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Climate Change and Agriculture: Assessing Impacts, Risks and Pathways to Resilience

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Abstract

Climate change is increasingly affecting agricultural production through rising temperatures, changing rainfall patterns, droughts, floods, heat stress, water scarcity and changing pest and disease pressure. These effects influence crop growth, yield, quality, farm income and food security, with rainfed and resource-constrained farming systems being particularly vulnerable. Evidence from India indicates that major crops such as wheat, rice and maize may experience substantial yield losses under increasing temperature and water stress. However, the magnitude of impact varies with crop, location, irrigation and management practices. Climate-resilient cultivars, adjusted sowing dates, efficient irrigation, groundwater conservation, crop diversification, agroforestry and improved weather information can reduce climatic risks. Building resilient agricultural systems therefore requires an integrated approach combining scientific knowledge, efficient resource management, ecosystem conservation, farmer capacity building and supportive policies.

Keywords: Agriculture, Climate change, Crop productivity, Drought and heat stress, Food security

Introduction

Agriculture is closely connected with climate. Temperature, rainfall, solar radiation, soil moisture and the availability of water together determine the conditions under which crops grow and reproduce. Consequently, even relatively small changes in climatic conditions can alter crop growth, development, yield and quality. The relationship is particularly important in India, where a large proportion of cultivated land remains dependent on the monsoon. Climate variability therefore becomes not simply an environmental concern, but also a production, economic and livelihood concern.

The available evidence shows that Indian agriculture is already experiencing the effects of increasing temperatures, irregular rainfall, droughts, floods and extreme weather events. Shukla *et al.* (2023) reported an increasing trend in temperature in India and highlighted the sensitivity of agricultural production to changes in temperature and monsoon rainfall. Similarly, Prakash (2024) noted that droughts, heat waves, storms, flooding, delayed monsoons and seasonal temperature variations can interfere with crop establishment, crop management and harvesting.

The concern extends beyond production alone. Lower yields can reduce farm income, increase pressure on irrigation resources and contribute to instability in food supply and prices. At the same time, agricultural expansion into forests can create a feedback relationship in which environmental degradation increases climate vulnerability and climate change subsequently affects agricultural productivity (Kunte and Bhat, 2024).

Climate Change and Agricultural Vulnerability

Climate change affects agriculture through several interconnected pathways. Rising temperature can accelerate crop development and shorten the duration available for grain filling. Heat stress during sensitive reproductive stages may reduce photosynthesis, flowering, fertilisation and final yield. Increased minimum temperatures are also important

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because they raise crop maintenance respiration and can reduce net biomass accumulation (Shukla *et al.*, 2023). The major climatic drivers and their corresponding effects on agricultural production are summarised in table 1.

Table 1: Major pathways through which climate change affects agricultural production

Climate-related change	Major agricultural effect	Possible consequence
Rising temperature	Heat stress, faster crop development, shorter grain-filling period.	Reduced yield and crop duration.
Irregular rainfall	Delayed sowing, dry spells, waterlogging.	Crop failure and unstable production.
Drought and water scarcity	Reduced soil moisture and irrigation availability.	Lower productivity and increased production risk.
Floods and intense rainfall	Erosion, nutrient leaching and crop damage.	Soil degradation and yield loss.
Changing pest and disease conditions	Increased infestation and disease pressure.	Higher crop losses and management costs.
Changing crop suitability	Traditional crops become less suitable in some regions.	Shifts in cropping patterns.
Reduced water availability	Greater competition for surface and groundwater.	Higher irrigation costs and resource depletion.
Extreme events	Physical damage to crops and infrastructure.	Farm income and livelihood losses.

Changes in rainfall create a second major pathway. It is not only the total quantity of rainfall that matters; its timing, intensity and distribution across the growing season are equally important. Irregular rainfall may delay sowing, produce temporary waterlogging, intensify soil erosion and nutrient loss, or create prolonged dry periods. Prakash (2024) particularly emphasised the importance of inconsistent monsoon behaviour, which can increase both water scarcity and excessive rainfall-related problems.

Agricultural vulnerability is therefore multidimensional. Kunte and Bhat (2024) described vulnerability in terms of exposure, sensitivity, potential impact and adaptive capacity. A region with high temperature exposure may not necessarily suffer the same degree of damage as another region if it has better irrigation, appropriate crop varieties, stronger infrastructure and greater access to information and financial support.

The evidence also indicates that vulnerability is particularly high in rainfed agriculture. Shukla *et al.* (2023) observed that rainfed agriculture is expected to be among the most affected, while rabi crops may become especially sensitive to changes in minimum temperature and rainfall uncertainty. Kunte and Bhat (2024) similarly reported that low net irrigated area, low groundwater availability, drought proneness and high dependence on rainfall are important factors contributing to agricultural vulnerability in several Indian regions.

Impacts on Crop Production and Productivity

The effects of warming are particularly evident in temperature-sensitive crops. In wheat, for example, higher temperature can shorten the grain-filling period and accelerate maturity. Historical evidence from the Indo-Gangetic Plains shows that unusually high temperatures have caused premature wheat maturity and substantial production losses (Shukla *et al.*, 2023). Simulation studies compiled by Shukla *et al.* (2023) indicated that a 1, 2 and 3 °C temperature increase could reduce wheat grain yield by approximately 8.1, 18.7 and 25.7%, respectively, under the specified modelling conditions. Rice, maize and groundnut also showed substantial reductions as temperature increased.

Future projections further indicate substantial risks to major cereal crops, although the magnitude of impact varies among crops, regions and climate scenarios. Without adequate adaptation, earlier assessments have projected considerable reductions in agricultural production under future warming conditions (Shukla *et al.*, 2023).

However, the response of agriculture to climate change is not uniformly negative. Crop responses depend on latitude, crop type, irrigation, soil conditions, management and the magnitude of climatic change. Elevated CO_2 may provide some degree of fertilisation benefit for certain crops, but the available evidence indicates that increasing temperature and water stress can offset such gains. Annie *et al.* (2023) noted that crop responses differ according to location, irrigation practices and climatic conditions, while excessive temperatures generally exert a negative influence on productivity. The interaction among temperature, rainfall variability, water stress, soil processes and biotic stresses ultimately translates climatic changes into changes in crop productivity, farm income and food security (Figure 1).

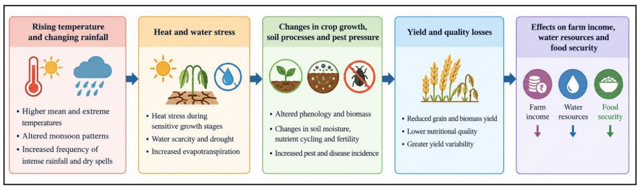

Figure 1: Conceptual pathway of climate change impacts on agricultural production [Annie *et al.* (2023), Shukla *et al.* (2023), Prakash (2024) and Kunte and Bhat (2024)]

Water Resources: A Critical Dimension

Water is perhaps the most immediate link between climate change and agricultural productivity. Increasing temperature raises evaporative demand, while declining or poorly distributed rainfall reduces the availability of water for crops. Farmers may consequently increase groundwater extraction, creating another layer of vulnerability.

The coupled socio-hydrological modelling study of Javansalehi and Shourian (2024) illustrated this interaction clearly. Under projected climate scenarios, rainfall decreased while maximum and minimum temperatures increased. The resulting changes were associated with lower crop yields, increased irrigation demand and greater dependence on groundwater. In their study area, groundwater use increased from 10.70 MCM year^{-1} in the base period to 25.61 and 28.59 MCM year^{-1} under SSP1-2.6 and SSP5-8.5 scenarios, respectively.

The implications extend beyond individual farms. Excessive groundwater withdrawal can reduce aquifer storage and increase competition among agricultural, domestic and environmental users. Climate change can thus create a cycle of declining rainfall, greater irrigation demand, increased groundwater extraction and declining water security.

Importantly, the modelling results also demonstrate that management interventions can change this trajectory. Improving irrigation efficiency and restricting groundwater extraction reduced irrigation requirements and produced an average groundwater-level increase of 0.5 m. The water resources sustainability scenario also increased simulated crop yields by 6%. These results indicate that adaptation should not be viewed only as a response to climate change; it should also address the underlying efficiency of agricultural resource use.

Soil, Pests, Diseases and Crop Quality

Climate change affects agricultural soils through changes in moisture availability, erosion, nutrient cycling and salinity. Intense rainfall can accelerate erosion and nutrient leaching, whereas prolonged dry periods can reduce soil moisture and biological activity. Kunte and Bhat (2024) further highlighted the importance of soil organic carbon, which contributes to water retention, drainage and resistance to erosion and nutrient loss.

Warmer and more humid conditions can also modify the distribution and abundance of pests, pathogens and weeds. Prakash (2024) reported that warmer temperatures may promote insect and weed proliferation, while altered rainfall conditions can favour the spread of some diseases. Consequently, climate change may increase production costs through greater requirements for crop protection.

Crop quality is another emerging concern. Prakash (2024) reported that changes in climatic conditions can influence attributes such as taste, texture and storage characteristics, while increased atmospheric CO_2 may reduce protein concentration in some crops. Thus, climate change may affect both the quantity and nutritional quality of agricultural output.

Deforestation and the Climate-Agriculture Feedback

The relationship between agriculture and climate change is not one-directional. Agriculture depends on ecosystems, but agricultural expansion can also contribute to environmental degradation. Kunte and Bhat (2024) identified deforestation, agricultural expansion and climate change as interconnected processes. Forest loss can alter rainfall, runoff, soil conditions and local climatic regulation, thereby increasing agricultural vulnerability.

This creates an important policy dilemma: expanding agriculture may increase short-term cultivated area, but conversion of forests can weaken the ecological conditions upon which agriculture itself depends. Forests support water cycles, soil fertility, local climate regulation and pollination, making forest conservation relevant to agricultural sustainability rather than separate from it.

Agroforestry provides one practical means of reconciling these objectives. The integration of trees with crops can contribute to microclimate regulation, carbon storage and diversification of farm resources. Kunte and Bhat (2024) identified agroforestry as an important form of climate-smart agriculture and noted its potential for combining agricultural production with forest conservation.

Socio-Economic Consequences and Food Security

The effects of climate change ultimately reach the farm household. Yield reductions reduce income, while higher irrigation, crop protection and input costs can further narrow profit margins. Climate shocks may also influence farmers' crop choices. Javansalehi and Shourian (2024) showed that economically constrained farmers may favour profitable crops even when such crops require greater quantities of water, potentially intensifying pressure on already limited water resources.

Climate change therefore has a strong food-security dimension. Production losses can reduce food availability, while simultaneous disruption of supply chains and price instability can affect access to food. Prakash (2024) emphasised that repeated extreme events can cause crop failures and increase risks of food poverty and malnutrition, particularly among vulnerable populations.

The distribution of impacts is also unequal. Regions characterised by large rainfed areas, high drought proneness, limited irrigation, groundwater constraints and a large proportion of small and marginal farmers are likely to possess lower adaptive capacity (Kunte and Bhat, 2024). Adaptation policy must therefore consider not only technological feasibility but also affordability, access to information, markets, credit and institutional support.

Adaptation and Mitigation Strategies

Adaptation needs to operate at several levels. At the farm level, changes in sowing dates, crop duration, cultivar selection, nutrient management, irrigation scheduling and crop diversification can reduce exposure to climatic stress. Shukla *et al.* (2023) identified adjustment of sowing dates, development of climate-resilient varieties and improved agronomic practices as important adaptation options.

Crop simulation models can strengthen these decisions by allowing researchers to test different combinations of climate, soil and management conditions before they are implemented in the field. Annie *et al.* (2023) emphasised that crop models can assess climate impacts on crop growth, yield and soil-water balance and can help evaluate adaptation measures at farm level. Their review also indicates that optimisation of planting dates and cultivars can improve yields under several climate scenarios, while weather forecasts, shelter belts, diversification and water-efficient practices can reduce production risk.

Water management deserves particular emphasis. Drip and deficit irrigation, improved water harvesting, supplemental irrigation and groundwater regulation can improve water-use efficiency. The results of Javansalehi and Shourian (2024) provided quantitative evidence that irrigation efficiency can simultaneously conserve water and improve crop yield.

At the landscape level, agroforestry, soil conservation, forest protection and restoration can strengthen ecological resilience. Kunte and Bhat (2024) argued that forest protection and agricultural development need not remain competing objectives; improved productivity on existing agricultural land, together with agroforestry and appropriate incentives, can reduce pressure for further forest conversion.

Taken together, these measures indicate that climate resilience is best achieved through a combination of crop, soil, water, ecosystem and information-based interventions rather than through a single adaptation practice (Figure 2).

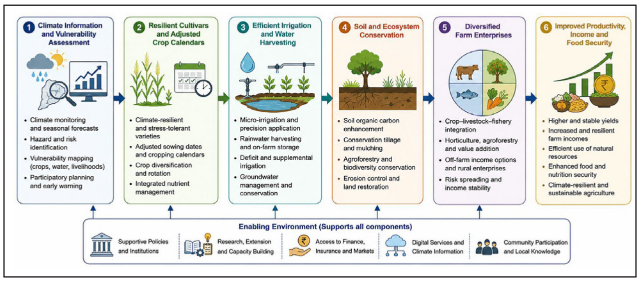

Figure 2: Integrated framework for climate-resilient agriculture

Role of Climate Information and Modelling

An important shift in climate adaptation is the movement from reacting to climatic shocks towards anticipating them. Global and regional climate models can provide future projections of temperature and precipitation, while crop simulation models translate these climatic changes into potential effects on specific crops and management systems. Annie *et al.* (2023) highlighted the usefulness of combining climate models with crop models to identify vulnerable crops and regions and to support adaptation planning.

Nevertheless, model-based assessments must be interpreted carefully. The accuracy of crop simulations depends on the quality of climate, soil and management data, as well as appropriate calibration and validation. Annie *et al.* (2023) noted that poor input data and differences in modelling decisions can increase uncertainty, making careful model selection and evaluation essential.

This suggests that strengthening agricultural weather networks, soil databases, crop observations and local climate information is as important as developing sophisticated models. Seasonal weather forecasts can then be translated into practical decisions on sowing, irrigation, fertilisation and harvesting.

Conclusion

Climate change is increasingly influencing agricultural production through a combination of rising temperatures, rainfall variability, droughts, floods, water scarcity, changing pest and disease pressure and ecosystem degradation. The impacts are particularly serious for rainfed and resource-constrained farming systems, where adaptive capacity is often limited. Evidence from India shows that increasing temperature can shorten the crop duration and reduce the productivity of major crops, such as wheat, rice and maize; while irregular rainfall can amplify both drought and flood risks.

Yet the future of agriculture under climate change is not predetermined. The available studies demonstrate that timely adaptation can substantially reduce losses. Adjusting sowing dates, adopting heat- and drought-tolerant cultivars, improving irrigation efficiency, conserving groundwater, diversifying crops, strengthening weather-based decision-making and promoting agroforestry can together improve resilience. Crop simulation and coupled socio-hydrological models can further help identify appropriate interventions under different future scenarios.

The central requirement, therefore, is an integrated approach in which climate adaptation, water conservation, agricultural productivity and ecosystem protection are considered together. Agriculture must produce more reliably while using water, soil and land more efficiently. At the same time, forests and other natural ecosystems need to be protected because they provide services essential for sustainable agriculture. As Kunte and Bhat (2024) concluded, climate-smart agriculture and agroforestry offer pathways for simultaneously strengthening food production and ecological resilience. Ultimately, building climate-resilient agriculture will depend not on a single technology or intervention, but on the coordinated application of scientific knowledge, farmer experience, climate information, resource conservation and supportive policy.

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