Available online at www.agrifarming.org

DOI: http://dx.doi.org/10.18782/2582-7146.293

ISSN: 2582 – 7146

Current Research in
Agriculture and Farming

Curr. Rese. Agri. Far. (2025) 6(6), 46-53

Peer-Reviewed, Refereed, Open Access Journal

Review Article

Climate Change Impacts on Agriculture and Adaptive Mitigation Strategies

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Received: 21.10.2025 | Revised: 29.11.2025 | Accepted: 18.12.2025

ABSTRACT

Climate change poses one of the most significant threats to global agricultural productivity, food security, and rural livelihoods. Rising temperatures, altered precipitation patterns, increased frequency of extreme weather events, and elevated atmospheric CO_2 concentrations are profoundly reshaping agricultural systems worldwide. Research indicates that for every 1°C increase in global mean temperature, yields of major cereal crops such as wheat, maize, rice, and soybean decline by approximately 3–7% (Zhao et al., 2017). Developing nations, particularly in tropical and arid regions, face disproportionately severe consequences due to limited adaptive capacity. This review synthesizes current scientific evidence on climate change impacts on crop production, livestock, water resources, and soil health, while examining adaptive mitigation strategies including climate-smart agriculture, drought-resistant crop varieties, conservation tillage, agroforestry, precision farming, and carbon sequestration techniques. The integration of traditional knowledge with modern technological innovations emerges as essential for building resilient and sustainable agricultural systems.

Keywords: *Climate Change; Agricultural Productivity; Food Security; Climate-Smart Agriculture; Adaptive Mitigation Strategies.*

INTRODUCTION

Climate change has emerged as one of the most pressing global challenges of the twenty-first century, with agriculture standing at the intersection of both its causes and consequences. The Intergovernmental Panel on Climate Change (IPCC, 2023) reports that the global average surface temperature has risen by approximately 1.1°C above pre-industrial levels, with projections indicating further increases of 1.5–4.5°C by 2100 under varying emission scenarios.

Cite this article: Bhupnesh, Meena, N.K., Kumari, L., Kaaviya, A. V., & Kumari, A. (2025). Climate Change Impacts on Agriculture and Adaptive Mitigation Strategies, *Curr. Rese. Agri. Far.* 6(6), 46-53. doi: http://dx.doi.org/10.18782/2582-7146.293

Agriculture, which contributes approximately 10–12% of global greenhouse gas (GHG) emissions through enteric fermentation, manure management, rice cultivation, and synthetic fertilizer application, is both a significant contributor to and a victim of climate change (Smith et al., 2014). The agricultural sector sustains the livelihoods of over 2.5 billion people worldwide and is fundamental to achieving Sustainable Development Goals related to hunger, poverty, and environmental sustainability (FAO, 2023). The United Nations estimates that food production must increase by at least 60% by 2050 to feed a projected global population of 9.6 billion (Tilman et al., 2011). However, climate change threatens to undermine this imperative through declining crop yields, increased pest and disease incidence, water scarcity, and soil degradation.

A recent comprehensive analysis published in Nature found that warming will likely reduce global yields for all major crops except rice by 2050, with the probability of loss ranging from 0.701 for sorghum to 0.946 for wheat under high-emission scenarios, even after accounting for economic development and farmer adaptation (Jagermeyr et al., 2025). The World Resources Institute (WRI, 2024) reports that one-quarter of the world's crops are grown in areas facing highly stressed or unreliable water supplies, with 33% of rice, wheat, and maize production dependent on vulnerable water systems. These converging pressures necessitate an urgent and integrated approach combining adaptation and mitigation strategies to ensure agricultural sustainability and global food security.

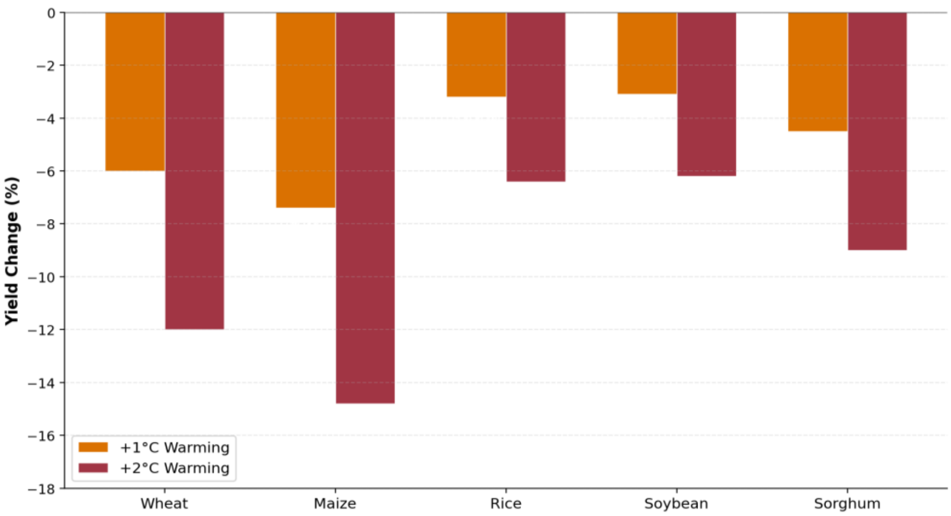
Figure 4: Contrasting agricultural landscapes under normal conditions (left) and climate change-induced drought stress (right)

2. Climate Change Impacts on Agriculture

2.1 Impact on Crop Production and Yields

Temperature is the dominant driver of projected crop yield changes globally. Research demonstrates that each 1°C increase in global mean temperature reduces global yields of wheat by approximately 6.0%, maize by 7.4%, rice by 3.2%, and soybean by 3.1% (Zhao et al., 2017). A large-scale meta-analysis by Challinor et al. (2014) further confirmed that average yields of C3 and C4 crops decrease by 4.9% per degree of warming. Critically, threshold effects amplify these losses at higher temperatures: wheat yields decline by 6.1% per degree when warming is below 2.38°C, but this increases to 8.2% per degree beyond that threshold (Nguyen et al., 2025).

Arid regions are anticipated to experience the most severe crop losses, while tropical zones face compounding challenges of heat stress, water scarcity, and increased pest pressure (Nguyen et al., 2025). Conversely, some northern latitudes may experience temporary yield benefits due to extended growing seasons and CO_2 fertilization effects; however, these gains are insufficient to offset global losses and are projected to diminish as temperatures continue to rise (Proctor et al., 2025).



Source: Adapted from Zhao et al. (2017) and IPCC AR6 (2023)

Figure 1: Projected crop yield changes (%) under +1°C and +2°C warming scenarios for major cereal crops (Adapted from Zhao et al., 2017; IPCC, 2023)

2.2 Impact on Water Resources and Irrigation

Agriculture accounts for approximately 70% of global freshwater withdrawals, making it the largest consumer of water resources worldwide (UN Water, 2024). Climate change is exacerbating water stress through altered precipitation patterns, accelerated glacier melting, declining groundwater tables, and increased evapotranspiration rates. The WRI (2024) reports that demand for irrigation water is projected to rise by 16% by 2050, driven partly by warming temperatures that increase crop water requirements.

In India, nearly 270 million metric tonnes of crop production—approximately 24% of the country's total—is grown in watersheds where water extraction exceeds natural replenishment rates (WRI, 2024). Northern India already loses up to one foot of groundwater annually, and this depletion may triple by 2080 as temperatures continue to warm. Furthermore, 40% more rainfed crops will face unreliable water supplies by 2050 compared to 2020, with the greatest increases occurring in India, the United States, Australia, Niger, and China (WRI, 2024). This growing tension between agricultural water demand and dwindling supplies threatens food security across all major producing regions.

2.3 Impact on Livestock and Fisheries

Livestock production is significantly affected by climate change through heat stress, reduced feed availability, altered disease vectors, and declining water quality (Thornton et al., 2022). Heat stress reduces reproductive efficiency, milk production, and growth rates in cattle, poultry, and swine. Rising temperatures also expand the geographical range of vector-borne diseases such as bluetongue virus, Rift Valley fever, and tick-borne infections, posing threats to animal health and productivity (Rojas-Downing et al., 2017).

In fisheries and aquaculture, rising ocean temperatures, ocean acidification, and altered hydrological cycles are disrupting fish distribution, breeding patterns, and aquaculture productivity (Barange et al., 2018). Projected impacts on agriculture and capture fisheries are expected to lower the availability and increase the cost of feed ingredients, such as fishmeal and fish oil, consequently raising aquaculture production costs and threatening the sustainability of small-scale producers (De Silva & Soto, 2009).

2.4 Impact on Soil Health and Biodiversity

Climate change accelerates soil degradation through increased erosion, salinization, nutrient depletion, and loss of soil organic carbon. The FAO (2025) highlights that agricultural expansion is responsible for nearly 90% of global deforestation, contributing to land degradation and carbon emissions. Elevated temperatures increase the decomposition rate of soil organic matter, reducing soil fertility and water-holding capacity (Lal, 2015). Simultaneously, changes in temperature and precipitation alter soil microbial communities, disrupting nutrient cycling processes essential for plant growth. The loss of agricultural biodiversity further reduces the resilience of farming systems to environmental shocks.

3. Greenhouse Gas Emissions from Agriculture

The agricultural sector is a major source of anthropogenic greenhouse gas emissions, contributing approximately 10–12% of global GHG emissions (IPCC, 2023). In the United States alone, agriculture accounted for approximately 0.6 billion metric tonnes of CO_2 equivalent emissions in 2024—about 10% of total national emissions and nearly half of all non-CO_2 emissions (CBO, 2025). The primary agricultural GHGs include nitrous oxide (N_2O) from crop fertilization and soil management, methane (CH_4) from enteric fermentation in ruminants and rice paddy cultivation, and carbon dioxide (CO_2) from fossil fuel use in farm machinery.

Crop production and livestock operations each account for approximately half of agricultural emissions. Cattle alone contribute about 35% of all agricultural GHG emissions, while crop fertilization represents the single largest source of nitrous oxide, a gas approximately 265 times more potent than CO_2 over a 100-year period (CBO, 2025). Projections indicate that agricultural emissions will continue to grow by approximately 0.25% per year over the next three decades without significant intervention (CBO, 2025).

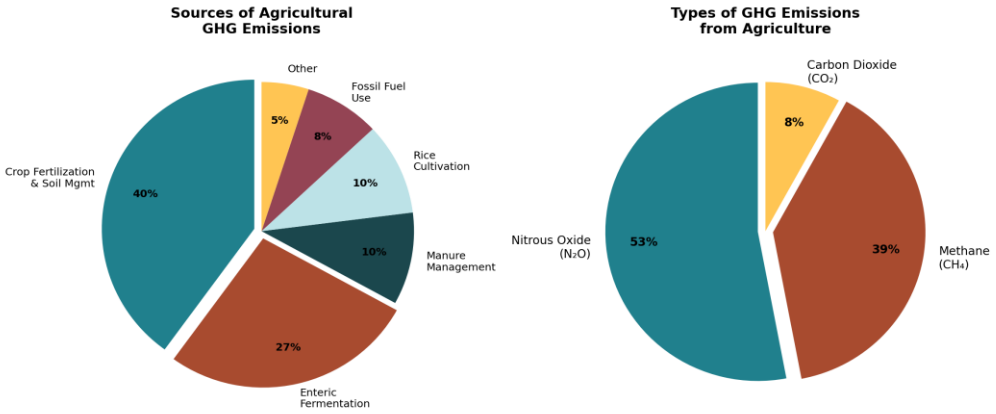
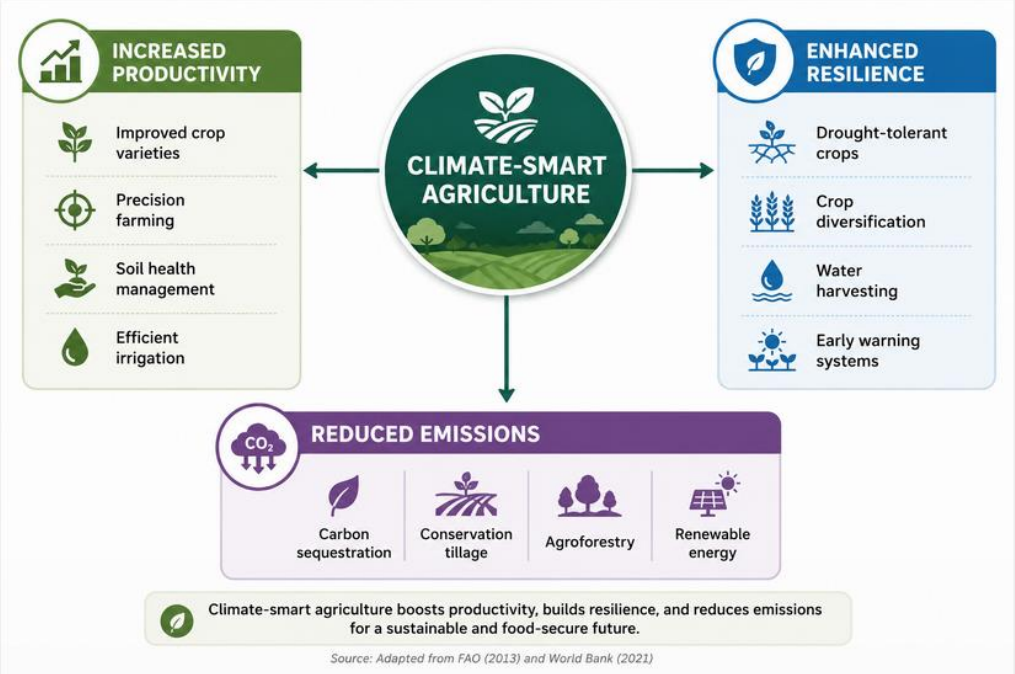


Figure 2: Agricultural greenhouse gas emissions by source and type (Adapted from IPCC, 2023; CBO, 2025)

4. Adaptive Mitigation Strategies

4.1 Climate-Smart Agriculture (CSA)

Climate-Smart Agriculture (CSA) is an integrated approach to managing agricultural landscapes—including cropland, livestock, forests, and fisheries—that addresses the interlinked challenges of food security and climate change (FAO, 2013). CSA simultaneously pursues three pillars: sustainably increasing agricultural productivity and incomes; building resilience and adaptive capacity to climate change; and reducing or removing greenhouse gas emissions where possible (World Bank, 2021). The World Bank has scaled up its investment in CSA significantly, increasing financing to nearly $3 billion annually since the adoption of the Paris Agreement.



Source: Adapted from FAO (2013) and World Bank (2021)

Figure 3: Climate-Smart Agriculture (CSA) integrated framework showing three pillars (Adapted from FAO, 2013; World Bank, 2021)

4.2 Development of Climate-Resilient Crop Varieties

The development of drought-tolerant, heat-resistant, and flood-adapted crop varieties through conventional breeding and modern biotechnology represents a cornerstone of agricultural adaptation. Crops such as pearl millet, sorghum, rye, amaranth, camelina, and quinoa are already contributing to food security in climate-vulnerable regions (Raza et al., 2024). Advanced genome sequencing, CRISPR-based gene editing, and high-throughput phenotyping have made it technically feasible to create climate-resilient cultivars with enhanced stress tolerance (Raza et al., 2024).

Notable innovations include Kernza, a perennial wheat-like cereal developed by the Land Institute in Kansas, which offers strong drought tolerance, reduces soil erosion, absorbs significantly more nitrate pollution than conventional crops, and requires fewer tillage operations (Nowell, 2022). Similarly, the Salk Institute is engineering plants with deeper root systems containing higher levels of suberin, a carbon-capturing polymer that enhances both carbon sequestration and drought tolerance. These innovations demonstrate the potential for breeding programmes to simultaneously address adaptation and mitigation objectives.

4.3 Conservation Tillage and Carbon Sequestration

Conservation tillage practices, including no-till and reduced tillage systems, play a critical role in both reducing emissions and sequestering atmospheric carbon in agricultural soils. Research demonstrates that transitioning from conventional tillage to no-till systems can increase soil carbon sequestration by 0.5–1.0 tonnes per hectare annually (Lal, 2015). Cover cropping further enhances carbon storage by providing continuous soil cover and additional organic matter inputs, while leguminous cover crops can fix 50–300 kg of nitrogen per hectare annually, reducing dependence on synthetic fertilizers (Kumar et al., 2023).

Agroforestry systems offer even greater carbon sequestration potential, with some systems storing 2–5 tonnes of carbon per hectare annually through integrated tree-crop-livestock management (Kumar et al., 2023). These practices collectively offer a pathway to transform agriculture from a net emitter to a significant carbon sink, while simultaneously improving soil health, water retention, and farm profitability.

4.4 Precision Agriculture and Technological Innovation

Precision agriculture leverages advanced technologies including Internet of Things (IoT) sensors, remote sensing, artificial intelligence, geographic information systems (GIS), and data analytics to optimize resource use efficiency and minimize environmental impacts (Basso and Antle, 2020). By enabling site-specific management of water, fertilizers, and pesticides, precision agriculture can reduce input costs by 15–20% while maintaining or improving yields (EEA, 2023).

IoT-based smart irrigation systems can significantly improve water use efficiency by delivering precise amounts of water based on real-time soil moisture, weather forecasts, and crop phenological stage (UNU, 2025). Satellite-based crop monitoring and predictive analytics enable early detection of drought stress, pest outbreaks, and nutrient deficiencies, allowing farmers to implement timely interventions. These technologies are particularly valuable in the context of climate adaptation, as they enable data-driven decision-making that accounts for increasing climate variability and uncertainty.

4.5 Integrated Water Management

Adaptive water management strategies are essential given the growing gap between agricultural water demand and supply. These include rainwater harvesting, micro-irrigation technologies (drip and sprinkler systems), constructed wetlands, and managed aquifer recharge programmes (Molden et al., 2010). Deficit irrigation strategies, which deliberately apply less water than the full crop requirement during drought-tolerant growth stages, can reduce water consumption by 20–40% with minimal yield penalties (Fereres & Soriano, 2007).

At the landscape level, integrated watershed management approaches that coordinate water allocation across agriculture, industry, and domestic use are critical for ensuring equitable and sustainable water access under climate change (WRI, 2024). Policy frameworks that incentivize efficient water use, invest in water infrastructure, and support farmer training in water management practices are essential components of a comprehensive adaptation strategy.

CONCLUSION

Climate change represents an existential threat to global agricultural systems, with cascading impacts on crop production, water resources, livestock, soil health, and ultimately food security for billions of people. The scientific evidence unequivocally demonstrates that rising temperatures will reduce yields of major staple crops by 3–8% per degree of warming, with arid and tropical regions bearing the most severe consequences. The agricultural sector's dual role as both a contributor to and victim of climate change necessitates a holistic approach that simultaneously addresses adaptation and mitigation.

Adaptive mitigation strategies, encompassing climate-smart agriculture, development of climate-resilient crop varieties, conservation tillage, carbon sequestration, precision agriculture, and integrated water management, offer viable pathways to build agricultural resilience while reducing greenhouse gas emissions. The integration of traditional ecological knowledge with modern technological innovations, supported by strong policy frameworks and international cooperation, is essential for achieving sustainable agricultural transformation.

Future research priorities should focus on refining climate projections at regional and local scales, developing crop varieties adapted to multiple simultaneous stresses, scaling precision agriculture technologies for smallholder farmers in developing countries, and establishing robust monitoring and evaluation systems for adaptation interventions. Achieving food security in a changing climate will require unprecedented collaboration among scientists, policymakers, farmers, and the private sector to implement evidence-based solutions at the pace and scale demanded by the crisis.

Acknowledgements:

The authors thank all contributors for their assistance in manuscript preparation.

Funding: None.

Conflict of Interest:

No conflict of interest declared.

Author Contributions:

All authors reviewed and approved the manuscript.

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