New Understanding of Climate Change and Food Systems since the IPCC Sixth Assessment Report:

Global and Regional Impacts, Solutions, Structural Trends, and Research Directions

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Executive Summary

We survey advances contributed by peer-reviewed studies since the IPCC AR6 food system chapter. The focus is on recent (2020-present) assessments of climate change impacts both on global food systems and vulnerable agricultural regions, as well as promising actions for both mitigation and adaptation (Fig. 1). It includes a review of the ongoing structural changes in food production and processing and a description of how Shared Socioeconomic Pathways (SSPs), Representative Agricultural Pathways (RAPs), and AgMIP model ensembles are being used to study them. A new Global Adaptation Pathways effort is getting underway that will provide key tools for implementation. Finally, we identify important emerging areas for research.

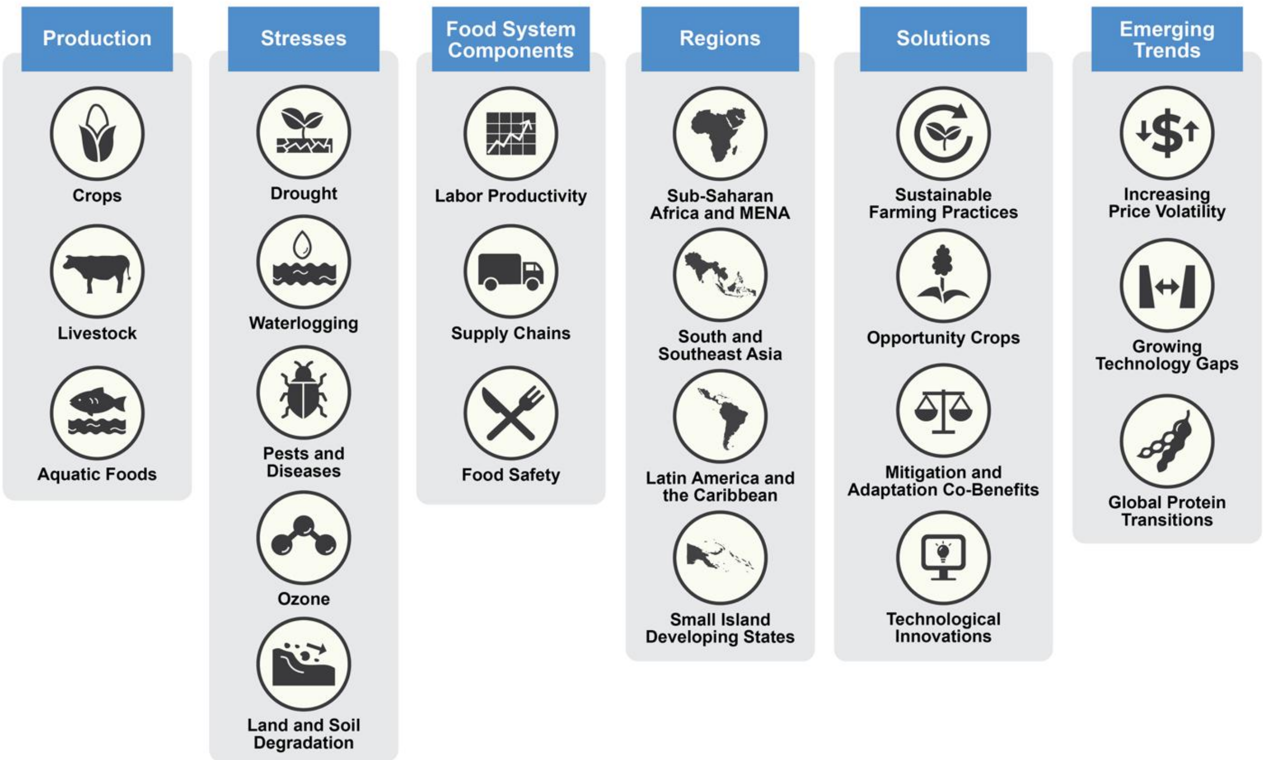

Fig. 1. Key update topics in climate change and food systems.

What are the Likely Impacts of Climate Change on Global Food Systems to Mid-Century and Beyond?

Production

- Likely decline vs. a no-climate-change baseline under SSP3-7.0 (regional rivalry and high GHG emissions) (high confidence)
- Residual production losses remain even with adaptation (high confidence)
- Variability in production increases across most staples (high confidence)
- Malnutrition rises due to flood and drought-driven food insecurity (high confidence)

Crops, Livestock, and Aquatic Foods

- ***Maize:*** Widespread declines in mid- to low-latitudes; risk of non-linear peak-then-decline in some mid-latitudes (medium-high confidence)

- ***Rice, Wheat, and Soybean:*** Mixed signs with CO_2 benefits in cooler/wetter zones offset by heat/water/ozone constraints; growing risk of food quality/food safety issues (medium confidence)

- ***Fruits and Vegetables:*** Exposure to heat and chilling events causing yield deficits; water stress and extreme rainfall already eroding yield stability (medium confidence)

- ***Livestock:*** Heat stress, forage quality decline, and water stress lead to productivity losses and higher costs of cooling for health maintenance (medium confidence)

- ***Fisheries:*** Most tropical and subtropical fisheries face biomass declines due to both overfishing and increasing sea surface temperatures (high confidence)

- ***Aquaculture:*** Coastal production exposed to increasing heat, disease, severe storms, and oxygen decline (medium-high confidence)

Stresses

Drought

- Overall production losses for staple crops due to drought are project to be low, but regional variability indicates high-risk zones (in South America, Africa, Eastern Europe, and Southeast Asia) could face higher losses (high confidence)

Waterlogging

- Waterlogging is currently underrepresented in crop models, leading to underestimated risks in future yield projections (medium-high confidence)

Pests and Diseases

- Insect pests are tightly coupled to climatic conditions and they are expanding their ranges, shifting seasonal timing, and increasing the number of generations per year (high confidence)

Ozone

- Elevated tropospheric ozone concentrations are projected to cause yield declines in staple crops by damaging leaf tissue and reducing photosynthetic capacity (medium-high confidence)

Land/Soil Degradation

- Climate change is expected to lead to increased soil erosion in many locations worldwide affecting ecosystem services and human well-being (high confidence)

Food System Components

- Food system components are at risk to climate change in varying ways (Table 1). Confidence in the direction and nature of these risks is growing.

Table 1. Food System Components at Risk to Climate Change

Component	Measure	Impact Driver	Direction of Change	Confidence
Labor	Productivity	Heat/Humidity	↓	Medium-High
Supply Chains	Disruption	Compound extreme events	↑	Low-Medium
	Cold-chain energy demand	Heat	↑	Medium-High
Food Safety	Mycotoxins/pathogens	Heat/Humidity	↑	Low-Medium

Regions

What are the Likely Impacts of Climate Change on Most Vulnerable Regions and Food Systems to Mid-Century and Beyond?

Vulnerable Regions

- **Alarms continue to be raised** about the threats that climate change poses to agricultural regions, both because these regions are more prone to climatic change and its impacts and because of socioeconomic factors including income and development levels (high confidence)

- Areas of particular vulnerability include **Sub-Saharan Africa (SSA), Middle East and North Africa (MENA), South Asia (SA) and Southeast Asia (SEA), Latin America and the Caribbean (LAC), and Small Island Developing States (SIDS)** (high confidence)

- **Many smallholder farmers in Africa, Asia, Latin America, and low-lying coastal populations in SIDS** — have reached "soft limits" to adaptation (i.e., adaptation options may be available but are currently not feasible)

- **Limits to adaptation** are largely driven by financial, governance, institutional, and policy constraints; inequity and poverty further restrict adaptive capacity, creating disproportionate climate impacts for the most vulnerable groups (high confidence)

Solutions

What Solutions Best Enhance Resilience and/or Reduce GHG Emissions?

Sustainable farming practices

- The use of no-till and cover crops on corn and soybean rotations has been tested in a multi-model ensemble across the U.S. Mid-West, leading to better estimates of the impacts of the practices on soil organic carbon
- The results show that adopting no-till combined with cover crops would increase SOC stocks by 0.36 ± 0.12 Mg ha-1 yr-1 aggregated across the entire U.S. Midwest cropland
- At the regional scale, this corresponds to a net SOC gain of 16.4 Tg C yr-1 compared to business-as-usual baselines. These benefits are approximately halved when each management change is practiced individually, and the modest gains are only fully realized when continued over the long-term in soils with low initial carbon stock

Opportunity Crops

- Many underutilized species are significantly more climate-resilient than staples such as maize and soy in Sub-Saharan Africa (high confidence)
- Opportunity crops such as sorghum and cowpea offer promising adaptation benefits due to their greater water use efficiency (up to 30% higher than major cereals) and strong heat tolerance (withstanding temperatures above 38-42°C) (high confidence)

Mitigation and Adaptation Co-Benefits

- “Win–Win” outcomes for mitigation and adaptation have been identified in rice farming systems in India, Vietnam, and Bangladesh that utilize water-saving and low-emission management practices, such as Alternate Wetting and Drying (AWD) and System of Rice Intensification (SRI)

- These can reduce or avoid increases in methane emissions, indicating that well-targeted management strategies can support both adaptation and mitigation, even as temperatures rise and rainfall becomes more variable (high confidence)

Technological Innovations

- Machine learning (ML) is emerging as a critical technological innovation for improving projections of climate change impacts on agriculture and food systems because it can address long-standing limitations in traditional crop modeling
- ML techniques can capture complex, nonlinear interactions in crop growth that process-based models may miss, handle missing or noisy agricultural data, and generate high-resolution inputs such as soil properties, planting dates, and downscaled climate variables
- ML is already being used to forecast yields across scales, emulate computationally intensive crop models, and extract information from satellite imagery and text data, thereby reducing key sources of uncertainty in climate-impact assessments
- By enhancing data quality, supporting model calibration, and complementing process-based approaches, machine learning strengthens the evidence base needed for robust, spatially explicit projections of future climate risks to agriculture—provided that the research community coordinates on shared datasets, benchmarks, and methodological standards

Emerging Trends

In Conjunction with Climate Change, What are Emerging Trends in the Structure of Food Production and Processing?

Increasing Price Volatility Correlated Across Interconnected Markets

- Causative factors of increasing price volatility include:
    - Pandemics (e.g., COVID-19)
    - Conflicts (e.g., Ukraine)

- Interconnectedness of energy and commodity markets and climate change mitigation:
    - Spread of biofuels put upward pressure on maize prices
    - Downward pressure on fossil-fuel-based fertilizer production

- Climate variability will compound these dynamics:
    - Extreme temperature and precipitation events will impact crop yields and biofuel feedstock supply simultaneously

- Increasing price volatility will amplify food security risks for import-dependent and low-income populations who are most vulnerable to price spikes.

Growing Technology Gaps

- Adoption of precision agriculture and increasingly sophisticated technologies (e.g., GPS guidance, variable rate technology, robotics, machine vision) will be unevenly distributed

- Most benefit for Global North, capturing efficiency and productivity gains, while compounding barriers for smallholder farmers due to:
    - High upfront costs
    - Lack of necessary infrastructure
    - Limited technical support

Global Protein Transitions

- Increase in global demand for protein and projected continued surge driven primarily by rising incomes and consumption in middle-income countries

- Daily per capita intake of meat, dairy, fish, and other animal products is projected to continue rising, with India and Southeast Asia projected to account for the largest growth

- Expected to drive an expansion of livestock production, aquaculture, and plant-based alternatives, intensifying pressure on land, water, and feed resources that are already under strain

- In 2022, aquaculture production surpassed wild capture fisheries for the first time in history

What are the Significant Directions for Climate Change and Food Systems Research?

Nutrition

- Integrating nutrition into studies of climate impacts on food has lagged, but there is now momentum for collaboration between climate and nutrition research communities to conduct modeling studies that are critical for development of robust adaptation measures

Food Systems Emissions Accounting and Mitigation

- A critical frontier since AR6 involves comprehensive emissions accounting across the entire agrifood value chain, from the production of farm inputs through food processing, distribution, consumption and waste disposal

Global Adaptation Pathways

- The Global Adaptation Initiative is establishing a conceptual and methodological foundation for pathways representing a broad range of sectors for use in local, regional, and global climate change and agri-food assessments. These pathways would provide structured, time-dependent strategies that link near-term actions to long-term sustainability objectives, guided by scenario frameworks such as the SSPs

Introduction

The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) found that climate change due to increased greenhouse gas emissions is increasingly disrupting food and agriculture through gradual warming and precipitation changes, as well as more frequent heat extremes, heavy rainfall events, and droughts that directly affect crops, livestock, fisheries, and water resources (Calvin et al., 2023). Although global agricultural productivity has continued to rise, climate change has significantly slowed this growth over the past 50 years — especially in mid- and low-latitude regions — while ocean warming and acidification have harmed aquaculture and fisheries. Due to the multiple non-climate drivers that affect all aspects of food systems, detecting and attributing specific impacts to climate change is difficult; however, there is high confidence that climate change has caused mostly negative impacts on crop production, as well as on food quality and marketability, though these disruptions differ regionally (Calvin et al., 2023). At the same time, while some improvement in food security has been achieved in South and Southeast Asia, as well as South America – reducing total food insecurity globally – hunger has continued to increase in most of Africa and Western Asia, and between 638 million to 720 million people (7.8-8.8% of the global population) are estimated to have faced hunger in 2024 (FAO et al., 2025).

Looking ahead, the IPCC AR6 projected strong regional (i.e., multiple-country) patterns of change affecting many of the world's major agricultural systems, with climate change tending to reduce productivity in lower latitudes and dry regions where systems are already near their thermal and water use limits, and increase productivity in some cooler and wetter regions and seasons where positive CO_2 effects dominate (Calvin et al., 2023; Jägermeyr et al., 2021). According to the IPCC, climate change will increase the number of people at risk of hunger between 8 million (under less extreme SSP1-6.0) and 80 million (under more extreme SSP3-6.0) by mid-century, concentrated in Sub-Saharan Africa, South Asia and Central America (Bezner Kerr et al., 2023). AR6 further projected that food systems will face growing risks from unsustainable land and water use, demographic pressures, and degraded ecosystems, including forests, coral reefs, and coastal wetlands.

At the same time, adaptation measures offer substantial co-benefits: inclusive climate services, early warning systems, improved water management, and risk-sharing mechanisms can strengthen agricultural decision-making, boost productivity, protect livelihoods, and enhance resilience. Mitigation opportunities also exist — such as emerging technologies to reduce methane (CH_4) and nitrous oxide (NO_x) emissions from agriculture — but adoption remains constrained by cost, system diversity, and rising global demand for food and livestock products (Calvin et al., 2023). Overall, the IPCC AR6 found that climate change is reshaping the sustainability and stability of the world's food systems, underscoring the need for integrated adaptation and mitigation strategies.

Since AR6, many assessments of climate change and food systems have been embracing the multi-model approach of the Climate Model Intercomparison Project (CMIP) (Eyring et al., 2016). In this approach, independent groups decide and follow strict protocols for model calibration and validation, sensitivity analyses, and subsequent scenario-based simulations enabling more rigorous characterization of projected results and their associated uncertainties across the ensemble or suite of model results. Crop model ensembles have consistently been shown to provide greater accuracy compared to observations than individual models (Asseng et al., 2013; Bassu et al., 2014; Li et al., 2015). This multi-model approach is currently being used to go beyond projecting impacts on yields and productivity to test both mitigation and adaptation solutions (Li et al., 2024). Areas for food system model improvement are also being increasingly tackled, leading to further upgrading of assessments.

The Agricultural Model Intercomparison and Improvement Project (AgMIP)'s multi-model approach is a systematic, collaborative framework that links climate, crop[1], and economic models across local to global scales to robustly assess climate change impacts on agriculture and food security (Rosenzweig et al., 2013). Using common protocols, ensembles, and uncertainty analysis, AgMIP studies produce reliable, actionable findings for decision-makers and for future model development. Integrated simulation-based research approaches are important sources of evidence to inform policy decisions towards climate mitigation and adaptation as well as broader questions of health and sustainability.

An example is the AgMIP Global Economics Team multi-model contributions to EAT-Lancet 2.0 (Rockström et al., 2025). The AgMIP Global Economics Team's results show that individual measures (e.g., increasing productivity, tackling food loss and waste, shifting to healthy diets, implementing land-use and mitigation policies) in isolation are insufficient to achieve high-level environmental objectives and might generate unintended consequences. Economic models

[1]Many of the AgMIP assessments use process-based crop models. These are analytical and computational tools that simulate biophysical, chemical, or ecological systems by explicitly representing the underlying mechanisms and processes that drive system behavior. Instead of relying solely on statistical correlations, these models incorporate cause-and-effect relationships—such as energy flows, water balance, plant physiology, nutrient cycling, and soil dynamics—to predict how a system will respond under different conditions. In agriculture and climate science, for example, process-based crop or soil models use equations describing photosynthesis, respiration, phenology, hydrology, and nutrient uptake to estimate yields, emissions, or other outcomes under varying climate, management, and environmental scenarios.

project that bundling the aforementioned measures can avoid 50% of projected agricultural greenhouse gas emissions by 2050 and almost 20% of anticipated land conversion, while moderating food price increases associated with ambitious climate change mitigation policies, with medium confidence due to large model uncertainty regarding food prices when simulating diet shifts (Sundiang et al., 2025).

In this paper, we survey advances contributed by peer-reviewed studies since the IPCC AR6 food system chapter (Bezner Kerr et al., 2023). The focus is on recent (2020-present) modeling assessments of climate change impacts both on global food systems and vulnerable agricultural regions, as well as promising actions for both mitigation and adaptation (Fig. 1). It includes emerging trends to structural changes in food production and processing and a description of how Shared Socioeconomic Pathways (SSPs), Representative Agricultural Pathways (RAPs), and AgMIP model ensembles are being used to study them, and of the new Global Adaptation Pathways effort getting underway. We assess what remains uncertain and what still needs to be done in regard to agricultural modeling for climate change.

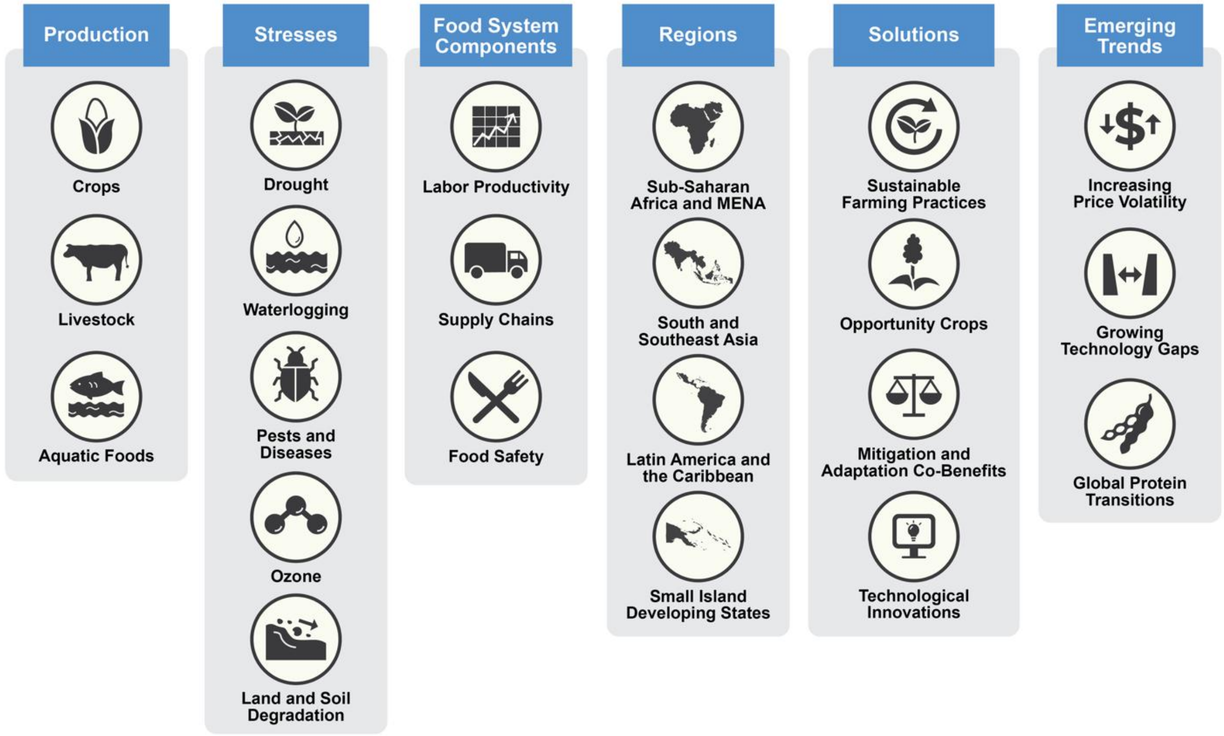

Fig. 1. Key update topics in climate change and food systems.

1) Likely Impacts of Climate Change on Global Food Systems to Mid-Century and Beyond

Production

Crops

Staple Crops

At the global scale, the multi-model ensemble approach is identifying and elucidating a wider range of threats to crop growth and production. The AgMIP community has undertaken concerted efforts to improve the representation of heat, drought, and irrigation limitations, as well as to utilize machine learning to explore factors that are not sufficiently represented in current crop models (e.g., impact of weeds; behavior of farmers; availability of labor) (Sweet et al., 2025). The roles of land/soil degradation and pests/diseases have also been further elucidated.

A recent analysis of the evolution of these impacts projected over the 21st century is largely consistent with the overall projected productivity of staple crops (i.e., maize, wheat, rice, and soybean) presented in AR6. Maize productivity declines at all warming levels studied (reaching -16% at 3.5°C). And while the productivity of C3 crops – which strongly benefit from CO_2 fertilization – generally increases with higher global warming levels, they all show signs of diminishing returns or reversal, with soy peaking at 2.5°C (+10%) and rice peaking at 3°C (9%) (Ruane et al., 2024). The study shows that there is uncertainty on when these global warming levels will occur ranging from 2018–2041 for 1.5°C, 2030–2058 for 2.0°C, 2046–2082 for 3.0°C, and 2061–2082 for 4.0°C (simulations with lower transient climate response reach 4.0°C after 2100). The focus on non-linear results reveals that stakeholders may be potentially misled by early century increases in some regions that may give way to decreasing yield at higher global warming levels. This non-linear risk of complacency issue has mainly been found in mid-latitude regions to date, although this peak-decline pattern is also seen in broad areas of Pakistan, Northern India, and Ethiopia.

Fruits and Vegetables

Projected climate change poses substantial risks to fruit production, particularly in temperate and mid-latitude regions where it depends on well-defined cold and warm seasons. Key climate impact drivers are rising temperatures, irregular precipitation, prolonged drought, and reduced winter chill (Osorio-Marín et al., 2024). These are expected to disrupt phenology, reduce land suitability, and undermine production stability. In tropical regions, intensified rainfall and flooding further threaten crop quality and increase socioeconomic volatility (Osorio-Marín et al., 2024).

Vegetables face similarly significant challenges. However, a large proportion of research papers studying climate change impacts on vegetable crops come from the United States, India, China, England and Germany, with little information published in Africa and Latin America (Dumitru et al., 2023). These studies show that climate change in these regions is reducing yield stability, increasing heat and drought stress, and altering key physiological processes such as vernalization and winter chilling, while also elevating microbiological safety risks by enabling pathogens to persist longer in soils, water, and crops (Dumitru et al., 2023). Research indicates that extreme temperatures can sharply reduce germination and survival in crops like arugula, and that many areas currently favorable for open-field tomato cultivation may become unsuitable in the future, collectively underscoring the vulnerability of horticultural systems to warming trends.

One modeling study in Africa with tomato, okra, african eggplant, and amaranth shows that all of them are vulnerable to climate change (Guarin et al., 2025). None of the vegetables simulated show an average yield increase, with larger losses under a high-emissions scenario. Okra is projected to experience the smallest losses when using a low-emissions scenario, and African eggplant is projected to have the smallest losses in a high-emissions scenario. Tomato shows mixed results in East Africa, but none of the other vegetables see notable benefit in any particular region. This may indicate a dependency on irrigation and/or indoor horticulture to supplement vegetable production in the coming decades.

Livestock

As rising global demand for animal-source foods intensifies pressure on production, projected climate change will continue to pose significant challenges to livestock systems. Heat stress reduces animal performance, productivity, meat quality, and shelf life, with cattle in colder climates especially vulnerable to rising temperatures in contrast to the relative thermo-tolerance of tropical breeds (Wankar et al., 2024). Compounding these risks, beef production requires substantial land, water, and feed resources and generates a high carbon footprint, making it increasingly difficult to maintain efficiency and sustainability as natural resources are depleted and greenhouse gas concentrations rise. Assessments of temperature variation, cattle populations, land use, methane emissions, and market value consistently indicate that sustaining beef production under climate change will require careful management of herd health and more efficient resource use.

Climate change also threatens rangeland and pasture systems by altering precipitation regimes, increasing temperature variability, and intensifying extreme events, all of which degrade forage quantity and nutritional quality and drive nutritional stress in grazing animals (Muzzo et al., 2024). These disruptions necessitate adaptive strategies such as genetic selection, epigenetic tools, and management innovations to build livestock resilience. Technologies – such as remote sensing and GIS to identify high-quality forage zones, and GPS-enabled collars to monitor cattle behavior — can support more precise nutrition and heat stress management. Additionally, establishing islands of functional plant diversity can enhance forage quality, lower carbon and nitrogen footprints, and improve overall animal welfare and productivity (Muzzo et al., 2024). Collectively, such approaches offer a pathway to sustaining livestock production and contributing to global food security in a warming world.

Aquatic Foods

Aquatic foods— composed of fish, invertebrates and algae captured or cultured in freshwater and marine ecosystems— provide an important source of high-quality protein and micronutrients for billions (Golden et al., 2021; Karl et al., 2024), while directly sustaining livelihoods for hundreds of millions (Virdin et al., 2023). Climate change is altering the pH, oxygen levels, ocean temperature, precipitation patterns and the frequency and intensity of storms, causing significant changes in species distribution, ecological disruption, and projected declines in the productivity of fisheries and aquaculture systems across the globe (Irfan et al., 2025).

A modeling assessment of impacts on marine fisheries by mid-century classifies projected hazards (e.g., ocean acidification, storms and cyclones, and changes in water temperature and circulation) as "high" across most of tropical Africa, Central America, and Southeast Asia, and project "very high" hazards for freshwater fisheries in water-stressed areas such as North Africa and the Middle East (Tigchelaar et al., 2021). Recent global modeling from the Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP) shows there is high confidence in projections of widespread declines in fish biomass production globally (>90% model agreement on declining projections for most affected countries), with medium confidence in the magnitude of change owing to the exclusion of fishing dynamics and management adaptation in the models. Productivity declines are projected to significantly impact nations heavily dependent on aquatic protein sources (e.g., Solomon Islands, Micronesia, and Portugal) as well as major aquatic food producers (e.g., China and Peru) (Blanchard & Novaglio, 2024).

Stresses

Drought

A recent modeling study found that while global production losses for maize, soybean, rice, and wheat due to drought are projected to remain relatively low (averaging under 2%) by 2050, these figures mask significant regional vulnerabilities where some countries could face losses exceeding 20% (Kraklow et al., 2025). By integrating socio-economic factors into a food insecurity index, the research highlights high-risk zones in South America, Africa, Eastern Europe, and Southeast Asia, emphasizing an urgent need for localized adaptation strategies. However, the authors note that these findings are subject to several layers of uncertainty, including limitations in how the model simulates grain carbon, the specific climate forcing data used, and the inherent structural design of the crop model itself.

Waterlogging

At the same time, water dynamics further amplify climate-related risks to crop production. Extreme rainfall and poor drainage increasingly lead to waterlogging, which restricts root oxygen supply, reduces nutrient availability, and can cause complete crop failure in low-lying and irrigated systems. Global modeling efforts reveal that waterlogging is currently underrepresented in crop models, leading to underestimated risks in future yield projections (Garcia-Vila et al., 2025; Liu et al., 2023; Nóia Júnior et al., 2023).

Pests and Diseases

Climate change is profoundly reshaping insect pest biology and ecology, with major implications for global food security. There is high confidence that insect pests, which are tightly coupled to climatic conditions, are expanding their geographic ranges, shifting their seasonal timing, and increasing the number of generations per year, all of which heighten crop damage and threaten yields across all continents (Ma et al., 2025; Subedi et al., 2023). For example, an increase in the *Agrotis ipsilon* moth's migration range has been tied to higher temperatures in China, while outbreaks of desert locust (*Schistocerca gregaria*) have been attributed to changes in rainfall patterns in East Africa (Subedi et al., 2023). Under 2°C of warming, pest-related yield losses are projected to grow for wheat, rice, and maize, with pests at mid–high latitudes responding most strongly to warming (Ma et al., 2025).

Climate extremes further shape pest impacts: moderate drought can intensify feeding pressure, while increased rainfall may wash away small pests but generally favors pest survival by reducing thermal and moisture stress. Land-use change, including deforestation and agricultural expansion, amplifies warming and decreases biodiversity, increasing pest outbreaks, while agricultural intensification (e.g., irrigation, fertilization) can inadvertently boost pest proliferation by improving host plant quality (Ma et al., 2025). In light of these trends, advancing pest monitoring technologies, predictive tools, and sustainable management strategies is essential to safeguard crop production (Subedi et al., 2023).

Tropospheric Ozone

In new much-needed agricultural modeling development, AgMIP uses Global Climate Model (GCM) projections, including O3 outputs, as inputs into crop models with O3 stress functionality to simulate climate- and O3-induced agricultural productivity losses. Elevated tropospheric ozone (O_3) concentrations are projected to cause significant yield declines in major staple crops by damaging leaf tissue and reducing photosynthetic capacity (Guarin et al., 2024). Future O3 concentrations are closely tied to the emissions of its precursors — CH_4, NO_x, carbon monoxide (CO), and volatile organic compounds (VOCs) — which are projected to continue to increase if not mitigated, i.e., following the shared socioeconomic pathways where increased regional conflict and limited global cooperation lead to doubling of CO_2 emissions and sustained CH_4 growth by 2100 (SSP3-7.0) or where fossil-fuel enabled growth leads to doubling of CO_2 emissions and a sharp rise in CH_4 by 2050 (SSP5-8.5) (Meinshausen et al., 2020).

Land/Soil Degradation

Climate change is expected to lead to increased soil erosion in many locations worldwide affecting ecosystem services and human well-being. Through a systematic review of 224 modeling studies, a recent global assessment of the impact of climate change on soil erosion shows a global increasing trend in soil erosion towards the end of the 21st century, with the highest increase projected in semi-arid regions (Eekhout & de Vente, 2022). Land use change characterized by agricultural expansion and deforestation aggravate the impact. Reforestation, agricultural land abandonment, and soil conservation practices can compensate for the impact of climate change on soil erosion, highlighting the need for soil conservation efforts and integrated land use planning.

Labor Productivity

Modeling is also tackling social impacts, especially in the realm of farm labor. Rising temperatures and humidity are projected to negatively affect human labor productivity in agriculture globally due to heat stress, which could limit working hours during key planting and harvest periods and reduce incomes (Fig. 2). Southeast Asia and Africa are projected to be impacted the most, followed by South Asia and Latin America. These physiological constraints on farm labor would compound production losses, particularly in tropical regions, where outdoor agricultural work is essential for food and income security (Orlov et al., 2024).

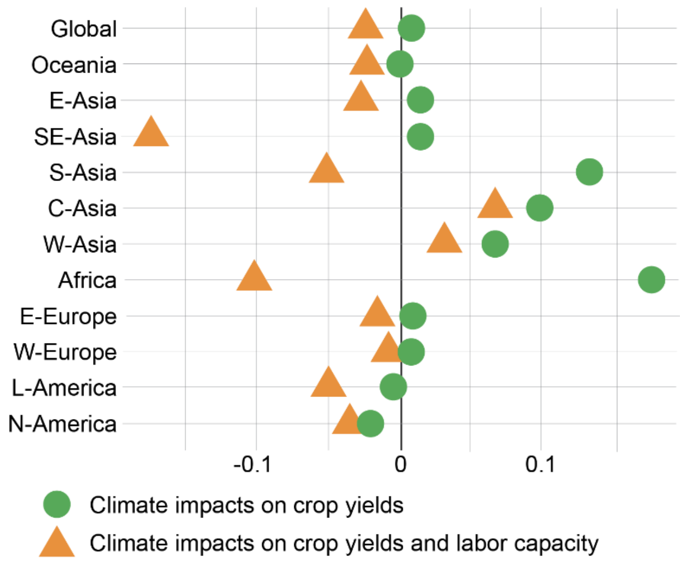

Fig. 2. Impacts on farmers income with and without heat stress effects on labor productivity. Median responses of the real income at the end (2071–2100) of the century under RCP7.0 relative to the historical time period. The income responses are simulated using the GRACE model and show the median changes across GCMs, crop models, and heat-labor exposure-response functions (ERFs). The circles in shades of green labeled ‘‘Climate impacts on crop yields’’ show the scenarios that only consider the climate-related yield responses of the four crops. The triangles in shades of orange labeled ‘‘Climate impacts on crop yields AND labour capacity’’ show the scenarios that consider both yield changes and heat-stress impacts on labor of the four crops (maize, wheat, soybean, rice) (Orlov et al., 2024). Reproduced in accordance with CC BY 4.0 license and permission from lead author.

Supply Chains

Supply chains in the coming decades are likely to be disrupted due to increasing frequency, duration, and intensity of extreme events. From coastal and inland flooding that can cause issues for food transportation to heat waves affecting cold chain efficiency and thus energy demand. However, recent studies find that, while research on the impact of extreme weather on crop yields is considerable, there has been much less work on connecting those impacts to supply chain disruptions (Mehrabi et al., 2022). This is an area for model development, including compounding and cascading risks and impacts (e.g., concurrent climate-related hazards across multiple breadbaskets), that needs to be more extensively assessed.

Food Safety

Climate change poses increasing threats to food safety throughout processing, storage, and distribution systems, with particular concern for mycotoxin contamination as well as pathogen proliferation, particularly in regions with limited cold-chain infrastructure (Misiou & Koutsoumanis, 2022). While there have been advances in the development of weather-based predictive models for mycotoxin contamination since AR6 (Kim et al., 2024), there are relatively few modeling studies that project climate change impacts on mycotoxin production or food pathogenicity owing to the complex interactions between environmental variables, microbial ecology, and food systems, as well as the limited availability of comprehensive data across diverse geographic regions and food distribution systems (Awad et al., 2024).

2) Likely Impacts of Climate Change on Most Vulnerable Regional Food Systems to Mid-Century and Beyond

In general, literature since AR6 shows that the regions whose food systems are most vulnerable to climate change remain the same. AR6 found that climate change is already undermining food and water security across multiple world regions, with the most acute impacts observed in Africa, Asia, Latin America, and Small Island Developing States (SIDS) (Calvin et al., 2023; Jägermeyr et al., 2021) (Fig. 3). Flood- and drought-driven food insecurity and malnutrition continue to rise in Africa and Latin America, and risks are projected to worsen substantially at 2°C of global warming or higher, leading to greater malnutrition and micronutrient deficiencies particularly in Sub-Saharan Africa, South Asia, Latin America, and SIDS.

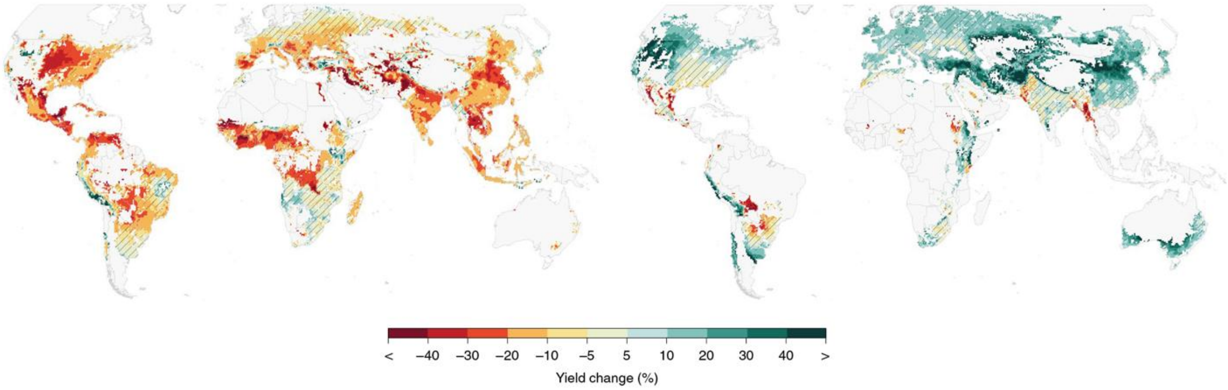

Fig. 3. Maps showing median yield changes (2069–2099) for maize (left) and wheat (right) under SSP585 across climate and crop models for current growing regions (>10 ha). Hatching indicates areas where <70% of the climate–crop model combinations agree on the sign of impact (Jägermeyr et al., 2021)**.** Reproduced with permission from lead author and journal.

Many communities — including smallholder farmers in Africa, Asia, Latin America, and low-lying coastal populations in SIDS — have reached “soft limits” to adaptation (i.e., adaptation options may be available but are currently not feasible). These limits are largely driven by financial, governance, institutional, and policy constraints; inequity and poverty further restrict adaptive capacity, creating disproportionate climate impacts for the most vulnerable groups (Calvin et al., 2023).

In accordance with the AR6 results, regions in the Global South are being much more comprehensively studied than previously, utilizing integrated modeling approaches that join physical, biophysical (crops and livestock), and socioeconomic analyses. Alarms continue to be raised about the threats that climate change poses to agricultural regions, both because these regions are more prone to climatic changes and impacts and because of socioeconomic factors including income and development levels. Areas of particular vulnerability that recent studies have focused on include Sub-Saharan Africa, the Middle East and North Africa (MENA) region, South and Southeast Asia, Latin America and the Caribbean, and Small Island Developing States.

Regions

Sub-Saharan Africa and MENA

Climate change poses profound risks to agricultural systems across Africa, where recent studies, including those using AgMIP’s Regional Integrated Assessment methodology, show that rising temperatures, rainfall variability, and more frequent extreme events will strain productivity and food security (Rosenzweig et al., 2021).

Sub-Saharan Africa. Maize is one of the most widely cultivated crops in Africa, yet its productivity is projected to decrease in most cultivated areas of Africa compared with the other cereals (Fig. 4). Maize yield losses are driven by shortened growing seasons (average of 7 and 10 days shorter under SSP1-2.6 and SSP3-7.0, respectively, in 2035-2064 compared with 1990-2019) and a low maximum temperature threshold, resulting in high temperatures causing heat stress during the reproductive period (Guarin et al., 2025).

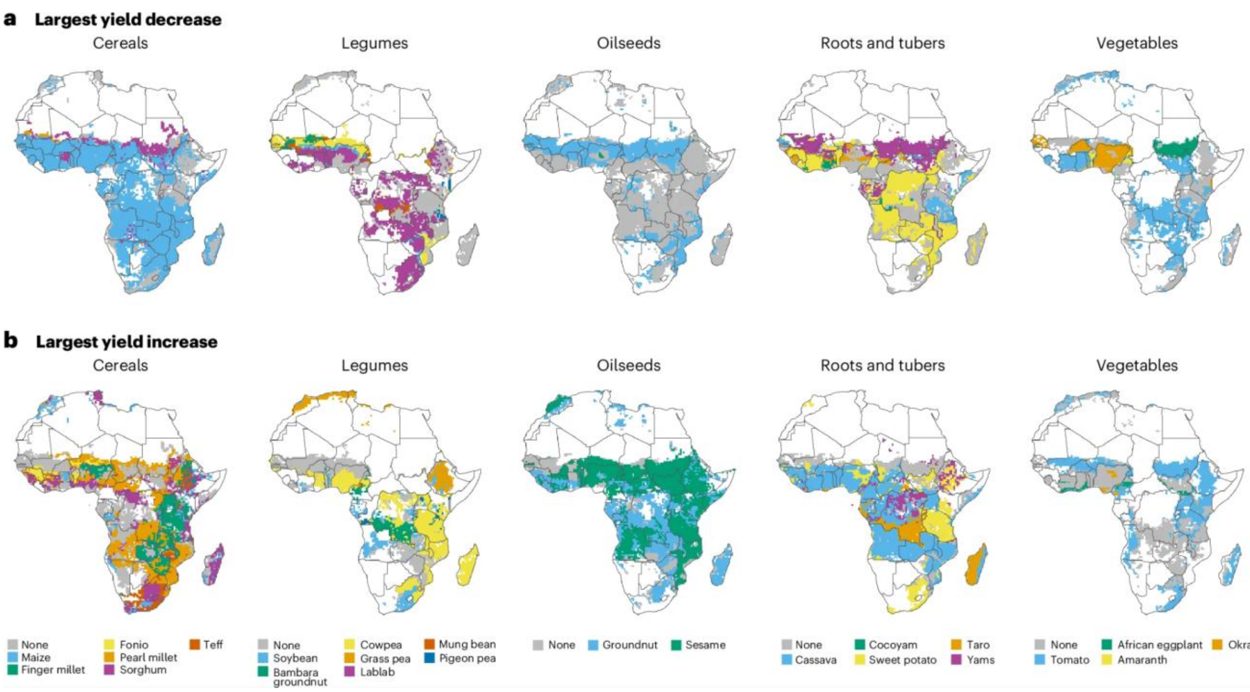

Fig. 4. Impacts of climate change on opportunity crops. Maps showing the cereals, legumes, oilseeds, roots and tubers, and vegetables with the largest simulated average yield decrease (a) and increase (b) compared with the other crops within each crop type for each grid cell under the high-emissions scenario SSP3-7.0. Simulations are based on the current harvest areas of each crop, thus not every crop is simulated in each grid cell. 'None' indicates that none of the simulated crops showed a yield decrease or increase in that grid cell. The benchmark crop for each group is in blue. Interactive versions of these maps for all crop types are available online at https://vacs.theplotline.org/ (Guarin et al., 2025). Reproduced with permission from lead author and journal.

Another recent study evaluated the impact of varying CO_2 concentrations, temperature and rainfall conditions on maize yield, for different nitrogen (N) inputs (0, 80, 160 kg N/ha) for five environments in SSA, including cool subhumid Ethiopia, cool semi-arid Rwanda, hot subhumid Ghana and hot semi-arid Mali and Benin using an ensemble of 25 maize models. The model intercomparison revealed that simulation of daily soil N supply and N leaching plays a crucial role in simulating climate change impacts for low-input systems. Climate change and N input interactions have strong implications for the design of robust adaptation approaches across SSA, because the impact of climate change in low input systems will be modified if farmers intensify maize production with balanced nutrient management (Falconnier et al., 2020).

Other recent modeling studies highlight substantial mid-century climate risks to East African staple crop (wheat and maize) production, with Ethiopia and Kenya facing significant but regionally differentiated impacts. In Ethiopia, a 48-member multi-crop model ensemble driven by ten downscaled climate projections indicates that wheat yields are highly sensitive to rising CO_2, temperature, and nitrogen constraints. Wheat results show a projected 36–40% decline by 2050, while maize shows more modest impacts. Uncertainty in the results is dominated by differences in crop growth and soil water-dynamics representations (Rettie et al., 2022). In Kenya, simulations using the calibrated DSSAT-CERES-Maize model project maize yield losses of 7–20% by mid-century and 22–41% by end-century under Representative Concentration Pathways (RCPs) 4.5 and 8.5, with warming during critical growth stages driving most of the decline; spatial hotspot analyses underscore the need for targeted adaptation measures such as maize–legume intercropping, drought-tolerant cultivars, soil water conservation, and optimized sowing (Kipkulei et al., 2025).

In West Africa's rainfed systems, climate change is expected to intensify weather variability, reduce yields, and heighten soil fertility challenges. Process-based crop models remain essential tools for projecting impacts and evaluating management responses. However, their effectiveness is constrained by limited soil, crop, and climate observational data availability and modeling gaps related to local farming realities, such as pests and diseases (Diancoumba et al., 2023).

MENA. Wheat production in the Mediterranean and MENA regions is highly vulnerable to climate change, with declining rainfall, rising temperatures, and soil degradation driving substantial yield losses. A recent modeling study projects regional wheat yield declines of 18–20% by 2040, 27–28% by 2070, and up to 28–30% by 2099 under RCP 4.5 and 8.5, with arid zones such as North Sinai (Egypt) and the Zagros region (Iran) experiencing extreme reductions of 60–88% also under late-century RCPs 4.5 and 8.5. In response to these projected impacts, targeted agronomic measures—including supplemental irrigation, optimized nitrogen inputs, and early-November sowing—were shown to boost yields by 30–50% and improve water productivity (Tita et al., 2025). In Morocco, provincial-scale projections using an advanced stacked machine-learning ensemble similarly show declines of about 10% by 2040 under SSP2-4.5 and up to 60% under high-emission SSP5-8.5, with maximum temperature identified as the dominant driver of yield loss, reinforcing the need for climate-informed agricultural planning across North Africa (Eddamiri et al., 2024).

South and Southeast Asia

South Asia. Rice-wheat systems, essential for food security in India and Pakistan, are projected to experience considerable yield losses under mid-century (2040-2069) climate conditions. The AgMIP climate analysis showed a range of ~2-3°C temperature increase under RCP 8.5, and a range of 100-200 mm increase in annual rainfall with potential for increased rainfall variability.

An example is the AgMIP Regional Integrated Assessments from Pakistan and India show consistent declines across models with both rice and wheat yields projected to decrease between 6-30%, depending on crop model and climate scenario. When isolating climate change effects on future rice–wheat production, mid-century projections show that a majority of farmers (57-71%) could experience income losses due to yield reductions. Given that rice-wheat systems occupy 13.5 million hectares of South Asia (Tiwari et al., 2022) yet show stagnant productivity, climate change is expected to further erode food security without widespread adoption of climate-smart management, improved varieties, and more resilient water and nutrient strategies (Ahmed et al., 2024).

Southeast Asia. Climate change is projected to significantly stress rice-based systems across Southeast Asia by mid-century with some studies estimating losses of 10% or more, primarily due to higher temperatures, variable water availability, and other stressors affected by climate (e.g., pests and diseases) (Li et al., 2024).

In the Mekong Delta in Vietnam, soybean systems also face mounting climate pressures. Experiments modeled with the SIMPLE crop model show that drought stress — already a growing concern in the region — substantially reduces biomass accumulation and yield, with more severe impacts observed in seasons with lower rainfall (Pham et al., 2023). Higher temperatures further shorten the biomass development period, contributing to yield declines. Elevated CO_2 concentrations can partially offset these losses by increasing biomass and yields, but this benefit does not negate the damaging influence of increasing heat and water stress expected by mid-century. The results highlight soybean's vulnerability to climate variability and the importance of improved water management and climate-resilient varieties.

Latin America and the Caribbean

Latin America and the Caribbean dedicate about 38% of available land to agriculture, with major global contributions in soybeans, corn, cotton, sugar, beef, and poultry; and the region is expected to remain the world's largest soybean producer in the coming decade (Marin et al., 2023). But climate change — through rising temperatures, shifting rainfall, and more frequent extreme events — is projected to reduce production of key staple crops. Modeling studies point to a range of adaptation strategies, including drought- and heat-tolerant crop varieties, adjusted sowing dates, crop rotation, integrated crop–livestock systems, and conservation of forests and water resources (Marin et al., 2023).

Additionally, a study that utilized global climate projections to model soil erosion in continental South America showed that the region can experience significant changes in soil erosion caused by water in the coming years due to changes in the precipitation spatial and temporal patterns, threatening food security and biodiversity and impairing agroecosystems to provide services (Riquetti et al., 2023).

Another modeling study projects that marine heatwaves in the Mesoamerican and Caribbean regions, once rare, will become pervasive and consistent by the 2040s under high emissions scenarios (SSP5-8.5), and by the 2050s under an intermediate scenario (SSP 2-4.5), with potentially significant consequences for populations that rely on aquatic foods as a key source of nutrition and livelihoods (Phillips et al., 2025).

Increased investment in agricultural and food modeling is needed to improve understanding of climate impacts and design targeted, region-specific solutions.

Small Island Developing States (SIDS)

Small Island Developing States (SIDS) are among the world's most climate-vulnerable regions, facing escalating risks from sea-level rise and coastal extremes. A global assessment of future coastal flood risk shows that, without adaptation, direct economic damages could increase more than fourteenfold by the end of the century under high-emissions scenarios, while limiting warming to 1.5°C could avoid nearly half of these losses. Even with stringent mitigation, several SIDS are projected to experience damages amounting to substantial shares of national GDP, potentially triggering population displacement from low-lying areas. These findings reinforce the urgency of targeted adaptation investments and support for managing loss and damage in SIDS (Vousdoukas et al., 2023).

Sustainable development in small island states is further complicated by limited resources, environmental sensitivity, and competing land-use pressures. Using a combination of participatory Bayesian networks, land-use modelling, and impact assessment, scenario analysis for Curaçao demonstrates that well-designed zoning regulations can constrain coastal sprawl, reduce loss of rare vegetation by roughly one-third, and lower nutrient runoff by up to 22% compared with unregulated development. In contrast, unconstrained growth yields the greatest environmental harm per unit of economic gain. This research provides decision makers with actionable evidence on how spatial planning choices shape environmental and socio-economic outcomes, supporting more resilient development pathways under uncertainty (Steward et al., 2025).

Solutions

3) What Solutions Best Enhance Resilience and/or Reduce GHG Emissions?

Modeling studies, as well as numerous programs and conferences, are focusing more concertedly on advancing solutions that will enhance resilience and reduce GHG emissions in agricultural regions around the world[2]. These studies are providing evidence of good practices of "co-creation" of solutions with regional stakeholders and highlighting technological innovations that will serve to enhance resilience in the regions.

By examining the evolution of crop impacts as the world warms, a recent study identified several regional agricultural farming systems as being particularly challenged due to projected early century yield increases that switch to yield losses at higher warming levels (Ruane et al., 2024). These regions, where proactive adaptation efforts may be misled by early indications of climate benefits, include maize areas in the US Upper Midwest and portions of Europe and East Africa, wheat areas in Canada and South Asia, and rice in Pakistan.

The AgMIP Regional Integrated Assessment (RIA) methodology is a coordinated, multi-scale framework that evaluates climate change impacts and adaptation options for agriculture by integrating climate models, multi-model crop and livestock simulations, regional economic analysis, and stakeholder guidance (Rosenzweig et al., 2021). RIAs begin with participatory scoping to identify vulnerable systems and feasible adaptations, followed by the use of

[2]For example, see the Climate Adaptation and Resilience (CLARE) program; World Adaptation Science Program (WASP); Adaptation Futures Conference; UNFCCC; Adaptation Research Alliance; Global Research Alliance for Agricultural Greenhouse Gases.

harmonized, bias-corrected climate projections and ensembles of process-based biophysical models to quantify future yield, resource, and production outcomes.

Sustainable farming practices

Modeling studies are increasingly demonstrating capabilities to model sustainable farming practices, indicating that packages of adaptation and mitigation are more beneficial than isolated practices. The use of no-till and cover crops on corn and soybean rotations has been tested in a multi-model ensemble across the U.S. Mid-West, leading to better estimates of the impacts of the practices on soil organic carbon (Basso et al., 2025) (Fig. 5). The results show that adopting no-till combined with cover crops would increase SOC stocks by 0.36 ± 0.12 Mg ha-1 yr-1 aggregated across the entire U.S. Midwest cropland. At the regional scale, this corresponds to a net SOC gain of 16.4 Tg C yr-1 compared to business-as-usual baselines. These benefits are approximately halved when each management change is practiced individually, and the modest gains are only fully realized when continued over the long-term in soils with low initial carbon stock.

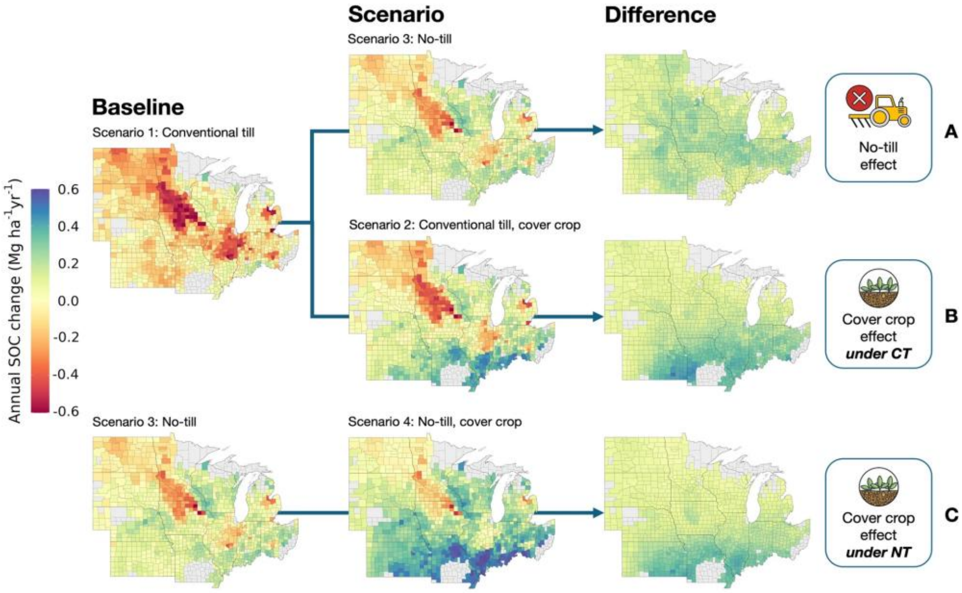

Fig. 5. Multi-model ensemble (MME) testing of sustainable practices in the US Midwest. MME mean annual soil organic carbon (SOC) change rates across scenarios based on different soil textures and initial SOC stock levels across 46 M ha. Annual SOC change (Mg ha-1 yr-1, 0-30 cm) across scenarios (1 to 4, from left to right), soil texture (Sandy, Loam and Clay), and initial SOC stock level (Low, < 40 Mg C ha-1; Medium, 40-80 Mg C ha-1; and High, > 80 Mg C ha-1). Annual SOC change values derived from all unique identifiers (UIDs) mean across the US Midwest cropland (each grid represents an individual simulation-based unit). All scenarios use maize-soybean crop rotation (Basso et al., 2025). Reproduced in accordance with CC BY-NC-ND 4.0 license and permission from lead author.

In another study, two soil-crop models, DayCent and STICS, were used to test crop yields and SOC dynamics, a critical measure for sustainability, in SSA under contrasting organic resource amendments (Couëdel et al., 2026). Both models represented SOC and yield dynamics with similar accuracy across sites and treatments. They reproduced SOC dynamics well (Normalized Root Mean Square Error below 30%) in the two clayey soils sites but not in the two sandy soils. In most sites they reproduced SOC differences between high (Farmyard manure, Thithonia and Calliandra) and low-quality (maize stover and sawdust) organic resources. They reproduced the positive effects of high-quality organic resources and the addition of mineral N on maize yield well. Collecting detailed plant (leaf area index, plant N uptake) and soil (water, nitrogen dynamics) in-season data from long-term experiments will be critical to improve their accuracy for tropical conditions.

Opportunity Crops

The foundational research for the Vision for Adapted Crops and Soils assessed "opportunity crops"[3] in both Sub-Saharan and North Africa across the full food basket for multiple indicators (MacCarthy et al., 2026). Recent modeling work conducted by AgMIP compared the productivity of 19 opportunity crops, including for many which no prominent process-based crop model previously existed, against five reference crops into the 2050s, and projected that many underutilized species are significantly more climate-resilient than staples such as maize and soy in Sub-Saharan Africa. Over half of the opportunity crops analyzed exhibited average yield increases under the SSP3-7.0 scenario in the 2050s (2035-2064), with teff, grass pea, sesame, and cassava projected to be among the most resilient (Guarin et al., 2025). In contrast, of the five reference crops assessed (maize, soybean, groundnut, cassava, and tomato) all are projected to decline except cassava, primarily due to shortened growing seasons and heat stress during reproductive stages (Guarin et al., 2025; Yang et al., 2025).

Evidence from 22 countries in the Middle East and North Africa — which are among the world's most water-stressed environments — shows that opportunity crops such as sorghum and cowpea offer promising adaptation benefits due to their high-water productivity (up to 30% greater than major cereals) and strong heat tolerance, withstanding temperatures above 38-42°C (Devkota et al., 2025). Although cultivation areas have declined in recent years, these crops contribute substantially to dietary calories and provide more resilient food sources under

[3]Previously known as "orphan crops"or "underutilized or neglected species," these are indigenous food plant species characterized by high nutritional value, resilience to climate change, and viability in marginal environments.

hotter, drier future conditions. Expanding their use could play a critical role in safeguarding mid-century food and nutrition security in dryland regions.

Mitigation and Adaptation Co-Benefits

Rice is highly vulnerable to climate change, but at the same time, conventional flooded rice systems remain a major source of methane emissions (Li et al., 2024). Management options that enhance both mitigation and adaptation are therefore essential. Several studies have evaluated water-saving and low-emission rice management practices, Alternate Wetting and Drying (AWD) and System of Rice Intensification (SRI) (Li et al., 2024). Importantly, several SRI configurations reduce or avoid increases in methane emissions, indicating that well-targeted management strategies can support both adaptation and mitigation, even as rising temperatures and more variable rainfall negatively impact production. Another study compared SRI and AWD with continuous flooding across three districts in Bangladesh using an integrated climate-crop-economic modeling framework (Rosenzweig et al., 2026). Results of these studies demonstrate potential "win–win" outcomes for mitigation and adaptation and highlight the need to account for spatial and socioeconomic heterogeneity when assessing scaling potential across rice-farming populations (Fig. 6).

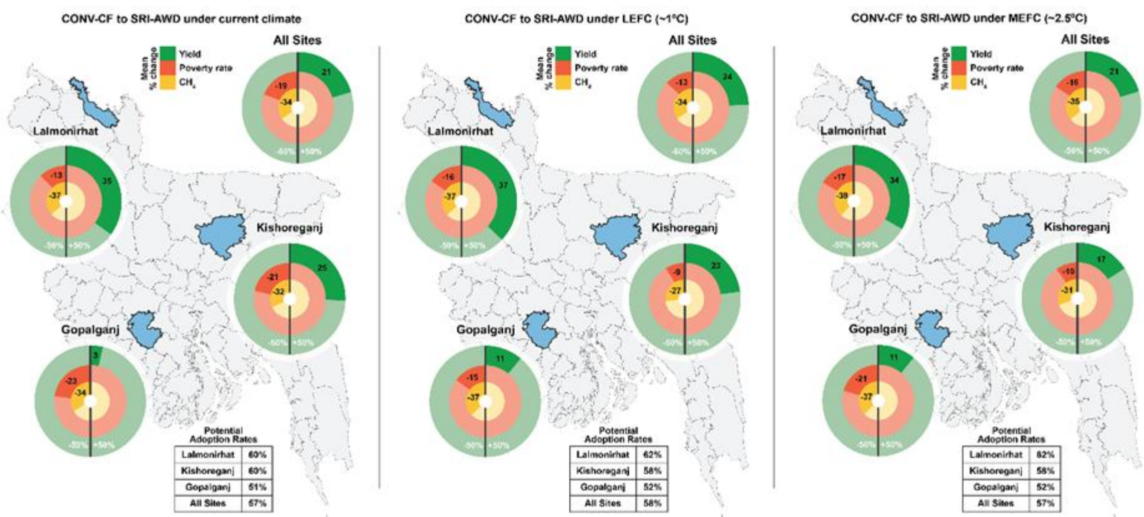

Fig. 6. Mitigation and adaptation co-benefits of sustainable rice intensification (SRI) and alternate wetting and drying (AWD) in Bangladesh. Adoption analysis: District-level impacts from switching from conventional to SRI with AWD under (a) Baseline climate; (b) Less Extreme Future Climate (LEFC) (SSP2-4.5); and (c) More Extreme Future Climate (MEFC) (based on range of projected temperature and precipitation from SSP2-4.5). Circle plots show mean % change in yield, poverty rate, and methane emissions. Tables show district-wise adoption rate (Rosenzweig et al., 2026). Reproduced in accordance with CC BY 4.0 license and permission from lead author.

A study in semi-arid Zimbabwe evaluated co-benefits and trade-offs between climate change adaptation and mitigation under three co-developed agricultural development pathways, Business as Usual, Unsustainable Development, and Sustainable Development, combined with three adaptation options and applied to heterogeneous smallholder systems (small, medium and large farms) (Homann-Kee Tui et al., 2023). The pathways and interventions were developed iteratively with stakeholders to reflect plausible future socio-economic, biophysical, institutional and market conditions.

The study found that while changes in crops to drought-tolerant varieties had limited impact on crop and livestock productivity, if at least half of the population adopted the measures, farm net returns were projected to increase by as much as 20%. However, the impact on the environmental footprint was low (with negligent changes in GHG emissions). Increasing land allocations to feed and fodder improved the quality and quantity of feed supply, e.g., by converting land into high-yielding Leucaena, was a way to further increase cattle productivity per tropical livestock unit and organic soil amendment. CH_4 emissions were reduced but N_2O emissions increased. Finally, shifting cattle to goats supported by a market incentive of 15% higher output price and increased offtake rates; this package was attractive to 81% of the farms and increased farm net returns by a range of 19–51%. Along with more substantial increases in incomes, the improved feed base reduced the herds' CH_4 from enteric fermentation emissions by around 5%, but it increased N_2O by 10–20%, and CO_2 emissions by 15–20%. The findings highlight a central policy trade-off in marginal regions: maximizing livelihood gains may increase emissions, while mitigation-oriented strategies yield smaller economic improvements.

Technological Innovations

Technological innovations in agricultural modeling will also be vital to improve projections of climate-related agricultural risks and therefore help stakeholders be better prepared to manage them. For example, in South Africa, integrating remote sensing data into process-based models through data assimilation can dramatically improve maize, wheat, and rice yield predictions and the ability to diagnose yield gaps. Implementation in small-scale contexts remains a challenge but an analysis of eight farms across the Eastern Cape in South Africa shows that integration of remote sensing-derived leaf area index using a recalibration-based data assimilation approach in maize can support efficient decision-making processes with respect to planting dates as well as irrigation and fertilizer application schedules, both for subnational farming regions and for national assessments (Dlamini et al., 2025).

Machine learning (ML) is also emerging as a critical technological innovation for improving projections of climate change impacts on agriculture and food systems because it can address long-standing limitations in traditional crop modeling (Sweet et al., 2025). ML techniques can capture complex, nonlinear interactions in crop growth that process-based models may miss, handle missing or noisy agricultural data, and generate high-resolution inputs such as soil properties, planting dates, and downscaled climate variables. They are already being used to forecast yields across scales, emulate computationally intensive crop models, and extract information from satellite imagery and text data, thereby reducing key sources of uncertainty in climate-impact assessments. By enhancing data quality, supporting model calibration, and complementing process-based approaches, machine learning strengthens the evidence base needed for robust, spatially explicit projections of future climate risks to agriculture—provided that the research community coordinates on shared datasets, benchmarks, and methodological standards (Sweet et al., 2025).

Emerging Trends

4) What Are the Emerging Trends in the Structure of Food Production and Processing?

Likely structural changes to agriculture, fishing, and food processing in the next few decades may include: economic changes (e.g., increasing commodity price volatility), technological advancement (e.g., increased adoption of precision agriculture), protein transitions, and new opportunities for food system decarbonization.

Increasing Price Volatility

Recent economic modeling has demonstrated that global crises such as COVID-19 and the Russia-Ukraine war, along with longer-standing trends in biofuel production and climate change, are increasing price volatility in agricultural markets in ways that are likely to persist for decades (Karkowska & Urjasz, 2024; Zolotnytska et al., 2025). In particular, the growing interconnectedness of energy and agricultural markets— driven by biofuel mandates, oil-ng dependent farm inputs, and the financial globalization of commodity markets—is likely to deepen in the coming decades as volatility transmission between markets becomes more direct (Karkowska & Urjasz, 2024).

During recent crises, market connectedness indices more than doubled, reaching 65% compared to 15–30% during stable periods (Karkowska & Urjasz, 2024). Projected biofuel expansion is likely to put sustained upward pressure on corn prices, with complex spillover effects for wheat through substitution dynamics and competition for acreage (Zolotnytska et al., 2025). These trends indicate that food price stability will become increasingly dependent on energy policy decisions in major biofuel-producing countries, and that price shocks will propagate more rapidly across food commodities and regions, amplifying food security risks for import-dependent and low-income populations who are most vulnerable to price spikes. Climate variability is poised to compound these dynamics, as temperature and precipitation anomalies will impact crop yields and biofuel feedstock supply simultaneously, creating correlated shocks across interconnected markets (Zolotnytska et al., 2025).

Growing Technology Gaps

The adoption of precision agriculture technologies, which have the potential to significantly improve environmental efficiency and farm profitability, will almost certainly accelerate over the coming decades. However, its benefits will be unevenly distributed across countries and farm production systems. Large-scale, mechanized farms in high-income countries — particularly grain and oilseed operations in the U.S., Australia, Canada, and Western Europe — will continue to adopt increasingly sophisticated technologies (e.g., GPS guidance, variable rate technology, robotics, machine vision), driving productivity gains and resource efficiencies that strengthen their competitive position in global markets (McFadden et al., 2024).

Meanwhile, small-scale farmers, who constitute the vast majority of agricultural producers worldwide, face compounding barriers: high upfront costs, lack of necessary infrastructure, limited technical support, aging farmer demographics, and a variety of social and cultural factors that impede adoption (John & Arul Leena Rose, 2024; Pandeya et al., 2025). Precision agriculture technologies that are being deployed in developing countries tend to be oriented around simpler tools (e.g., leaf color charts, tensiometers) rather than the data-driven systems that are transforming industrialized agriculture (Sharma et al., 2024). The result will likely be a widening technology gap that reshapes global agricultural competitiveness, as large operations in industrialized agricultural economies capture efficiency and productivity gains that remain out of reach for the smallholders who continue to produce a significant share of the global food supply.

Global Protein Transitions

Global protein production is undergoing a structural transformation that will reshape food systems over the coming decades (Karl et al., 2024). In 2022, aquaculture surpassed wild capture fisheries for the first time in history, producing roughly 94 million tons of farmed aquatic animals compared to 92 million tons from capture fisheries (FAO, 2024). This milestone reflects the increase in global demand for protein, which is projected to continue surging, driven primarily by rising incomes and consumption in middle-income countries (OECD & FAO, 2025). Daily per capita intake of meat, dairy, fish, and other animal products is expected to rise by 6% in middle-income countries over the coming decade, with India and Southeast Asia projected to account for 39% of global consumption growth by 2034 (OECD & FAO, 2025). Increases in protein demand are expected to drive an expansion of livestock production, aquaculture, and plant-based alternatives, intensifying pressure on land, water, and feed resources that are already under strain (Lumsden et al., 2024). Understanding the trajectory of these dietary transitions is essential for food systems modeling, as protein demand will substantially shape agricultural land use and the feasibility of emissions reduction pathways through mid-century.

Research Directions

5) What Are Significant Directions for Climate Change and Food Systems Research?

Nutrition

Integrating nutrition into studies of climate impacts on food has lagged, but there is now momentum for collaboration between climate and nutrition research communities to conduct modeling studies that are critical for development of robust adaptation measures (Fanzo et al., 2025). Changes in climate across a range of geographies have been modeled, projected, and observed showing detrimental associations with dietary and nutrition outcomes, particularly undernutrition. Long-term climate change and near-term extreme weather events have multiple negative effects on food security, diets, and nutrition via complex, multidirectional pathways through food, health, water, and social protection systems. Many undernourished populations are vulnerable due to a range of determinants challenging their ability to adapt to climate risks. However, measuring climate-attributable malnutrition impacts, especially among the most vulnerable populations, and embedding key relationships into climate/food assessment models remains challenging.

Food Systems Emissions Accounting and Mitigation

A critical frontier since AR6 involves comprehensive emissions accounting across the entire agrifood value chain, from the production of farm inputs through food processing, distribution, consumption and waste disposal (Tubiello et al., 2022). In particular, researchers have increasingly emphasized opportunities to account for and mitigate GHG emissions from food systems beyond the farm-gate (Karl et al., 2025). New opportunities for decarbonization include mitigating emissions from food cold chain energy use and fluorinated gases (1.32 Gt CO_2eq in 2021); non-renewable wood harvesting for biomass cooking (0.75 Gt CO_2eq in 2021) and food waste disposal (1.3 Gt CO_2. in 2019), primarily stemming from CH_4 emissions in landfills (Flammini et al., 2023, 2024; Tubiello et al., 2022). The food system activity-oriented accounting lens has heightened awareness of the magnitude and breadth of emissions stemming from across the entire food value chain, and points to entirely new intervention areas for actors looking to decarbonize food systems. Establishment of carbon markets in agriculture is another trend which (like the technology divide) risks shutting out smallholders in Africa while benefiting larger farmers in higher income countries.

Global Adaptation Pathways

The need for adaptation pathways representing a broad range of sectors for use in local, regional, and global climate change and agri-food assessments is a key research area in need of more attention. These pathways would provide structured, time-dependent strategies that link near-term actions to long-term sustainability objectives, guided by scenario frameworks such as the SSPs. The Global Adaptation Pathways initiative seeks to establish a conceptual and methodological foundation for this[4]. By embedding pathways within SSP worldviews, the initiative aims to ensure coherence between global trajectories and sector-specific adaptation planning. Within this effort, AgMIP is supporting the development of Global Adaptation Pathways for Agriculture and Agri-food Systems, focusing on how agricultural adaptation can be systematically integrated into global frameworks.

The overall goal is to establish a coordinated, protocol-based framework for developing Global Adaptation Pathways aligned with SSPs and Shared Policy Assumptions (SPAs) across sectors (health, water, agriculture and agri-food systems, coastal/marine). The GAP initiative is uniquely positioned to provide a coordinated and replicable framework capable of addressing dynamic adaptation, shocks, limits to adaptation (e.g., if an adaptation doesn't work anymore, what next?), and cross-sector interactions, advancing both the science and policy relevance of adaptation pathways at global and regional scales.

[4]As well as AgMIP, participating institutions include IIASA, University of Munich, Deltares, University Utrecht, Wageningen University, Oregon State University, World Vegetable Center, University of Washington, Victoria University of Wellington, FINSCAPES, University of Nottingham, and many others.

6) Conclusion

Multiple advances have been contributed by peer-reviewed modeling studies since the IPCC AR6 food system chapter. Recent climate change assessments have deepened understanding of impacts both on global food systems and vulnerable agricultural regions, as well as on promising actions for mitigation and adaptation, and their confluence. These climate change-related impacts and responses are occurring in conjunction with major emerging trends in the structure of food production and processing, especially increasing price volatility, growing technology gaps, and rising income-based protein consumption patterns. The new Global Adaptation Pathways effort now getting underway will provide important tools for evaluating implementation.

Finally, there is substantial evidence that increases in funding for agricultural research and development (R&D) result in improved productivity and more affordable food. A study analyzing agricultural R&D in the United States estimates that increasing investment by 7% per year between 2025−2035 would result in a nearly 18% improvement in US agricultural total factor productivity by 2050 and declining commodity prices (Baldos, 2023). A separate analysis of five decades of investment into the CGIAR for enhancing yields of staple food crops has returned benefits ten times over as more affordable food, reduced hunger rates, and less negative impacts on land from agriculture (Alston et al., 2020). The point here is that agricultural modeling needs to be deeply embedded in these and other agricultural research programs so that actions to respond to future climate change as well as to other stresses can be tested rigorously and at local, regional, national, and global scales.

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