

# *What do we know about* **THE FUTURE OF FOOD SYSTEMS TRANSFORMATION IN RELATION TO CLIMATE CHANGE?**

Timothy Thomas (IFPRI) and Aditi Mukherji (CGIAR)

## *Key messages*

- Climate change poses major challenges to agriculture and food systems, but the latest foresight modeling suggests impacts may be more nuanced than previously thought. For example, economic feedback mechanisms affect global average impacts of climate change on yields and important differences arise between the various greenhouse gas (GHG) emissions scenarios and climate models.
- More importantly, global averages mask wide diversity in impacts across geographies, commodities, and people's ability to adapt.
- In addition to long-term impacts of changes in global averages, increasing climate variability is likely to lead to a higher frequency of production shocks from adverse climate events.
- Climate change is expected to lower GDP and therefore increase the number of food-insecure households and increase poverty. It may also slow growth of agricultural productivity, adversely impacting rural households.
- Agriculture and food systems (including diets, energy use, and land use change) play a key role in global emissions and strategies to reach net zero, but these strategies are at cross purposes with meeting food needs under climate change and rising demand for food globally. Foresight modeling can help decision-makers evaluate these trade-offs and ameliorate particularly adverse impacts.

## RECENT TRENDS AND CHALLENGES

Climate change is resulting in costlier shocks from extreme events. In 2022 alone, climate change wreaked havoc on agriculture when devastating floods occurred in Pakistan (Otto et al. 2023); the worst heatwave in India took a huge toll on the wheat harvest (Zachariah et al. 2023); the worst drought in 40 years in the Horn of Africa exacerbated food insecurity and caused famine in some places (Kimutai et al. 2025); devastating tropical cyclones destroyed infrastructure and property in places such as Florida (United States) and the Philippines; and landslides from flooding caused destruction and loss of lives in Latin America. Add to this ongoing sea level rise leading to frequent inundation of crops and salinization in the past decades in major river deltas in Bangladesh and Viet Nam, and it is clear how climate change is affecting the entire food system.

Governments worldwide are acknowledging the losses and damages caused by greenhouse gas (GHG)-induced climate change, creating a fund during the 27th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27) for assistance or reparations, depending on the perspective one takes. Seneviratne et al. (2021) describe in more detail the mechanisms through which devastating climate events are occurring more frequently.

## LATEST FORESIGHT RESEARCH

The primary reference for understanding the latest in climate change research is the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC). It is published in three large volumes. The first focuses on the latest research on the physical science related to climate and climate changes (IPCC 2021). The second focuses on the impact of climate change on the systems that people rely on for their well-being (IPCC 2022a). Chapter 5 (Bezner et al. 2022) focuses on agriculture. The third volume of the AR6 focuses on climate change mitigation (IPCC 2022b), with an important chapter on Agriculture, Forestry and Other Land Uses (AFOLU; Nabuurs et al. 2022). Other sources concerning GHG emissions mitigation from the AFOLU sector are Mukherji

et al. (2023, 2024). Summaries of the latest research on climate and food can be found in the CGIAR Climate Insights (2025). For a summary of the latest IMPACT foresight model results, see Rosegrant et al. (2024) or Rosegrant et al. (forthcoming).

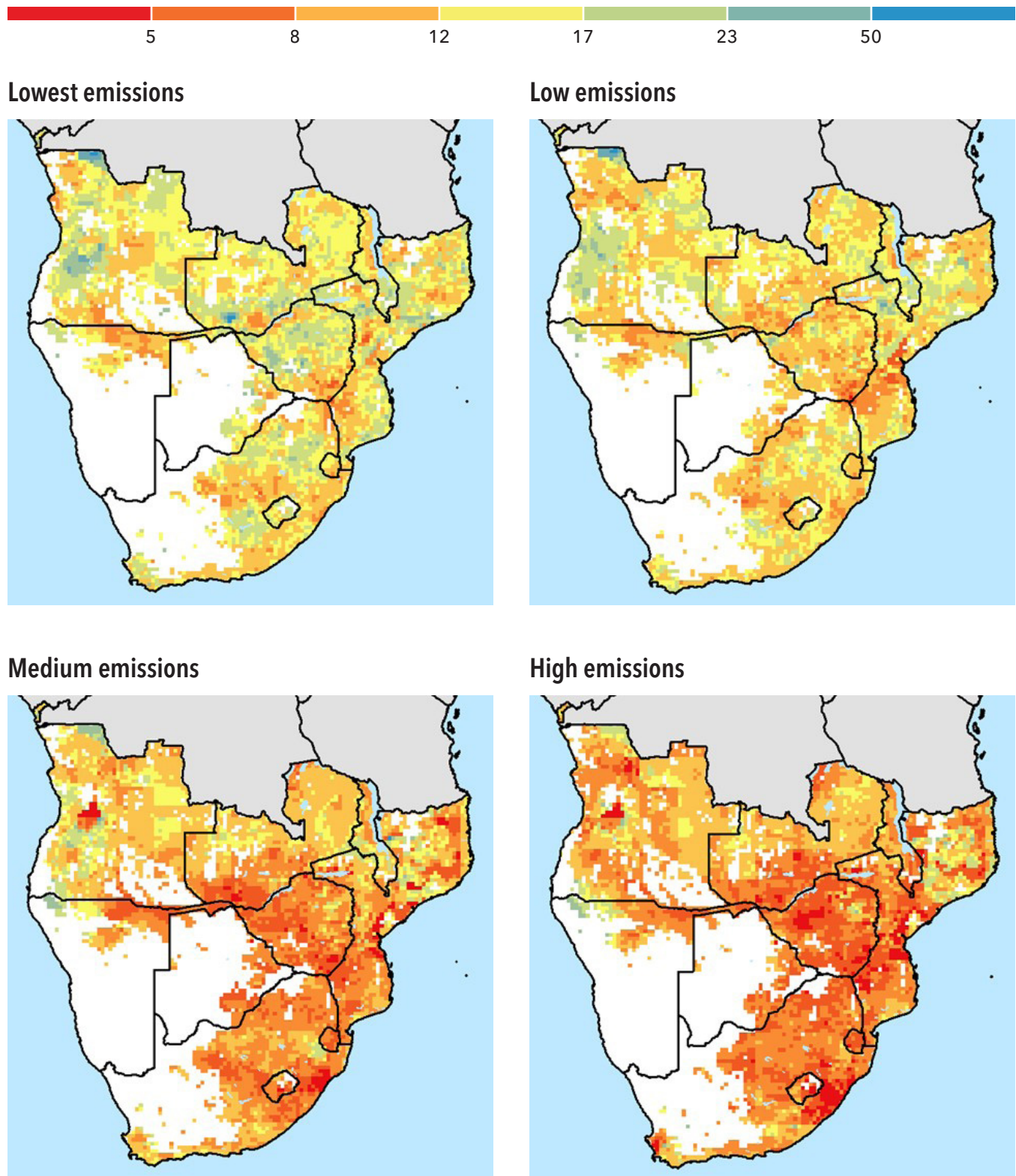
**Foresight models generally project modest global average impacts of climate change on agricultural productivity.** Several studies of the long-term impact of climate change find modest impacts on aggregate agricultural productivity at the global level (Jägermeyr et al. 2021; Rosegrant et al. 2024), reflecting that losses in some locations and crops are offset by gains in others. For example, Jägermeyr et al. (2021) estimate yield changes from climate change between 1983–2013 and 2069–2099 for the world’s four largest crops (using five climate models and 12 crop models, allowing for CO<sub>2</sub> fertilization, and focusing on the low- and high-emissions scenarios, SSP126 and SSP585, but not accounting for changes in technology or markets). Under these scenarios, they project global average yield losses of 6.4–24.1 percent for maize, yield changes of –2.0 to +2.1 percent for soybeans, and yield gains of 1.7–3.4 percent for rice and 8.8–17.5 percent for wheat. Global economic models project that changes in technology and markets will moderate these global average impacts, at least until mid-century (Rosegrant et al. 2024).

**Digging deeper reveals important differences in impacts.** Global averages conceal important differences between regions, countries, and even locations within a given country. In the process of spatially differentiating climate impact, it is possible to identify “hotspots” – locations where climate change will force major changes in the production systems currently used (Heikonen et al. 2025). More work can be done on this.

In addition to hotspots, a perhaps more significant impact hidden in the global averages is how interannual variability of climate can lead to considerable variability in yields. Extremely low or high rainfall or temperature in a given year can result in very low yields. Global averages offset low-yield years with normal- and high-yield years. Yet because of the devastating effect for farmers and for low-income consumers, years with climate shocks take on great importance.

Foresight analysis thus gives us two complementary messages. First, at the global level, production is projected to roughly keep pace with demand for food, livestock feed,

**FIGURE 1** Frequency of 1-in-20-year low maize yield events in southern Africa: Comparing frequency in the 2020s to the 2060s under various emissions scenarios



Source: Thomas et al. (2022b).

and stock for biofuels. And second, in certain locations or in certain years, production shocks will result in hardship, but foresight modeling can help identify risks in advance so that policy interventions can aid in adapting before the shocks are fully realized.

**The frequency and impact of extreme events will increase.** Thomas et al. (2022a, 2022b) modeled the impact of climate change on climate shocks – 1-in-20-year low-rainfall, high-temperature, or low-yield events in 10 countries of southern Africa – using a distribution of over 500,000 simulated climates (see Figure 1 for impact on low-yield events for maize). The authors noted a large increase in the frequency of low-yield events in most parts of the region (though in relatively small areas, low-yield events actually decreased). Another way of understanding their results is to say that 1-in-20-year low-yield events will have lower yields than before climate change. Other studies that have looked at the interannual variability of yields include Ostberg et al. (2018); Liu, Ye, and Shi (2021); Chen, Zhang, and Tao (2018); Stuch, Alcamo, and Schaldach (2020); Torriani et al. (2007); and Thornton et al. (2009).

**Heat stress is projected to adversely affect labor productivity.** Nelson et al. (2024) examine the impact of heat stress on manual work in the agriculture sector. They find that under the highest emissions scenario, the productivity of labor will drop from the current level of 86 percent to 70 percent by the end of the century. They also discover that certain regions will experience a much higher effect, and they investigate how much machinery will be required to replace human labor. Heat stress on human labor is currently not accounted for in most foresight modeling and suggests an important cause of productivity declines that should be incorporated in future scenarios (see also Parsons et al. 2021 and Dasgupta and Robinson 2023).

**There is little agreement regarding climate's impact on overall productivity growth.** Many studies have tried to estimate the impact of climate change on overall agricultural productivity (beyond what process-based models can estimate) and on the economy in general. Dell, Jones, and Olken (2012) suggest that in addition to the direct impact of temperature and precipitation on the level of production, it is theoretically possible that climate might impact the rate of growth of production. However, little agreement exists between studies that have endeavored to investigate this issue: some find very large impacts on agriculture and on the whole economy, while other

studies find modest impacts (Dell, Jones, and Olken 2012; Burke, Hsiang, and Miguel 2015; Burke, Davis, and Diffenbaugh 2018; Diffenbaugh and Burke 2019; Casey, Fried, and Goode 2022, 2023; Barrage 2020; Hassler et al. 2019; Golosov et al. 2014; Nordhaus and Boyer 2003; Donadelli et al. 2017; Letta and Tol 2019; Zhang et al. 2018; Chancellor et al. 2021; Ortiz-Bobea et al. 2021; Liang et al. 2017; Xiang et al. 2022; Kotz, Levermann, and Wenz 2024). Studies that impose a growth effect on their analysis (while excluding the level effect) find very large costs due to climate change (Burke, Davis, and Diffenbaugh 2018; Ortiz-Bobea et al. 2021). Despite disagreement concerning the magnitude of the impact of climate change on GDP, it is generally agreed that there is a negative impact of climate change on GDP not accounted for in most if not all foresight modeling scenarios. While the impact on the level effect of agricultural total factor productivity (TFP) is modeled by use of bioeconomic models, if climate exerts a growth effect on agricultural TFP as some research suggests, this is not accounted for in foresight modeling scenarios and could create a much more adverse projection for future agricultural productivity.

**CO<sub>2</sub> fertilization reduces nutrients in crops.** Finally, despite CO<sub>2</sub> fertilization tending to increase yields (especially of crops other than maize, sorghum, millet, sugarcane, and teff), it also has the effect of reducing protein, vitamin, and mineral content by harvested weight (Myers, Zanobetti, Kloog et al. 2014), and foresight models are able to project the impact on nutrition. Refer to the chapter on diets and nutrition by Sulser et al. in this volume to learn more. Furthermore, some disagreement arises in the scientific literature about the size of the CO<sub>2</sub> fertilization effect (Toreti et al. 2020; Li et al. 2017; Allen et al. 2020; Zhu et al. 2023; Yuan et al. 2019).

**Emissions from the food system are large and need to be reduced.** Crippa et al. (2021) calculate that 34 percent of the world's GHG emissions are from the food system, including production of fertilizer, land use and land use change, non-CO<sub>2</sub> emissions from enteric fermentation and wet soils, transportation, processing, and retail. Important avenues for getting the global food system to net zero emissions are through afforestation and reforestation, particularly on low-productivity agricultural lands. This often comes with a reduction in livestock production, particularly cattle, which are seen as drivers of deforestation for more pasture and are themselves large methane emitters (a powerful GHG), primarily through enteric fermentation.

Reducing emissions will also require changes in eating habits. Springmann et al. (2018) analyze options for making the global food system both more nutritious and sustainable while staying within planetary boundaries (Rockström et al. 2009a, 2009b), one of which is GHG emissions, but other agriculture-related boundaries include use of nitrogen and phosphorous fertilizers, deforestation, freshwater availability, and biodiversity loss. Springmann et al. (2018) argue that it would be difficult to stay within these boundaries and provide sufficient nutrition to people without major changes to consumer demand for food, including reducing consumption of proteins from livestock. The pushback on this research has primarily dealt with the difficulty of changing consumer behavior and the infeasibility for many people in developing countries of affording the suggested alternative diet, suggesting limits to how much diets will be able to change (Hirvonen et al. 2020).

## KEY GAPS AND OPPORTUNITIES FOR FURTHER RESEARCH

The preceding section highlighted some of the latest findings, but also pointed to how those findings could be expanded or included in foresight modeling scenarios, such as including climate impact on GDP or agricultural TFP growth and including the effects of heat stress on labor productivity effects of climate change.

While studies like Thomas et al. (2022a, 2022b) show the impact of climate uncertainty and interannual variability on the frequency of production shocks for southern Africa, more work could be done globally, potentially leading to solutions that mitigate increases in food insecurity and climate shocks that result from climate change. Furthermore, their work examines only the impact of climate uncertainty, but does not examine the impact of increasing climate variability, which could be included in future foresight modeling.

Other climate-related gaps in many foresight models include:

- The impact of climate change on livestock productivity.
- Estimating and accounting for losses from flooding, waterlogging, sea-level rise, storm surge, submersion, and salinization on yields and availability of agricultural land.
- Accounting for the impact of loss of glaciers and reduction in glacier melt for irrigation water.
- Accounting for other large losses of harvests that are increasing under climate change, including wildfires and landslides.
- The effect of climate change on pests and diseases, and how these changes impact crop and livestock productivity.
- Careful analysis of climate change impact by growing season in countries with multiple seasons.

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The authors of this chapter are **Timothy Thomas**, a Senior Research Fellow in the Foresight and Policy Modeling Unit at the International Food Policy Research Institute (IFPRI); and **Aditi Mukherji**, Director of the CGIAR Climate Change Adaptation and Mitigation Impact Platform.

Related chapters on the future of food system drivers and impacts, regional and national perspectives, food commodities, and foresight tools are available in our [Table of Contents](#).

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## INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

*A world free of hunger and malnutrition*

IFPRI is a CGIAR Research Center

1201 Eye St, NW, Washington, DC 20005 USA | T. +1-202-862-5600 | F. +1-202-862-5606 | Email: [ifpri@cgiar.org](mailto:ifpri@cgiar.org) | [www.ifpri.org](http://www.ifpri.org) | [www.ifpri.info](http://www.ifpri.info)

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