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Climate change impacts on agriculture and sustainable adaptation strategies in the Barind region of Bangladesh

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ABSTRACT

The Barind Tract of northwestern Bangladesh is a critical climate risk hotspot where agricultural productivity is increasingly threatened by climatic variability. This study provides an updated assessment of recent climate trends (2019–2023) and their impacts on major crop yields and socioeconomic vulnerability in the region. Using a mixed-methods approach, the research integrated meteorological data from the Bangladesh Meteorological Department, agricultural statistics from the Bangladesh Bureau of Statistics, and primary data from household surveys and farmer interviews. The findings reveal a significant warming trend, with average annual temperatures rising by approximately 2°C (from 29.5°C to 31.5°C), alongside a substantial decline in annual rainfall of nearly 250 mm over the five-year period. These climatic shifts have translated into severe productivity losses, with rice and wheat yields declining by 25% and 20%, respectively. Correlation analysis confirmed a strong positive relationship between rainfall and rice productivity, highlighting the vulnerability of rain-fed systems. Furthermore, the study identifies an increasing frequency of chronic drought events and escalating water stress driven by declining groundwater tables and rising irrigation costs. The results underscore the urgent need for climate-resilient agricultural planning, including crop diversification and improved water management strategies, to safeguard food security and rural livelihoods in drought-prone inland regions.

INTRODUCTION

Climate change poses a growing risk to global agricultural systems, particularly in regions where farming is highly climate-dependent and adaptive capacity is limited. Rising temperatures, altered rainfall patterns, and an increasing frequency of extreme weather events are disrupting crop production, degrading soil and water resources, and increasing uncertainty for farmers and policymakers worldwide (IPCC, 2019; Skendžić et al., 2021). These risks are most pronounced in tropical and subtropical regions, where heat stress, drought, and water scarcity threaten food security and rural livelihoods, underscoring the need for climate risk-informed agricultural management and adaptation strategies (Wiebe et al., 2019).

Bangladesh is widely recognized as a global climate risk hotspot due to its low-lying deltaic geography, exposure to floods and cyclones, high population density, and strong dependence on agriculture (Climate Central, 2021; Dasgupta et al., 2015). While coastal flooding, cyclones, and salinity intrusion dominate national-level climate discourse, inland drought risks are intensifying, particularly in the northwestern Barind Tract. These risks are amplified by socioeconomic vulnerabilities such as poverty, limited access to irrigation technology, and heavy reliance on groundwater, which together constrain adaptive capacity and heighten livelihood insecurity (World Bank, 2024; World Bank, 2021).

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Recent increases in atmospheric carbon dioxide (CO_2) concentrations provide a critical global context for these observed climatic stresses. Global annual mean CO_2 levels rose steadily from approximately 411 ppm in 2019 to over 420 ppm by 2023, reaching record highs despite temporary emission reductions during the COVID-19 period (NOAA; IPCC). Elevated CO_2 concentrations intensify the greenhouse effect, contributing to rising temperatures, increased evapotranspiration, and greater variability in precipitation across South Asia, thereby exacerbating drought risk in climate-sensitive agricultural regions such as northwestern Bangladesh.

Empirical evidence indicates that the Barind Tract is experiencing pronounced climatic changes relative to other regions of Bangladesh. Several studies have identified the Barind region as a climate hotspot, reporting significant increases in both maximum and minimum temperatures alongside rising drought frequency (Rahman et al., 2017). Observations from the Bangladesh Meteorological Department further confirm that inland regions of Bangladesh exhibit higher warming rates compared to coastal areas (BMD). Elevated temperatures intensify evapotranspiration and heat stress, increasing crop water demand and reducing yield stability under already water-limited conditions.

Rainfall variability represents an additional and critical driver of agricultural risk in the Barind region. Declining and erratic rainfall patterns, particularly during the pre-monsoon and post-monsoon periods (Shahid, S., & Behrawan, 2008; Karim et al., 2012). Delayed monsoon onset and prolonged dry spells disrupt traditional cropping calendars and increase the incidence of agricultural drought. These rainfall anomalies are especially damaging in the Barind Tract due to limited surface water availability, compact clayey soils, and poor soil moisture retention.

Climate-induced changes in temperature and rainfall have translated directly into crop-specific productivity impacts. Studies conducted by the Bangladesh Rice Research Institute report significant reductions in rice yields under drought and heat stress, particularly during sensitive phenological stages such as flowering and grain filling (BRRI). Wheat production has also been shown to be highly sensitive to rising temperatures, with shortened growing periods and increased heat stress leading to yield declines. In contrast, maize and pulse crops demonstrate comparatively greater tolerance to moisture and heat stress, supporting crop diversification as a key adaptation strategy for drought-prone Barind agriculture.

Groundwater dependency constitutes a critical linkage between climate variability and agricultural vulnerability in the Barind Tract. Research indicates a continuous decline in groundwater levels driven by increased irrigation demand and reduced natural recharge (Rahman et al., 2012; BWDB). Climate-induced reductions in rainfall further exacerbate groundwater depletion, increasing irrigation costs and limiting water access for smallholder farmers. This overreliance on groundwater has been identified as a central factor intensifying production risk and long-term sustainability challenges in Barind agriculture.

Beyond biophysical impacts, climate change has significant socioeconomic consequences for rural communities in the Barind region. Declining crop yields, rising production costs, and increasing climate uncertainty contribute to income instability, food insecurity, and seasonal migration. Smallholder farmers are disproportionately affected due to limited financial resources, weak institutional support, and constrained access to climate-resilient technologies. These dynamics highlight the interconnected nature of climatic, agricultural, and livelihood risks in drought-prone regions.

Despite a substantial body of research on climate change and agriculture in Bangladesh, important gaps persist. Most studies emphasize national-scale trends or coastal hazards, while drought-prone inland regions such as the Barind Tract remain underrepresented. Moreover, integrated assessments that link recent climatic trends with crop-specific yield responses and socioeconomic vulnerability using updated datasets remain limited (Dasgupta et al., 2015; World Bank, 2021). Addressing these gaps is essential for advancing evidence-based climate risk management and developing region-specific adaptation strategies.

In this context, the present study provides an updated assessment of recent climate variability (2019-2023) and its impacts on major crop productivity in the Barind areas of Bangladesh. By linking climatic trends with agricultural and socioeconomic responses, the study contributes empirical evidence to support climate-resilient agricultural planning and policy formulation in drought-prone regions, consistent with the objectives of climate risk management frameworks.

MATERIALS AND METHODS

Study area

The study was conducted in the Barind Tract, a drought-prone agro-ecological zone located in northwestern Bangladesh. The region encompasses parts of Rajshahi, Naogaon, and Chapai Nawabganj districts and is characterized by slightly elevated terrain compared to the surrounding floodplains, with elevations ranging from approximately 15 to 20 m above mean sea level (Rahman et al., 2011; BBS, 2020). The Barind Tract is bounded by the Ganges River to the south and the Mahananda River to the west, forming a distinct physiographic unit within the country's northwestern landscape (BMDA, 2018).

Climatically, the Barind region experiences pronounced heat and moisture stress. Summer temperatures frequently exceed 40 °C, particularly during the pre-monsoon period, imposing severe heat stress on crops (IPCC, 2014; Islam et al., 2020). Annual rainfall averages between 1,200 and 1,500 mm, substantially lower than the national mean of over 2,200 mm, with rainfall being highly erratic and concentrated during the monsoon season (BMD, 2023; Shahid, 2010). This rainfall pattern results in recurrent dry spells and a high incidence of agricultural drought driven by elevated evapotranspiration (World Bank, 2018).

The soils of the Barind Tract are predominantly red-brown, clayey, and compact, with low organic matter content and limited water-holding capacity (SRDI, 2019). These properties lead to rapid soil moisture depletion following rainfall events. Agricultural production is therefore heavily dependent on groundwater irrigation, as surface water availability is constrained by the region's elevated topography and the absence of perennial rivers (BMDA, 2018). Prolonged and intensive groundwater extraction has resulted in declining water tables, exacerbating water scarcity and increasing irrigation costs (ADB, 2021).

Agriculture is the primary livelihood in the Barind region, with rice, wheat, maize, and pulses constituting the dominant cropping systems (BBS, 2022). Rice cultivation is particularly vulnerable due to its high water requirement, while wheat is sensitive to rising temperatures during critical growth stages (Lobell et al., 2011; IPCC, 2014). In response to increasing climate stress, farmers have begun adopting drought-tolerant crop varieties and diversifying cropping patterns (DAE, 2021). Given the region's strong socioeconomic dependence on agriculture, climate-induced production losses have direct implications for household income, food security, and seasonal migration (UNDP, 2015).

Data sources

This study employed both quantitative and qualitative data collected from primary and secondary sources, following established climate risk management and agricultural vulnerability assessment approaches (IPCC, 2014; World Bank, 2018).

Meteorological data, including daily and monthly records of temperature and rainfall for the period 2019–2023, were obtained from the Bangladesh Meteorological Department (BMD). These data were used to assess recent climatic variability and drought conditions in the Barind region, consistent with previous climate trend studies in Bangladesh (Shahid, 2010).

Agricultural data covering the same period were collected from the Bangladesh Bureau of Statistics (BBS) and the Department of Agricultural Extension (DAE). These datasets included crop yield statistics and information on cropping patterns for major crops cultivated in the study area and are widely used in national-level agricultural assessments (BBS, 2022).

Primary data were collected through household-level surveys and semi-structured interviews conducted with farmers in selected villages across the Barind Tract. The surveys captured information on farmers' perceptions of climate variability, observed impacts on crop production, adaptation practices, and livelihood challenges, following participatory climate risk assessment methodologies (UNDP, 2015). Secondary sources, including peer-reviewed journal articles, research reports, and government policy documents related to climate change and agriculture in Bangladesh, were also reviewed to contextualize the findings (IPCC, 2014; World Bank, 2018).

Data analysis

Climatic data were analyzed to identify recent trends and variability in temperature and rainfall. Temporal trend analysis was conducted using descriptive statistics and graphical visualization techniques, including line and bar charts, to illustrate changes over the five-year study period, as commonly applied in regional climate variability studies (Shahid, 2010; Islam et al., 2020). The frequency of dry spells and drought-like conditions was assessed based on deviations from seasonal rainfall norms (World Bank, 2018).

Crop yield variability was examined for rice, wheat, maize, and pulses in relation to observed climatic conditions. Year-to-year fluctuations in yield were analyzed to identify sensitivity to temperature extremes and rainfall variability, consistent with crop–climate impact assessment frameworks (Lobell et al., 2011; IPCC, 2014).

To quantify the relationship between climate variables and crop productivity, correlation and regression analyses were applied, with temperature and rainfall as explanatory variables and crop yields as response variables. These analyses were used to assess the strength and direction of climate–yield relationships and to identify crops most vulnerable to climatic stress (Challinor et al., 2014).

Qualitative data from farmer surveys and interviews were analyzed using thematic analysis. Responses were coded and grouped into key themes related to perceived climate risks, adaptation strategies, water management practices, and livelihood impacts (UNDP, 2015). The integration of quantitative and qualitative analyses enabled a comprehensive assessment of climate risk and adaptive responses within the Barind agricultural system (IPCC, 2014).

RESULTS

Trends in rainfall and temperature (2019–2023)

Trend analysis of meteorological data for the period 2019–2023 indicates a clear pattern of increasing temperature and declining rainfall in the Barind region (Figure 1). Average annual temperature increased steadily from 29.5 °C in 2019 to 31.5 °C in 2023, representing an overall rise of approximately 2 °C within five years. In contrast, annual rainfall declined from 1,400 mm in 2019 to 1,150 mm in 2023, reflecting a reduction of nearly 250 mm over the same period.

The inverse relationship between rising temperature and declining rainfall suggests intensifying drought stress in the Barind Tract. Reduced precipitation combined with elevated evapotranspiration is likely to exacerbate soil moisture deficits, particularly during the critical pre-monsoon and early monsoon periods, thereby increasing agricultural vulnerability.

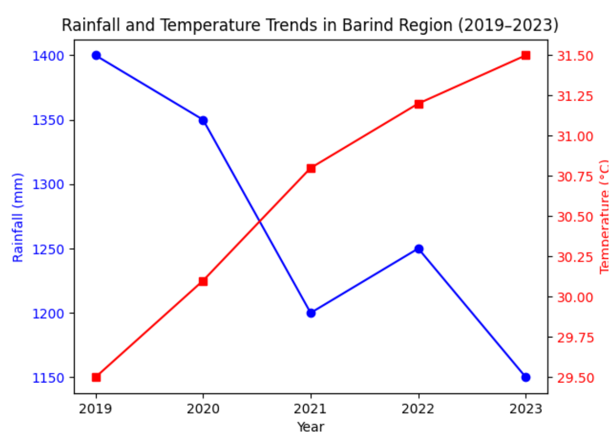

Figure 1: Rainfall and temperature trends in the Barind region (2019–2023).

Variability in rice and wheat yields

Substantial interannual variability was observed in the yields of rice and wheat during the study period (Figure 2). Rice yield declined consistently from 3.2 t ha⁻¹ in 2019 to 2.4 t ha⁻¹ in 2023, representing a reduction of approximately 25%. Wheat yield followed a similar downward trend, decreasing from 2.5 t ha⁻¹ to 2.0 t ha⁻¹, equivalent to a 20% decline.

The concurrent reduction in yields of both staple crops suggests that climatic stressors particularly declining rainfall and rising temperature have adversely affected crop productivity. Rice, being highly water-intensive, exhibited greater sensitivity to rainfall variability, while wheat appeared vulnerable to heat stress during critical growth stages.

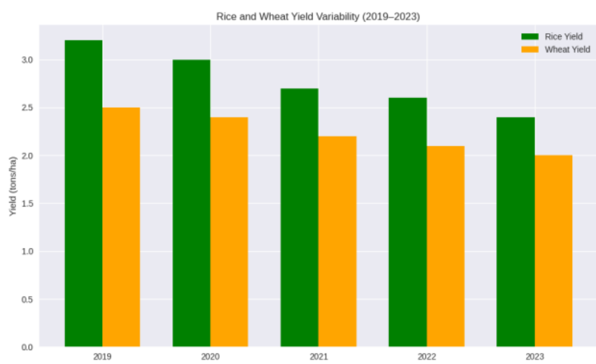

Figure 2. Rice and wheat yield variability in the Barind region (2019-2023).

Relationship between rainfall and rice yield

Correlation analysis revealed a strong positive relationship between annual rainfall and rice yield (Figure 3). Years characterized by lower rainfall corresponded with reduced rice productivity, most notably in 2021 and 2023. For instance, in 2023, when annual rainfall dropped to approximately 1,150 mm, rice yield declined to its lowest level (2.4 t ha⁻¹).

This relationship confirms that rainfall variability is a key driver of rice production in the Barind region. Even moderate reductions in precipitation can result in substantial yield losses, highlighting the high climate sensitivity of rain-fed and partially irrigated rice systems in drought-prone environments.

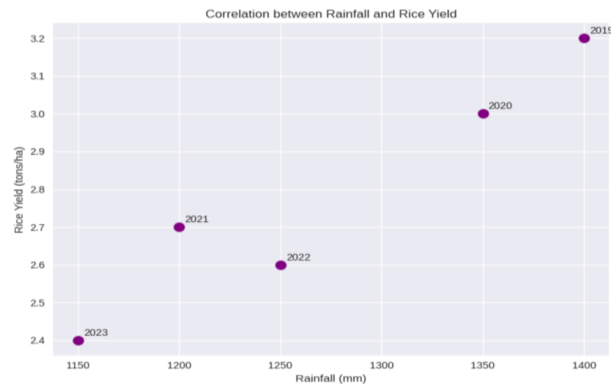

Figure 3: Scatter plot showing the relationship between rainfall and rice yield.

Frequency and severity of drought events

During the study period, the Barind region experienced three notable drought episodes, with particularly severe conditions recorded in 2021 and 2023. Analysis using the Standardized Precipitation Index (SPI) indicated moderate to severe drought conditions during these years. Farmers reported delayed sowing, crop wilting, and partial to complete crop failure, especially in rain-fed fields.

The increasing frequency of drought events was primarily attributed to erratic monsoon onset, uneven rainfall distribution, and early monsoon withdrawal. These findings suggest that drought risk in the Barind region is no longer episodic but increasingly chronic, posing serious challenges to agricultural sustainability.

Water stress and irrigation constraints

Water scarcity emerged as a critical constraint on agricultural production. Groundwater remains the principal source of irrigation; however, excessive reliance on deep tube wells has led to declining water tables. Survey results showed that 68% of farmers faced difficulties accessing irrigation water during the dry season, while 52% reported increased fuel or electricity costs for groundwater pumping.

Limited surface water availability, caused by the region's elevated topography and poor water retention capacity, further compounds irrigation challenges. Rising irrigation costs have forced many farmers to reduce irrigated acreage or abandon dry-season cropping altogether.

Farmer adaptation practices

Despite increasing climate stress, farmers in the Barind region have begun adopting a range of adaptation strategies. Crop diversification was the most widely adopted practice (55%), followed by the use of drought-tolerant crop varieties (45%) and shifts toward less water-intensive crops such as pulses and maize (40%). Other practices included rainwater harvesting (30%) and mulching for soil moisture conservation (25%).

In addition to these measures, local innovations such as community-based irrigation sharing and traditional soil moisture management techniques were observed. Although government and NGO-led programs have provided training and input support, overall adoption remains constrained by limited awareness, financial barriers, and inadequate institutional coverage.

DISCUSSION

The observed trends of rising temperature and declining rainfall in the Barind region are consistent with national and regional climate assessments reported by the Bangladesh Meteorological Department and earlier studies on climate variability in Bangladesh (BMD; Rahman et al., 2017; Shahid & Behrawan, 2008). While much of the existing literature has focused on coastal hazards such as salinity intrusion and cyclones (World Bank, 2021), this study highlights that inland drought-prone regions like the Barind Tract are equally vulnerable to climate extremes.

By providing localized, crop-specific evidence, this study fills an important knowledge gap and demonstrates that climate risks in Bangladesh are spatially diverse and context-specific.

Drivers of observed climatic and agricultural changes

Several interrelated factors explain the observed trends. Erratic monsoon rainfall and shorter rainy seasons reduce effective soil moisture availability. Rising temperatures increase evapotranspiration, accelerating soil drying and intensifying crop water stress. Concurrently, unsustainable groundwater extraction has lowered aquifer levels, making irrigation increasingly costly and unreliable. These climatic pressures interact with inherent soil constraints such as compact clay structure and low organic matter to create a compound vulnerability in the Barind agricultural system.

Sensitivity of Barind agriculture to climate extremes

Barind agriculture is highly sensitive to climate extremes due to its dependence on water-intensive crops and limited natural water storage. The strong correlation between rainfall and rice yield indicates that even modest rainfall reductions can lead to significant productivity losses. Although crops such as wheat, maize, and pulses exhibit relatively greater resilience, overall agricultural productivity remains vulnerable due to limited access to climate-smart technologies and continued reliance on traditional cropping systems.

Implications for food security and livelihoods

The declining trend in crop yields has serious implications for food security and rural livelihoods. Reduced staple crop production threatens household food availability, while rising irrigation costs reduce farm profitability. Seasonal migration is likely to intensify as agricultural livelihoods become increasingly uncertain. Given the Barind region's contribution to national rice and wheat production, continued yield declines could undermine Bangladesh's broader food self-sufficiency.

Adaptation and mitigation strategies

Climate adaptation initiatives in the Barind region of northwestern Bangladesh have largely centered on the promotion of drought-tolerant rice varieties and irrigation expansion. Varieties developed by the Bangladesh Rice Research Institute (BRRI), such as BRRI dhan56 and BRRI dhan71, have demonstrated improved performance under moderate water stress and have contributed to stabilizing rice yields in drought-prone environments (Nayak, 2022; Rahman, 2020). However, rice is not the only crop cultivated in the Barind tract. Farmers also produce wheat, maize, pulses, oilseeds, and a wide range of vegetables. Developing drought-tolerant varieties for all crops and vegetable species is scientifically complex, time-intensive, and economically demanding. Moreover, varietal development alone cannot address the underlying soil moisture constraints characteristic of the Barind's low organic matter content and declining soil structure. Therefore, while climate-resilient crop varieties remain important, they cannot serve as the sole or universal adaptation strategy.

Irrigation-based adaptation, particularly through deep tube well expansion by the Barind Multipurpose Development Authority (BMDA), has increased cropping intensity and supported dry-season production. Nevertheless, this approach has intensified groundwater depletion and increased production costs due to rising energy requirements (Hossain et al., 2018; Islam, 2019). In a region already characterized by limited recharge and high evapotranspiration, irrigation-dependent agriculture poses long-term sustainability challenges (Hossain et al., 2016). Consequently, adaptation efforts must move beyond extraction-based solutions toward strategies that enhance the soil's intrinsic capacity to retain moisture and sustain crops under variable rainfall conditions.

Given these limitations, improving soil physical, chemical, and biological properties represents a more sustainable and cross-cutting solution for the Barind region. Soil amendment through biochar, biofertilizers, compost, and other organic inputs can substantially enhance water-holding capacity, increase soil organic carbon, improve aggregate stability, and stimulate beneficial microbial activity (Hossain et al., 2022; Islam, 2023). Biochar, in particular, enhances soil porosity and moisture retention while contributing to long-term carbon sequestration (Hossain et al., 2022). Biofertilizers promote nutrient cycling and improve root development, thereby increasing crop resilience under drought stress (Islam, 2023). Unlike crop-specific breeding approaches, soil-centered interventions benefit multiple crops simultaneously, including cereals, pulses, oilseeds, and vegetables.

Such soil restoration strategies align with the broader mitigation and adaptation frameworks recommended by the Food and Agriculture Organization (FAO) and the Intergovernmental Panel on Climate Change (IPCC), which emphasize soil carbon enhancement and ecosystem-based approaches as sustainable climate solutions. By improving soil structure and moisture retention, farmers can reduce irrigation demand, lower input costs, and enhance productivity stability across diverse cropping systems.

In this context, the most viable long-term strategy for the Barind region is not the development of drought-tolerant varieties for every crop, but rather the rehabilitation of soil health to create a resilient production base. A soil-centered adaptation model integrating biochar, biofertilizers, organic amendments, crop diversification, and community-based water management offers a more inclusive, economically feasible, and environmentally sustainable pathway for strengthening climate resilience in the region.

CONCLUSION

The analysis of climatic and agricultural data from the Barind region over the last five years demonstrates a clear trend of rising temperatures and declining rainfall. Average temperatures increased by approximately 2°C, while annual rainfall decreased by around 250 mm. These climatic changes have contributed to more frequent drought events, reduced soil moisture retention, and declining groundwater levels, placing additional stress on agricultural systems. Correspondingly, crop yields have declined, with rice productivity falling by nearly 25% and wheat by 20%. Statistical analyses indicate a strong positive correlation between rainfall and rice yield, underscoring the high sensitivity of Barind agriculture to rainfall variability and the compounded vulnerability of water-intensive crops under erratic climatic conditions.

The observed climatic trends have significant implications for agricultural sustainability and rural livelihoods in the Barind region. Water-intensive crops such as rice are increasingly vulnerable to water scarcity, prompting shifts in cropping patterns toward less water-demanding crops such as maize, pulses, and drought-tolerant varieties. Groundwater over-extraction has intensified irrigation challenges, raising costs and limiting access for smallholder farmers. These biophysical constraints, combined with declining crop productivity, have heightened socioeconomic stress, leading to food insecurity, income reduction, and seasonal migration as households seek alternative livelihoods.

Policy recommendation

Adaptation and mitigation strategies are critical to enhance resilience in the Barind region. For farmers, adopting climate-resilient crop varieties, implementing water-efficient irrigation techniques, and integrating indigenous practices such as mulching, mixed cropping, and adjusted sowing dates with modern technologies can reduce vulnerability and improve productivity. For policymakers, strengthening institutional support through subsidies, credit facilities, and extension services is essential to promote climate-smart agriculture. Investments in sustainable water management strategies, including rainwater harvesting, solar-powered irrigation, and community-based water-sharing schemes, are urgently needed. Additionally, national policy frameworks such as the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) and the National Adaptation Plan (NAP) should be leveraged to implement long-term adaptation strategies, enhance crop diversification, and ensure equitable distribution of resources to safeguard food security and support rural livelihoods under ongoing climate change.

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