars and to support farmers in growing crops better suited to emerging climate patterns. Identifying where these areas of high exposure and sensitivity overlap with populations that are more susceptible to harm—based on their wealth status, gender inequality, and degree of malnutrition, among other factors—can improve targeting of resources to the most vulnerable.

Advancing models to better understand climate change impacts

Uncertainty about the future climate—due to differences among climate models and emissions scenarios—and increased variability and intensity of precipitation due to higher temperatures make it reasonable to expect increasingly frequent extreme climate events. However, current models are inconsistent in projecting increased variability, and modeling the impact of extreme events on food security and agricultural productivity is challenging, given the current limitations of biophysical models. As computer processing speeds increase, doors are opening to allow better modeling of the changes in frequency of extreme events (Thomas, Robertson et al. 2022; Thomas, Schlosser et al. 2022), which will make it possible to compare the effectiveness of various interventions, not simply in raising mean yields but also in mitigating the impact of such climate shocks. Nonetheless, much work remains to be done in this area. Some recent efforts have quantified feedback mechanisms that have not been previously incorporated into most bioeconomic models, including measures of livestock productivity losses (Hertel and de Lima 2020; Thornton et al. 2022). However, aquaculture still needs to be incorporated into bioeconomic models of climate change impact.

An important area for further research is the impact of climate change on labor productivity losses due to heat stress. While substantial work is being done on heat stress in non-agricultural settings, little is known about the impact in the agriculture sector, where heat stress is likely worse because most work is done outdoors (Hertel and de Lima 2020). One recent study addresses this gap, revealing that some regions worldwide are already experiencing significant declines in agricultural workers' ability to perform physical labor due to heat exposure during critical crop-growing periods. The resulting declines in worker productivity will exacerbate challenges by increasing the demand for labor, reducing output, and driving up food prices, which will place additional strain on vulnerable populations (Nelson et al. 2024). Further research is needed to understand these impacts, as well as study of potential adaptation strategies, which could include shifting to crops that thrive in cooler seasons, increasing mechanization, and providing more access to shade, drinking water, and body-cooling measures (Nelson et al. 2024).

Substantial work has been done on the direct climate impacts on economic growth. One study shows that economic productivity is nonlinear with temperatures across all countries, peaking at an annual average of 13°C and declining sharply at higher temperatures (Burke et al. 2015). This relationship is consistent globally and evident in both agricultural and non-agricultural activities across developed and developing nations. Other work finds that higher temperatures significantly reduce economic growth in poor countries, lowering growth rates in addition to output levels, and broadly affect agriculture, industry, and political stability (Dell et al. 2012).[3] These findings highlight climate's role in economic development and, like the results on TFP and agricultural yields, point to substantial negative impacts on poorer nations. This work has not generally been incorporated into bioeconomic modeling, despite the important implications for household food security. Additional work on the relationship between economic growth under climate change in agricultural growth and general economic growth would be valuable. Likewise, in addition to the work described above on the decline of nutrient availability in foods due to the CO_2 fertilization effect, more research is needed on the implications for nutrition outcomes and the identification of interventions that could alleviate negative impacts of climate change on nutrition.

Challenges for adaptation

While the adverse impacts of climate change on agricultural production are many and severe, there are also many opportunities for adaptation that should be taken up by researchers and policymakers. Some of these adaptations occur across geographic scales—shifting maize, for example, to cooler locations, changing planting dates, or identifying cultivars more suited to the future climate. Others can be very local, such as barns with cooling for livestock or mechanization to replace agricultural labor. However, there is little evidence that adaptation measures, even if they are locally effective, are sufficient in the aggregate. Using comprehensive panel data across diverse geographies and a wide range of outcomes—including mortality, agricultural productivity, crime, conflict, economic output, and damage from flooding and tropical cyclones—a recent study finds limited evidence of effective adaptation (Burke et al. 2024). Among 21 outcomes studied, 6 show statistically significant

---

[3] See also Barrage (2020); Burke, Davis, and Diffenbaugh (2018); Casey, Fried, and Goode (2022, 2023); Diffenbaugh and Burke (2019); Donadelli et al. (2017); Golosov et al. (2014); Hassler et al. (2019); Letta and Tol (2019); and Nordhaus and Boyer (2003) for the whole economy.

declines in sensitivity to climate change, 5 show increased sensitivity, and the others show no significant change. This suggests that the adaptation measures studied in the paper have not significantly reduced overall climate impacts. To reduce future damage, it is crucial to identify scalable, effective adaptation strategies (Burke et al. 2024).

Looking ahead, the impacts of climate change will be compounded by other major changes. In many countries, population growth is increasing demand for food and often for agricultural land to produce that food. This is likely to create pressure to expand agriculture into forests or other natural areas, leading to further increases in GHG emissions and possibly to losses in biodiversity, ecosystem services, and tourism. As populations grow and change, agricultural labor may move to other sectors, either seasonally or permanently. In response to this pressure, farms may consolidate, further freeing labor for agricultural processing or shifting it to manufacturing or services. Within households, changes in income sources can lead to reallocation of labor, with implications for the time requirements of both women and youth. Combining climate modeling and household survey analysis allows us to address these multidimensional analytical challenges. Country-level modeling enables researchers to project shifts among sectors, and impacts on food security, poverty, and gross domestic product (GDP). Providing this foresight to decision-makers can inform policymaking for adaptation and mitigation as well as food security.

Increasing the resilience of the poor, women, and other vulnerable populations

The vulnerability of marginalized populations can be expected to intensify as the impacts of climate change become more severe, unless policies, investments, and actions adequately address the disproportionate impacts of climate change on these groups. To ensure that climate action yields more equitable outcomes, while accelerating progress toward adaptation and low-emission development pathways, more research is needed on effective mechanisms to address climate injustice. Finding ways to make climate governance at multiple scales more representative and inclusive of the perspectives and knowledge of vulnerable communities will be essential. For example, women's leadership in climate governance and the inclusion of grassroots women's organizations in climate decision-making processes can ensure that policies, investments, and interventions reflect women's diverse needs and priorities (Morgan et al. 2024). Frameworks such as the Women's Empowerment in Agrifood Systems Governance (WEAGov) can be used to measure the extent of women's inclusion and leadership in climate governance (see Chapter 6) (Ragasa et al. 2022). Collective, group-based approaches are powerful vehicles for strengthening women's empowerment and building resilience to climate change (Cabot Venton et al. 2021), including by increasing access to public entitlements (Kumar et al. 2021) and ensuring that agricultural information reaches women (Alvi et al. 2021) (see Chapters 8 and 14). But more research is needed on the scope for these platforms to accelerate climate action while reducing inequalities and on the factors that determine the effectiveness of more inclusive climate governance.

To avoid maladaptation, climate action to increase resilience must go hand-in-hand with addressing inequalities and facilitating empowerment of vulnerable groups. Action must include targeted interventions that build the resilience capacities of the most vulnerable people to respond to current and future climate-related challenges, including displacement and migration (see Chapter 13). Promising interventions include those that reduce climate risks, such as crop insurance and financial products tailored to smallholder producers (see Chapter 10), including women, and social protection programs that also promote adaptation and mitigation objectives (see Chapter 11) (Hidrobo et al. 2024; Timu and Kramer 2021). However, more research is needed on the effectiveness of these interventions in increasing resilience and the extent to which they can reduce inequalities and facilitate empowerment. More research is also needed on mechanisms to ensure that climate finance for adaptation efforts, such as loss and damage funds, and mitigation actions that reach and benefit the most vulnerable agrifood system actors, are not diverted by powerful interests (see Chapters 15 and 18). Policy research must also move beyond a focus on agricultural production to include building resilience along entire agrifood value chains, especially for micro, small, and medium enterprises that play important roles in supply chains and can contribute to low-emission development (see Chapter 7) (Liverpool-Tasie and Parkhi 2020).

Last, while the evidence on inequalities in climate change impacts, adaptive capacities, and policy processes has grown considerably over the past decade, much of this evidence comes from local case studies. The FAO's *Unjust Climate* report has begun to quantify the differential impacts of climate change across LMICs—but key gaps remain (FAO 2024). For example, many analyses have been done at the level of the household head, ignoring intrahousehold differences in climate change impacts. More individual-level data are needed for monitoring adaptation progress among the most vulnerable groups and for more effective targeting of interventions.

Conclusions

Climate change will slow progress on food and nutrition security, with impacts varying by location, time, and scale. To counter the impact of climate change, investments in increasing productivity must be a high priority. As an example, the African Union recently approved the 10-year Strategy and Action Plan for the Comprehensive Africa Agriculture Development Programme (CAADP), reaffirming the commitments of member states to use 10 percent of public spending to finance agriculture with the goal of achieving 6 percent annual growth of agricultural GDP (see Chapter 19). Follow-through and focusing on productivity investments not only by the African Union but also by donors, international agencies, and governments around the world will be essential.

To increase the effectiveness of larger investments in productivity and to achieve complementary objectives, a number of additional actions should be taken. Greater effort is needed to integrate climate considerations into agricultural and food policies, national planning, and budgets, while also designing climate interventions that support gender equality and nutrition. Many adaptation and mitigation options address both climate and food security constraints, such as risk, uncertainty, imperfect markets, and lack of credit or insurance. For instance, redirecting subsidies for fertilizer, water, and energy into productivity-enhancing investments could drive agricultural growth and reduce GHG emissions (see Chapters 3 and 18) (Rosegrant et al. 2022). However, to be effective, climate solutions must be tailored to local contexts through inclusive planning processes that integrate local knowledge, values, and diverse perspectives. This has implications for the ways in which research is conducted (that is, in partnership with local research institutes and taking into consideration the priorities of diverse stakeholders) and policy decisions are made. Nature-based climate solutions, such as agroforestry, conservation agriculture, and natural water storage, can both contribute to reducing GHG emissions and also increase availability of safe water resources, make air safer to breathe, and increase food security.

Greater attention is being given to the unequal impacts of climate change—and climate interventions—due to poverty, gender, and other social differences. It is also recognized that climate interventions risk exacerbating these inequalities if they do not address resource gaps and prioritize solutions that meet the needs of the most vulnerable. More effective interventions would integrate technical solutions with enabling and empowering measures and approaches, such as expanding information and financial services, promoting inclusive governance arrangements, and addressing constraints to women's participation.

Future work must go beyond measuring and predicting biophysical and socioeconomic impacts to integrate adaptation and mitigation into development agendas and prioritize actions that advance development goals including food security, better nutrition, and gender equality. To prevent maladaptation, more research is needed to identify and assess interventions that enhance nutritional outcomes and build resilience in vulnerable groups, especially women and the poor. This will require better data collection, monitoring, and evaluation efforts to track progress toward these outcomes as climate actions are scaled up.

References

Adger, W.N. 2006. "Vulnerability." *Global Environmental Change* 16 (3): 268–281.

Adger, W.N., N.W. Arnell, and E.L. Tompkins. 2005. "Successful Adaptation to Climate Change Across Scales." *Global Environmental Change* 15 (2): 77–86.

Adger, W.N., S. Huq, K. Brown, D. Conway, and M. Hulme. 2003. "Adaptation to Climate Change in the Developing World." *Progress in Development Studies* 3 (3): 179–195.

Alvi, M., P. Barooah, S. Gupta, and S. Saini. 2021. "Women's Access to Agriculture Extension Amidst COVID-19: Insights from Gujarat, India and Dang, Nepal." *Agricultural Systems* 188: 103035.

Ayers, J.M., and S. Huq. 2009. "The Value of Linking Mitigation and Adaptation: A Case Study of Bangladesh." *Environmental Management* 43: 753–764.

Barooah, P., M. Alvi, C. Ringler, and V. Pathak. 2023. "Gender, Agriculture Policies, and Climate-Smart Agriculture in India." *Agricultural Systems* 212: 103751.

Barrage, L. 2020. "Optimal Dynamic Carbon Taxes in a Climate–Economy Model with Distortionary Fiscal Policy." *Review of Economic Studies* 87 (1): 1–39.

Beach, R.H., T.B. Sulser, A. Crimmins, et al. 2019. "Combining the Effects of Increased Atmospheric Carbon Dioxide on Protein, Iron, and Zinc Availability and Projected Climate Change on Global Diets: A Modelling Study." *Lancet Planetary Health* 3: e307–e317.

Below, T., A. Artner, R. Siebert, and S. Sieber. 2010. "Micro-Level Practices to Adapt to Climate Change for African Small-Scale Farmers: A Review of Selected Literature." IFPRI Discussion Paper 953. IFPRI, Washington, DC.

Bizikova, L., J.E. Parry, J. Karami, et al. 2015. "Review of Key Initiatives and Approaches to Adaptation Planning at the National Level in Semi-Arid Areas." *Regional Environmental Change* 15: 837–850.

Brown, L.R. 2018. *Aflatoxins in Food and Feed: Impacts, Risks, and Management Strategies*. GCAN Policy Note 9. Washington, DC: IFPRI.

Bryan, E., W. Akpalu, C. Ringler, and M. Yesuf. 2010. "Global Carbon Markets: Opportunities for Sub-Saharan Africa in Agriculture and Forestry." *Climate and Development* 2 (4): 309–331.

Bryan, E., M. Alvi, S. Huyer, and C. Ringler. 2024. "Addressing Gender Inequalities and Strengthening Women's Agency to Create More Climate Resilient and Sustainable Food Systems." *Global Food Security* 40: 100731.

Bryan, E., T. Deressa, G. Gbetibouo, and C. Ringler. 2009. "Adaptation to Climate Change in Ethiopia and South Africa: Options and Constraints." *Environmental Science and Policy* 12 (4): 413–426.

Bryan, E., E. Kato, and Q. Bernier. 2021. "Gender Differences in Awareness and Adoption of Climate-Smart Agriculture Practices in Bangladesh." In *Gender, Climate Change and Livelihoods: Vulnerabilities and Adaptations*, eds. J. Eastin and K. Dupuy, 123–142. Wallingford, UK: CABI.

Bryan, E., C. Ringler, B. Okoba, J. Koo, M. Herrero, and S. Silvestri. 2013a. "Can Agriculture Support Climate Change Adaptation, Greenhouse Gas Mitigation and Rural Livelihoods? Insights from Kenya." *Climatic Change* 118 (2): 151–165.

Bryan, E., C. Ringler, B. Okoba, C. Roncoli, S. Silvestri, and M. Herrero. 2013b. "Adapting Agriculture to Climate Change in Kenya: Household Strategies and Determinants." *Journal of Environmental Management* 114: 26–35.

Bryan, E., S. Theis, J. Choufani, A. De Pinto, R. Meinzen-Dick, and C. Ringler. 2017. "Gender-Sensitive, Climate-Smart Agriculture for Improved Nutrition in Africa South of the Sahara." In *2017 Annual Trends and Outlook Report (ATOR): A Thriving Agricultural Sector in a Changing Climate: Meeting Malabo Declaration Goals Through Climate-Smart Agriculture*, eds. A. De Pinto and J.M. Ulimwengu, 114–135. Washington, DC: IFPRI.

Bryant, C.R., B. Smit, M. Brklacich, T.R. Johnston, J. Smithers, Q. Chiotti, and B. Singh. 2000. "Adaptation in Canadian Agriculture to Climatic Variability and Change." In *Societal Adaptation to Climate Variability and Change*, eds. S.M. Kane and G.W. Yohe, 181–201. Dordrecht, Netherlands: Springer.

Burke, M., W.M. Davis, and N.S. Diffenbaugh. 2018. "Large Potential Reduction in Economic Damages Under UN Mitigation Targets." *Nature* 557: 549–553.

Burke, M., S.M. Hsiang, and E. Miguel. 2015. "Global Non-Linear Effect of Temperature on Economic Production." *Nature* 527: 235–239.

Burke, M., M. Zahid, M.C.M. Martins, et al. 2024. "Are We Adapting to Climate Change?" NBER Working Paper 32985. National Bureau of Economic Research, Cambridge, MA.

Burton, I. 1997. "Vulnerability and Adaptive Response in the Context of Climate and Climate Change." *Climatic Change* 36: 185–196.

Burton, I., and B. Lim. 2005. "Achieving Adequate Adaptation in Agriculture." *Climatic Change* 70: 191–200.

Cabot Venton, C., S.A. Prillaman, and J. Kim. 2021. "Building Resilience Through Self Help Groups: Evidence Review." In *The Resilience Evaluation, Analysis, and Learning Award Conference Proceedings*. Washington, DC: Food Security and Nutrition Network.

Casey, G., S. Fried, and E. Goode. 2022. "Projecting the Impacts of Temperature Change: The Role of Macroeconomic Dynamics." Paper presented at the International Monetary Fund Economic Review Conference, Rabat, Morocco, June 23.

Casey, G., S. Fried, and E. Goode. 2023. "Projecting the Impact of Rising Temperatures: The Role of Macroeconomic Dynamics." *IMF Economic Review* 71: 688–718.

CGIAR. CGIAR Research Program on Climate Change, Agriculture and Food Security. 2018. "Influencing Policies for Improved Food Security and Adaptation to Climate Change in the Philippines- CCAFS and PIM Inputs." In *Climate Change, Agriculture and Food Security Annual Report 2018*. Outcome Impact Case Report. Montpellier, France.

Choi, J.-S., and P. G. Helmberger. 1993. "How Sensitive Are Crop Yields to Price Changes and Farm Programs?" *Journal of Agricultural and Applied Economics* 25: 237–244.

Cho, S., and B. McCarl. 2017. "Climate Change Influences on Crop Mix Shifts in the United States." *Scientific Reports* 7: 40845.

Dell, M., B.F. Jones, and B.A. Olken. 2012. "Temperature Shocks and Economic Growth: Evidence from the Last Half Century." *American Economic Journal: Macroeconomics* 4 (3): 66–95.

De Pinto, A., N. Cenacchi, H.Y. Kwon, J. Koo, and S. Dunston. 2020. "Climate Smart Agriculture and Global Food-Crop Production. *PLoS ONE* 15 (4): e0231764.

De Pinto, A., G. Seymour, E. Bryan, and P. Bhandari. 2020. "Women's Empowerment and Farmland Allocations in Bangladesh: Evidence of a Possible Pathway to Crop Diversification." *Climatic Change* 163 (2): 1025–1043.

Deressa, T.T., and R.M. Hassan. 2009. "Economic Impact of Climate Change on Crop Production in Ethiopia: Evidence from Cross-Section Measures." *Journal of African Economies* 18 (4): 529–554.

Deressa, T.T., R.M. Hassan, and C. Ringler. 2011. "Perception of and Adaptation to Climate Change by Farmers in the Nile Basin of Ethiopia." *Journal of Agricultural Science* 149 (1): 23–31.

Deressa, T.T., R.M. Hassan, C. Ringler, T. Alemu, and M. Yesuf. 2009. "Determinants of Farmers' Choice of Adaptation Methods to Climate Change in the Nile Basin of Ethiopia." *Global Environmental Change* 19: 248–255.

De Salvo, M., D. Begalli, and G. Signorello. 2013. "Measuring the Effect of Climate Change on Agriculture: A Literature Review of Analytical Models." *Journal of Development and Agricultural Economics* 5 (12): 499–509.

Diffenbaugh, N.S., and M. Burke. 2019. "Global Warming Has Increased Global Economic Inequality." *PNAS* 116 (20): 9808–9813.

Djoudi, H., B. Locatelli, C. Vaast, et al. 2016. "Beyond Dichotomies: Gender and Intersecting Inequalities in Climate Change Studies" *Ambio 45* (Suppl 3): 248–262.

Donadelli, M., M. Jüppner, M. Riedel, and C. Schlag. 2017. "Temperature Shocks and Welfare Costs." *Journal of Economic Dynamics and Control* 82: 331–355.

Easterling, W.E., P.K. Aggarwal, P. Batima, et al. 2007. "Food, Fibre and Forest Products." In *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Working Group II Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, eds. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, 273–313. Cambridge, UK: Cambridge University Press.

Fan, S., D. Headey, D. Laborde, D. Mason-D'Croz, C. Rue, T.B. Sulser, and K. Wiebe. 2018. *Quantifying the Cost and Benefits of Ending Hunger and Undernutrition: Examining the Differences Among Alternative Approaches*. IFPRI Issue Brief. Washington, DC: IFPRI.

FAO (Food and Agriculture Organization of the United Nations). 2010. *"Climate-Smart" Agriculture: Policies, Practices and Financing for Food Security, Adaptation and Mitigation*. Rome.

FAO. 2024. *The Unjust Climate: Measuring the Impacts of Climate Change on Rural Poor, Women and Youth*. Rome.

Feng, X., H. Tian, J. Cong, and C. Zhao. 2023. "A Method Review of the Climate Change Impact on Crop Yield." *Frontiers in Forests and Global Change* 6: 1198186.

Gardezi, M., S. Michael, R. Stock, S. Vij, A. Ogunyiola, and A. Ishtiaque. 2021. Prioritizing Climate-Smart Agriculture: An Organizational and Temporal Review." *WIREs Climate Change* 13 (2): e755.

Gbetibouo, G.A., and R.M. Hassan. 2005. "Measuring the Economic Impact of Climate Change on Major South African Field Crops: A Ricardian approach. *Global and Planetary Change* 47: 143–152.

Gbetibouo, G.A., R.M. Hassan, and C. Ringler. 2010. "Modelling Farmers' Adaptation Strategies for Climate Change and Variability: The Case of the Limpopo Basin, South Africa." *Agrekon* 49 (2): 217–234.

Gbetibouo, G.A., C. Ringler, and R.M. Hassan. 2010. "Vulnerability of the South African Farming Sector to Climate Change and Variability: An Indicator Approach." *Natural Resources Forum* 34 (3): 175–187.

Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski. 2014. "Optimal Taxes on Fossil Fuel in General Equilibrium." *Econometrica* 82 (1): 41–88.

Hachigonta, S., G. Nelson, T.S. Thomas, and L.M. Sibanda, eds. 2013. *Southern African Agriculture and Climate Change: A Comprehensive Analysis*. IFPRI Research Monograph. Washington, DC: IFPRI.

Hasegawa, T., H. Wakatsuki, H. Ju, et al. 2022. "Summary Results from Different Types of Models: A Global Dataset for the Projected Impacts of Climate Change on Four Major Crops." *Scientific Data* 9: 58.

Hassan, R., and C. Nhemachena. 2008. "Determinants of African Farmers' Strategies for Adapting to Climate Change: Multinomial Choice Analysis." *African Journal of Agricultural and Resource Economics* 2 (1): 83–104.

Hassler, J., P. Krusell, C. Olovsson, and M. Reiter. 2019. "Integrated Assessment in a Multi-Region World with Multiple Energy Sources and Endogenous Technical Change Preliminary." 2019 Meeting Papers 809. Society for Economic Dynamics, Minneapolis.

Hertel, T.W., and C.Z. de Lima. 2020. "Viewpoint: Climate Impacts on Agriculture: Searching for Keys under the Streetlight."*Food Policy* 95: 101954.

Hidrobo, M., V. Mueller, E. Bryan, Z. Nesbitt-Ahmed, P. Laderach, and S. Roy. 2024. *Leveraging Social Assistance to Strengthen Women's and Girls' Climate Resilience: What Is the Potential, and What Are Promising Program Designs?* CGIAR Initiative on Fragility, Conflict, and Migration Policy Brief. Washington, DC: IFPRI.

Hossain, F., D. Falzon, M.F. Rahman, and S. Huq. 2021. "Toward Climate Justice: Making the Polluters Pay for Loss and Damage." In *Principles of Justice and Real-World Climate Politics*, eds. S. Kenehan and C. Katz, 149–170. London: Rowman & Littlefield.

Huang, K., and N. Sim. 2016. "Why Do Econometric Studies Disagree on the Effect of Warming on Agricultural Output? A Meta-Analysis." School of Economics and Public Policy Working Papers 2016-04. University of Adelaide, School of Economics and Public Policy, Adelaide, Australia.

Huq, S., H. Reid, M. Konate, A. Rahman, Y. Sokona, and F. Crick. 2004. "Mainstreaming Adaptation to Climate Change in Least Developed Countries (LDCs)." *Climate Policy* 4 (1): 25–43.

Huyer, S., T. Gumucio, K. Tavenner, et al. 2021. "From Vulnerability to Agency in Climate Adaptation and Mitigation." In *Advancing Gender Equality Through Agriculture and Environmental Research: Past, Present, and Future*, 261–294. Washington, DC: IFPRI.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the IPCC*. Cambridge, UK: Cambridge University Press.

Jägermeyr, J., C. Müller, A.C. Ruane, et al. 2021. "Climate Impacts on Global Agriculture Emerge Earlier in New Generation of Climate and Crop Models." *Nature Food* 2 (11): 873–885.

Jagnani, M., C.B. Barrett, Y. Liu, and L. You. 2021. "Within-Season Producer Response to Warmer Temperatures: Defensive Investments by Kenyan Farmers." *The Economic Journal* 131 (633): 392–419.

Jalloh, A., G.C. Nelson, T.S. Thomas, R. Zougmoré, and H. Roy-Macauley, eds. 2013. *West African Agriculture and Climate Change: A Comprehensive Analysis*. IFPRI Research Monograph. Washington, DC: IFPRI.

Jones, J.W., G. Hoogenboom, C.H. Porter, et al. 2003. "The DSSAT Cropping System Model." *European Journal of Agronomy* 18: 235–265.

Kane, P.A., M.B. Barry, S. Eissler, et al. 2024. "Strengthening Women's Empowerment, Climate Resilience, and Nutrition Along the Goat Value Chain in Senegal: A Qualitative Study." IFPRI Discussion Paper 2274. IFPRI, Washington, DC.

Kates, R.W., W.R. Travis, and T.J. Wilbanks. 2012. "Transformational Adaptation When Incremental Adaptations to Climate Change are Insufficient." *PNAS* 109: 7156–7161.

Kato, E., P.B. Rwamigisa, H. Kamusiime, F. Sufian, and C. Ringler. 2023. "Do Informational Videos Impact Awareness, Knowledge, and Adoption of Climate-Smart Agricultural Practices? Insights from Rural Uganda." In *Reaching Smallholder Women with Information Services and Resilience Strategies to Respond to Climate Change*, eds. C. Ringler, M.F. Alvi, R. Birner, et al., 44–47. Washington, DC: IFPRI.

Keating, B.A., P.S. Carberry, G.L. Hammer, et al. 2003. "An Overview of APSIM, a Model Designed for Farming Systems Simulation." *European Journal of Agronomy* 18: 267–288.

Khatri-Chhetri, A., P.K. Aggarwal, P.K. Joshi, and S. Vyas. 2017. "Farmers' Prioritization of Climate-Smart Agriculture (CSA) Technologies." *Agricultural Systems* 151: 184–191.

Knox, J., T. Hess, A. Daccache, and T. Wheeler. 2012. "Climate Change Impacts on Crop Productivity in Africa and South Asia." *Research Letters* 7 (034032): 1–8.

Koo, J., C. Azzarri, A. Mishra, et al. 2022. "Effectively Targeting Climate Investments: A Methodology for Mapping Climate–Agriculture–Gender Inequality Hotspots." CGIAR GENDER Platform Working Paper #005. CGIAR GENDER Platform, Nairobi.

Kramer, B. 2023. "Climate Insurance: Opportunities for Improving Agricultural Risk Management in Kenya." In *Food Systems Transformation in Kenya*, eds. C. Breisinger, M. Keenan, J. Mbuthia, and J. Njuki, 285–304. Washington, DC: IFPRI.

Kristjanson, P., E. Bryan, Q. Bernier, et al. 2017. "Addressing Gender in Agricultural Research for Development in the Face of a Changing Climate: Where Are We and Where Should We Be Going?" *International Journal of Agricultural Sustainability* 15 (5): 482–500.

Kumar, N., K. Raghunathan, A. Arrieta, J. Amir, and S. Pandey. 2021. "The Power of the Collective Empowers Women: Evidence from Self-Help Groups in India." *World Development* 146: 105579.

Kurukulasuriya, P., R. Mendelsohn, R. Hassan, et al. 2006. "Will African Agriculture Survive Climate Change?" *World Bank Economic Review* 20 (3): 367–388.

Laborde, D., M. Parent, and C. Smaller. 2020. *Ending Hunger, Increasing Incomes, and Protecting the Climate: What Would It Cost Donors?* Winnipeg: International Institute for Sustainable Development; Washington, DC: IFPRI.

Lecoutere, E., A. Mishra, N. Singaraju, et al. 2023. "Where Women in Agri-Food Systems Are at Highest Climate Risk: A Methodology for Mapping Climate–Agriculture–Gender Inequality Hotspots." *Frontiers in Sustainable Food Systems* 7: 1197809.

Lee, Y., B. Haile, G. Seymour, and C. Azzarri. 2021. "The Heat Never Bothered Me Anyway: Gender-Specific Response of Agricultural Labor to Climatic Shocks in Tanzania." *Applied Economic Perspectives and Policy* 43 (2): 732–749.

Letta, M., and R. Tol. 2019. "Weather, Climate and Total Factor Productivity." *Environmental and Resource Economics* 73 (1): 283–305.

Liang, X., Y. Wu, R.G. Chambers, et al. 2017. "Determining Climate Effects on US Total Agricultural Productivity." *PNAS* 114 (12): E2285–E2292.

Lipper, L., and D. Zilberman. 2018. "A Short History of the Evolution of the Climate Smart Agriculture Approach and Its Links to Climate Change and Sustainable Agriculture Debates." In *Climate Smart Agriculture: Natural Resource Management and Policy*, vol. 52, eds. L. Lipper, N. McCarthy, D. Zilberman, S. Asfaw, and G. Branca, 13–30. Cham, Switzerland: Springer.

Liverpool-Tasie, L.S.O., and C.M. Parkhi. 2020. "Climate Risk and Technology Adoption in the Midstream of Crop Value Chains: Evidence from Nigerian Maize Traders." *Journal of Agricultural Economics* 72 (1): 158–179.

Lobell, D.B., M. Bänziger, C. Magorokosho, and B. Vivek. 2011. "Nonlinear Heat Effects on African Maize as Evidenced by Historical Yield Trials." *Nature Climate Change* 1: 42–45.

Lobell, D.B., W. Schlender, and J. Costa-Roberts. 2011. "Climate Trends and Global Crop Production Since 1980." *Science* 333 (6042): 616–620.

Maddison, D. 2007. "The Perception of and Adaptation to Climate Change in Africa." Policy Research Working Paper 4308. World Bank, Washington, DC.

Mason-D'Croz, D., T.B. Sulser, K. Wiebe, et al. 2019. "Agricultural Investments and Hunger in Africa Modeling Potential Contributions to SDG2 – Zero Hunger." *World Development* 116: 38–53.

Mbow, C., C. Rosenzweig, L.G. Barioni, et al. 2019. "Food Security." In *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, eds. P.R. Shukla, J. Skea, E. Calvo Buendia, et al., 437–550. Cambridge, UK: Cambridge University Press.

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1994. "The Impact of Global Warming on Agriculture: A Ricardian Analysis." *American Economic Review* 84: 753–771.

Mendelsohn, R., W. Nordhaus, and D. Shaw. 1996. "Climate Impacts on Aggregate Farm Value: Accounting for Adaptation." *Agricultural and Forest Meteorology* 80: 55–66.

Mertz, O., K. Halsnæs, J.E. Olesen, et al. 2009. "Adaptation to Climate Change in Developing Countries." *Environmental Management* 43: 743–752.

Miao, R., M. Khanna, and H. Huang. 2015. "Responsiveness of Crop Yield and Acreage to Prices and Climate." *American Journal of Agricultural Economics* 98 (1): 191–211.

Morgan, M.Y., E. Bryan, and M. Elias. 2024. "Women's Leadership in Climate-Resilient Agrifood Systems: Defining a Future Research Agenda." *Environmental Research: Climate* 3: 023001.

Morton, J.F. 2007. "The Impact of Climate Change on Smallholder and Subsistence Agriculture." *PNAS* 104 (50): 19680–19685.

Mwongera, C., K.M. Shikuku, J. Twyman, et al. 2017. "Climate Smart Agriculture Rapid Appraisal (CSA-RA): A Tool for Prioritizing Context-Specific Climate Smart Agriculture Technologies." *Agricultural Systems* 151: 192–203.

Myers, S.S., A. Zanobetti, I. Kloog, et al. 2014. "Increasing CO_2 Threatens Human Nutrition." *Nature* 510: 139–142.

Ndegwa, M.K., C. Ringler, F.N. Muteti, E. Kato, and E. Bryan. 2023. "Can Participatory Video-Based Extension Increase Awareness and Knowledge of Climate Adaptation Practices? Insights from Rural Kenya." In *Reaching Smallholder Women with Information Services and Resilience Strategies to Respond to Climate Change*, eds. C. Ringler, M.F. Alvi, R. Birner, et al., 40–43. Washington, DC: IFPRI.

Ndegwa, M.K., A. Shee, C.G. Turvey, and L. You. 2020. "Uptake of Insurance-Embedded Credit in Presence of Credit Rationing: Evidence from a Randomized Controlled Trial in Kenya." *Agricultural Finance Review* 80 (5): 745–766.

Nelson, G.C., M.W. Rosegrant, A. Palazzo, et al. 2010. *Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options*. Washington, DC: IFPRI.

Nelson, G.C., D. van der Mensbrugghe, H. Ahammad, et al. 2014. "Agriculture and Climate Change in Global Scenarios: Why Don't the Models Agree." *Agricultural Economics* 45 (1): 85–101.

Nelson, G.C., J. Vanos, G. Havenith, O. Jay, K.L. Ebi, and R.J. Hijmans. 2024. "Global Reductions in Manual Agricultural Work Capacity Due to Climate Change." *Global Change Biology* 30: e17142.

Nico, G., and C. Azzarri. 2024. "Climate Change and Sex-Specific Labor Intensity: An Empirical Analysis in Africa." *Global Food Security* 42: 100799.

Nordhaus, W.D., and J. Boyer. 2003. *Warming the World: Economic Models of Global Warming*. Cambridge, MA: MIT Press.

Ortiz-Bobea, A., T.R. Ault, C.M. Carrillo, R.G. Chambers, and D.B. Lobell. 2021. "Anthropogenic Climate Change Has Slowed Global Agricultural Productivity Growth." *Nature Climate Change* 11: 306–312.

Parry, M., A. Evans, M.W. Rosegrant, and T. Wheeler. 2009. *Climate Change and Hunger: Responding to the Challenge*. Rome: World Food Programme.

Quisumbing, A.R., N. Kumar, and J. Behrman. 2018. "Do Shocks Affect Men's and Women's Assets Differently? Evidence from Bangladesh and Uganda." Development Policy Review 36 (1): 3–34.

Ragasa, C., J. Kyle, P. Kristjanson, and S. Eissler. 2022. "Conceptualizing Women's Empowerment in Agrifood Systems Governance: A New Framework." IFPRI Discussion Paper 2153. IFPRI, Washington, DC.

Rakib, M., and J.A. Matz. 2016. "The Impact of Shocks on Gender-Differentiated Asset Dynamics in Bangladesh." *Journal of Development Studies* 52 (3): 377–395.

Reid, H., and S. Huq. 2008. *International and National Mechanisms and Politics of Adaptation: An Agenda for Reform*. New York: United Nations Development Programme.

Ricciardi, V., N. Ramankutty, Z. Mehrabi, L. Jarvis, and B. Chookolingo. 2018. "How Much of the World's Food Do Smallholders Produce?" *Global Food Security* 17: 64–72.

Robinson, S., S. Dunston, A. Mishra, et al. 2024. "The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Documentation for Version 3.6." Modeling Systems Technical Paper 1. IFPRI, Washington, DC.

Rosegrant, M.W., T.B. Sulser, S. Dunston, et al. 2024. "Food and Nutrition Security Under Changing Climate and Socioeconomic Conditions." *Global Food Security* 41: 100755.

Rosegrant, M.W., T.B. Sulser, and K. Wiebe. 2022. "Global Investment Gap in Agricultural Research and Innovation to Meet Sustainable Development Goals for Hunger and Paris Agreement Climate Change Mitigation." *Frontiers in Sustainable Food Systems* 6: 965767.

Rosén, L., L.O. Naess, A. Nightingale, and J. Thompson. 2017. "'Triple Wins' or 'Triple Faults'? Analysing the Equity Implications of Policy Discourses on Climate-Smart Agriculture (CSA)." *Journal of Peasant Studies* 45 (1): 150–174.

Rosenzweig, C., and F.N. Tubiello. 2007. "Adaptation and Mitigation Strategies in Agriculture: An Analysis of Potential Synergies." *Mitigation and Adaption Strategies for Global Change* 12: 855–873.

Schlenker, W., and M.J. Roberts. 2009. "Nonlinear Temperature Effects Indicate Severe Damages to US Crop Yields Under Climate Change." *PNAS* 106 (37): 15594–15598.

Silvestri, S., E. Bryan, C. Ringler, M. Herrero, and B. Okoba. 2012. "Climate Change Perceptions and Adaptation of Agro-Pastoral Communities in Kenya." *Regional Environmental Change* 12 (4): 791–802.

Smit, B., I. Burton, R. Klein, et al. 1999. "The Science of Adaptation: A Framework for Assessment." *Mitigation and Adaptation Strategies for Global Change* 4: 199–213.

Smit, B., O. Pilifosova, I. Burton, et al. 2001. "Adaptation to Climate Change in the Context of Sustainable Development and Equity." In *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, 877–912. Cambridge, UK: Cambridge University Press.

Smit, B., D. McNabb, and J. Smithers. 1996. "Agricultural Adaptation to Climatic Variation." *Climatic Change* 33: 7–29.

Smit, B., and M.W. Skinner. 2002. "Adaptation Options in Agriculture to Climate Change: A Typology." *Mitigation and Adaptation Strategies for Global Change* 7: 85–114.

Smith, P., J. Nkem, K. Calvin, et al. 2018. "Interlinkages Between Desertification, Land Degradation, Food Security and GHG fluxes: Synergies, Trade-Offs and Integrated Response Options." In *Special Report on Climate Change and Land*, 551–672. Geneva: Intergovernmental Panel on Climate Change.

Smithers, J., and B. Smit. 1997. "Human Adaptation to Climatic Variability and Change." *Global Environmental Change* 7 (2): 129–146.

Solomon, S., G. Plattner, R. Knutti, and P. Friedlingstein. 2009. "Irreversible Climate Change Due to Carbon Dioxide Emissions." *PNAS* 106 (6): 1704–1709.

Sulser, T., K.D. Wiebe, S. Dunston, et al. 2021. *Climate Change and Hunger: Estimating Costs of Adaptation in the Agrifood System*. Food Policy Report. Washington, DC: IFPRI.

Taylor, M. 2017. "Climate-Smart Agriculture: What Is It Good For?" *Journal of Peasant Studies* 45 (1): 89–107.

Thomas, T.S. 2024. "The Impact of Climate Change on Agriculture." In *ReSAKKS Annual Trends and Outlook Report 2024: Advancing the Climate and Bioeconomy Agenda in Africa for Resilient and Sustainable Agrifood Systems*, eds. G. Tadesse, K. Glatzel, and M. Savadogo, 64–77. Kigali: AKADEMIYA2063; Washington, DC: IFPRI.

Thomas, T.S., V. Nazareth, and R. Folledo. 2018. "A Biophysical Approach to Modeling Alternative Agricultural Futures Under Climate Change." In *The Future of Philippine Agriculture Under a Changing Climate: Policies, Investments and Scenarios*, eds. M.W. Rosegrant and M.A. Sombilla, 377–449. Singapore: ISEAS Publishing.

Thomas, T.S., R.D. Robertson, K. Strzepek, and C. Arndt. 2022. “Extreme Events and Production Shocks for Key Crops in Southern Africa Under Climate Change.” *Frontiers in Climate* 4: 787582.

Thomas, T.S., C.A. Schlosser, K. Strzepek, R.D. Robertson, and C. Arndt. 2022. “Using a Large Climate Ensemble to Assess the Frequency and Intensity of Future Extreme Climate Events in Southern Africa.” *Frontiers in Climate* 4: 787721.

Thornton, P.K., P. Kristjanson, W. Förch, C. Barahona, L. Cramer, and S. Pradhan. 2018. “Is Agricultural Adaptation to Global Change in Lower-Income Countries on Track to Meet the Future Food Production Challenge?” *Global Environmental Change* 52: 37–48.

Thornton, P., G. Nelson, D. Mayberry, and M. Herrero. 2022. “Impacts of Heat Stress on Global Cattle Production During the 21st Century: A Modelling Study.” *Lancet Planet Health* 6: e192–e201.

Timu, A.G., and B. Kramer. 2021. “Gender-Inclusive, Responsive, and Transformative Agricultural Insurance: A Literature Review.” CCAFS Working Paper 417. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen, Netherlands.

Twyman, J., M. Green, Q. Bernier, et al. 2014. “Gender and Climate Change Perceptions, Adaptation Strategies, and Information Needs Preliminary Results from Four Sites in Africa.” CCAFS Working Paper 83. CGIAR Research Program on CCAFS, Copenhagen.

UNEP (United Nations Environment Programme). 2024. *Adaptation Gap Report 2024: Come Hell and High Water—As Fires and Floods Hit the Poor Hardest, It Is Time for the World to Step Up Adaptation Actions*. Nairobi.

Waisman, H., C. Bataille, H. Winkler, et al. 2019. “A Pathway Design Framework for National Low Greenhouse Gas Emission Development Strategies.” *Nature Climate Change* 9: 261–268.

Waithaka, M., G. Nelson, T.S. Thomas, and M. Kyotalimye, eds. 2013. *East African Agriculture and Climate Change: A Comprehensive Analysis*. IFPRI Research Monograph. Washington, DC: IFPRI.

Xiang, T., T.H. Malik, J.W. Hou, and J. Ma. 2022. “The Impact of Climate Change on Agricultural Total Factor Productivity: A Cross-Country Panel Data Analysis, 1961–2013.” *Agriculture* 12 (12): 2123.

Yang, Y., D. Tilman, P. Smith, et al. 2024. “Climate Change Exacerbates the Environmental Impacts of Agriculture.” *Science* 385 (671): 3747.

ZEF (Center for Development Research) and FAO. 2020. *Investment Costs and Policy Action Opportunities for Reaching a World Without Hunger (SDG 2)*. Bonn, Germany.

Zhao, C., B. Liu, S. Piao, et al. 2017. “Temperature Increase Reduces Global Yields of Major Crops in Four Independent Estimates.” *PNAS* 114 (35): 9326–9331.