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# Climate Change and Challenges of Water and Food Security to Smallholder Farmers of Madhya Pradesh: An Overview

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## ABSTRACT

Projections suggest that nearly three-quarters of Himalayan glaciers will have retreated substantially by 2035. Additionally, a reduction in precipitation of approximately 10% is anticipated in Uttar Pradesh, India by 2050, potentially diminishing river drainage by 17%. Freshwater reserves are being depleted at an alarming rate, while expanding global populations and food requirements are eroding agricultural productivity worldwide. How well agriculture adapts to climate change will largely determine the future availability of food globally. India faces mounting challenges, including increasingly frequent droughts, intense flooding events, erratic monsoon patterns, and declining crop production linked to global climate change. Urbanization, rapid industrialization, and growing demands for irrigation water are placing extraordinary pressure on existing water resources. Land degradation is directly linked to rising global temperatures, with roughly 130 million hectares (mha) of Indian land showing various degrees of deterioration — encompassing 32.8 mha affected by water erosion, 10.8 mha by wind erosion, 8.5 mha by desertification, and a further 8.5 mha by waterlogging. This study identifies practical and cost-effective approaches to safeguarding food and water security under a changing climate, while recommending robust adaptation and mitigation strategies to reduce climate change impacts on irrigation and water resource systems.

## INTRODUCTION

Climate change represents one of the most critical threats to agricultural output, water availability, food security, and rural livelihoods across India, with disproportionate consequences for smallholder farmers. Those who are already economically marginalized and food insecure will be hit hardest. Farming communities in ecologically

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fragile settings already confront escalating risks of crop failure, livestock losses, and diminishing forest resources. These threats to water availability, food security, and rural livelihoods are particularly acute for small-scale farmers. Addressing climate change through inclusive policies that prioritize smallholder agriculture is therefore essential. Both adaptation and mitigation strategies in agriculture can offer tangible benefits to small farmers, and long-term resilience planning should build on short-term coping mechanisms. There is considerable scope for small farmers to contribute to soil carbon sequestration if supported by appropriate policy reforms. Collective action in adaptation and mitigation is widely acknowledged as indispensable for facilitating technology transfer in agriculture and natural resource management among smallholders and resource-dependent communities (Rao et al., 2013).

India accounts for roughly 2.3% of the world's land area and 4.2% of global water resources, yet sustains nearly 18% of the world's human population and 15% of its livestock. Agriculture constitutes the backbone of the Indian economy, contributing 18% of GDP at 2011–12 prices, providing 11% of export earnings, and employing 53.3% of the national workforce in 2013–14. According to the Agriculture Census 2010–11, the total number of operational farm holdings nationwide has nearly doubled from 71.01 million in 1970–71 to 138.35 million in 2010–11 (Fig. 1). Over the same period, the average operational holding size declined sharply from 2.28 ha to 1.15 ha (GOI, 2014). Small and marginal holdings (below 2.0 ha) together accounted for 85.01% of holdings, covering 44.58% of operated area in 2010–11, up from 83.29% with 41.14% in 2005–06 (DAC, 2015). This underscores the increasingly fragmented and smallholder-dominated character of Indian agriculture.

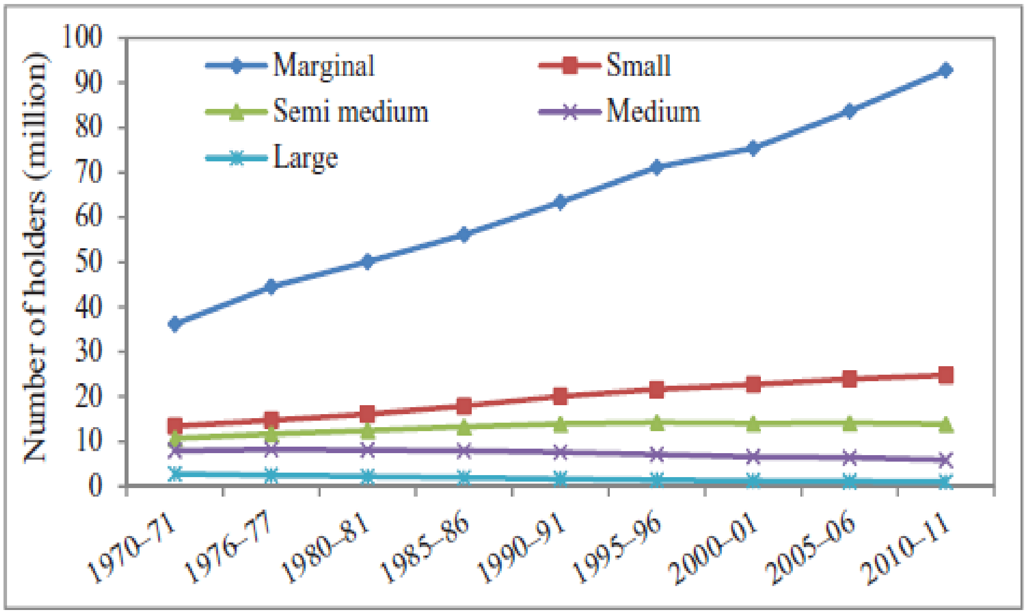


***Fig. 1: Number of operational holdings in India. Adapted from GOI (2014).***

## *Food Production*

India ranks among the top global producers of major food commodities. In cereal production, the country is surpassed only by China and the United States. India is the world's second-largest producer of rice and wheat and the leading producer of pulses. It also leads globally in milk production and ranks second in groundnut, vegetables, fruits, sugarcane, and cotton. According to fourth advance estimates for 2013–14, national food grain output reached 264.77 Mt (DAC, 2015). Pulses and oilseeds attained record production levels of 19.27 and 32.88 Mt respectively. Rice output reached 106.54 Mt, a national record, while wheat production hit 95.91 Mt. The state of Uttar Pradesh alone accounted for 19% of national food grain output in 2014–15 and contributed 7.8% to India's GDP through sugarcane cultivation. Small and marginal farmers play a disproportionately large role in high-value crop production, contributing approximately 70% of total vegetable output and 55% of fruit production despite managing only 44% of cultivated land area (Birthal, 2011). Their share in cereal and milk production stands at 52% and 69%, respectively, underscoring their dual role in supporting both agricultural diversification and national food security.

## *Food Demand*

The share of food grains in overall dietary consumption is gradually declining — it stood at 64% in the base year 2000 and is projected to fall to 57% by 2025 and 48% by 2050 (Amarasinghe et al., 2007). Non-grain crops and animal-based products are compensating for this shift. The contribution of non-grain crops is expected to grow from 28% in 2000 to 33–36% by 2025–2050, while animal products may rise from 8% to 12–16% over the same period. Factoring in these dietary transitions, total food grain demand is projected to reach 291 Mt by 2025 and 377 Mt by 2050, while production is estimated to track closely at 292 Mt and 385 Mt respectively. However, supply shortfalls are forecast for other cereals, oilseeds, and pulses — with deficits of 33% and 43% for non-rice/wheat cereals and 3% and 7% for pulses in 2025 and 2050. Singh (2009) further estimated that per capita caloric intake in India will grow from approximately 2,400 kcal/day to 3,000 kcal/day by 2050, driving cereal demand to 243 Mt. Rain-fed crop yields are projected to improve from 1.8 t/ha by 2030 to 2.0 t/ha by 2050, while irrigated cereal yields are expected to increase from 3.5 to 4.6 t/ha. Overall cereal production is projected to grow at around 0.9% per year, sufficient to meet demand by 2050. Table 1 provides a comparative overview of food demand projections from various studies.

Table 1: Food demand projections from different studies for India.

| Source of Study | Year | Rice | Wheat | Total Cereals | Pulses | Food Grains |
|---|---|---|---|---|---|---|
| Bansil (1996) | 2020 | — | — | — | — | 241.4 |
| Kumar (1998) | 2020 | 134.0 | 127.3 | 309.0 | — | — |
| Paroda and Kumar (2000) | 2020 | 111.9 | 79.9 | 229.0 | 23.8 | 252.8 |
| Radhakrishna and Reddy (2004) | 2020 | 118.9 | 92.4 | 221.1 | 19.5 | 240.6 |
| Mittal (2008) | 2021 | 96.8 | 64.3 | 245.0 | 42.5 | 287.6 |
|  | 2026 | 102.1 | 65.9 | 277.2 | 57.7 | 334.9 |
| Kumar et al. (2009) | 2021–22 | 113.3 | 89.5 | 233.6 | 19.5 | 253.2 |
| Amarasinghe and Singh (2009) | 2025 | 109 | 91 | 273 | 18.0 | 291.0 |
|  | 2050 | 117 | 102 | 356 | 21 | 1377.0 |
| Singh (2013) | 2020 | 106.7 | 85.72 | 220.0 | 23.2 | 243.2 |

## *Food Security and Climate Change*

The concept of food security has transformed significantly over the past half-century. During the 1950s, it was understood almost exclusively in terms of production adequacy. Contemporary understanding recognizes that beyond availability and physical access, food security also depends on the body's ability to absorb nutrients — a function closely linked to access to clean drinking water, sanitation, primary healthcare, and education. India continues to grapple with widespread undernourishment, ranking among the countries with the highest number of food-insecure people globally. During 2014–16, an estimated 194.6 million people (15.2% of the population) remained undernourished, compared to 210.1 million (23.7%) during 1990–92. The Global Hunger Index 2015, released by the International Food Policy Research Institute, placed India 25th among 117 countries. Anemia affects approximately 54% of pregnant women, and vitamin A deficiency is highly prevalent, recorded at 62% in 2003. Government initiatives have been deployed to address hunger and malnutrition, yet major gaps persist. IRRI research suggests that for every degree Celsius of warming, the world could lose around 15% of its rice harvest. India's agricultural performance is critically tied to the summer monsoon (June–September), which delivers approximately 75% of annual precipitation (Fig. 2). Variability in this monsoon, compounded by other hydro-meteorological extremes, substantially influences agricultural output across spatial scales.

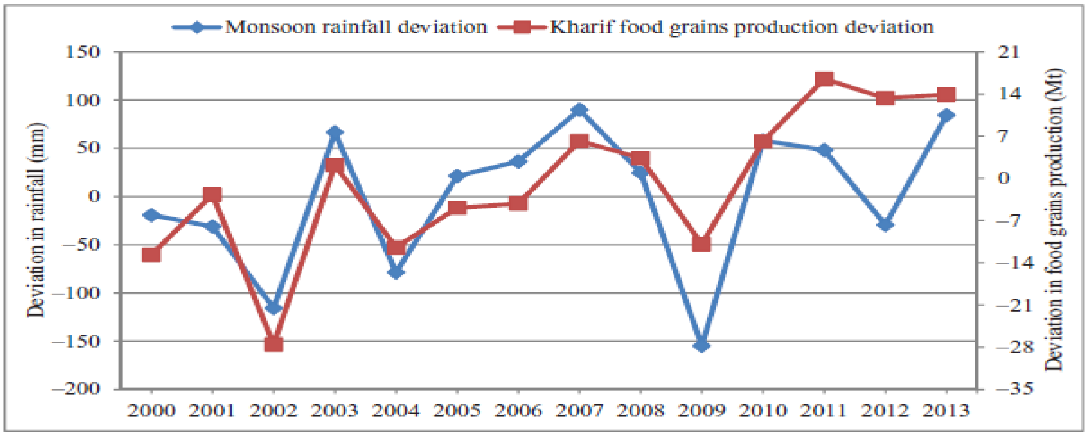


Fig. 2: Monsoon rainfall versus deviation in food grain production during kharif (rainy season) across different years.
Source: Adapted from Srinivasa Rao et al. (2013).

Beyond the summer monsoon, around 15% of India's annual precipitation falls during the winter months of December to March, which is critical for rabi (winter) crops. In addition to rainfall distribution, climatic variables such as solar radiation and temperature also exert significant influence on food grain production. Climate change is expected to intensify extreme weather events, amplifying threats of drought, flooding, pest outbreaks, and water scarcity in already stressed agro-ecosystems (Beddington et al., 2012). The broader impact on food systems is multifaceted (Gregory et al., 2005), though not all climatic changes will necessarily harm agricultural output (Lal, 2013).

Despite the inherent uncertainties in projecting regional-scale climate change, understanding potential impacts on key agricultural resources is vital for crafting effective policy responses (Rajeevan, 2013). Climate change can influence crops through four principal pathways (Hulme, 1996): first, shifts in temperature and precipitation that alter agro-ecological zone distribution; second, elevated $CO_2$ concentrations that may boost water use efficiency and photosynthetic rates; third, changes in water runoff affecting irrigation availability; and fourth, increased frequency of extreme events such as droughts and floods.

Birthal et al. (2014) modeled the projected effects of climate change on major crop yields across three future time horizons — 2035, 2065, and 2100 — under both moderate and severe climate change scenarios. Pulses appear most susceptible, with chickpea and pigeon pea yields potentially declining by around 25% by 2100 under high-emission scenarios (Table 2). Winter crops, particularly wheat, face yield reductions of approximately 22% by 2100 — roughly three times the projected decline in barley. Among kharif (rainy season) crops, rice shows the greatest vulnerability, with projected losses exceeding 15%, compared to 7% for sorghum and 4% for maize. Groundnut also faces significant yield losses, while rapeseed–mustard may benefit marginally. The severity of impacts is more muted for the near-term horizon of 2035, with maximum temperature and rainfall changes projected at 1.3°C and 7%, compared to 3.5°C and 27% by 2100.

Table 2: Projected changes in crop yields (%) under maximum temperature and rainfall changes by 2035, 2065, and 2100.

| Crop | 2035 | 2065 | 2100 |
|---|---|---|---|
| Rainy season | | | |
| Rice | -7.1 | -11.5 | -15.4 |
| Maize | -1.2 | -3.7 | -4.2 |
| Sorghum | -3.3 | -5.3 | -7.1 |
| Pigeon pea | -10.1 | -17.7 | -23.3 |
| Groundnut | -5.6 | -8.6 | -11.8 |
| Winter season | | | |
| Wheat | -8.3 | -15.4 | -22.0 |
| Barley | -2.5 | -4.7 | -6.8 |
| Chick pea | -10.0 | -18.6 | -26.2 |
| Rapeseed–mustard | 0.3 | 0.7 | 0.5 |

*Source: Adapted from Birthal et al. (2014).*

Although direct climate impacts on monsoon-season crops may initially be moderate, the growing incidence of extreme weather events — including altered rainy day frequency, intensified rainfall, prolonged droughts, temperature asymmetry, humidity shifts, and increased pest virulence — will heighten vulnerability over time. Winter crops face particular exposure due to accelerating temperature increases and greater rainfall uncertainty (Rajeevan, 2013). The ramifications of climate change extend beyond crops to the broader agricultural ecosystem. Livestock production in India, deeply intertwined with crop systems through residue utilization and by-products, will be adversely affected. Declining crop output will curtail fodder availability, while heat stress will suppress animal feed intake. Warming temperatures and shifting precipitation patterns are also expected to facilitate the spread of vector-borne diseases, trigger new disease outbreaks, and disrupt animal reproduction (Birthal et al., 2014).

By 2065, India's population is expected to surpass 1.7 billion, demanding far more diversified food supplies. Ensuring food security under resource constraints in a warming climate will be a formidable challenge. Nevertheless, adaptive measures — such as varietal substitution, adjusted planting schedules, rainwater harvesting, and the adoption of drought-resilient intercropping systems in rain-fed regions — can substantially reduce climate-related losses. For instance, timely crop planting could reduce wheat losses from 4–5 Mt to 1–2 Mt (Aggarwal, 2008). Ye and Ranst (2009) projected that food production trajectories could swing from an 18% surplus in 2005 to deficits of 22–32% by 2030–2050 under accelerating soil degradation.

Kumar and Parikh (2001) demonstrated that large-scale climatic shifts would cause substantial declines in rice and wheat yields, potentially threatening the food security of over one billion people in India by 2060. Kumar et al. (2011) warned of irrigated area reductions for multiple crops across northeastern, coastal, and Western Ghats regions. Hundal and Prabhjyot-Kaur (2007) found that even a modest temperature rise of 1–3°C above normal had already reduced rice and wheat productivity by 3% and 10% respectively in Punjab. Geethalakshmi et al. (2011) observed a 41% drop in rice productivity in Tamil Nadu with a 4°C temperature increase, and Saseendran et al. (2000) projected that a 5°C increase could drive continuous yield declines, with each additional degree of warming reducing rice yield by up to 6% in Kerala.

Srivastava et al. (2010) estimated that climate change would suppress monsoon sorghum productivity by up to 14% in central India and 2% in south-central zones by 2020, with further losses expected through 2050 and 2080. Winter crop yields were projected to fall by 7%, 11%, and 32% across these time horizons. Asha et al. (2012) documented significant reductions in the yields of multiple crops in rain-fed areas of Karnataka, with rainfall decline identified as the primary driver by over 92% of surveyed farmers. Vinesh et al. (2011) noted that climate-induced changes have compressed crop durations in rice and sugarcane, adversely affecting cane productivity in Uttar Pradesh and Uttarakhand. Kapur et al. (2009) cautioned that projected surface warming and precipitation shifts could reduce crop yields by 30% by mid-century, further contracting arable land.

## *Micro-level Assessment of Vulnerability to Climate Change*

Climate change modeling for India projects an average temperature rise of 1–4°C and a precipitation increase of 9–16% by the 2050s (Krishna Kumar et al., 2011). Rama Rao et al. (2013) mapped district-level vulnerability and found that by mid-century (2021–50), highly and very highly vulnerable districts would be concentrated in Rajasthan, Gujarat, Madhya Pradesh, Karnataka, Maharashtra, Andhra Pradesh, Tamil Nadu, eastern Uttar Pradesh, and Bihar. By end-of-century (2071–98), almost all districts in Rajasthan and large portions of Gujarat, Maharashtra, and Karnataka will face very high vulnerability, along with scattered districts in Madhya Pradesh, Uttar Pradesh, Bihar, Punjab, Haryana, Himachal Pradesh, Uttarakhand, and Andhra Pradesh. Low-vulnerability zones are largely concentrated along the western coastline and southern and eastern regions (Fig. 3).

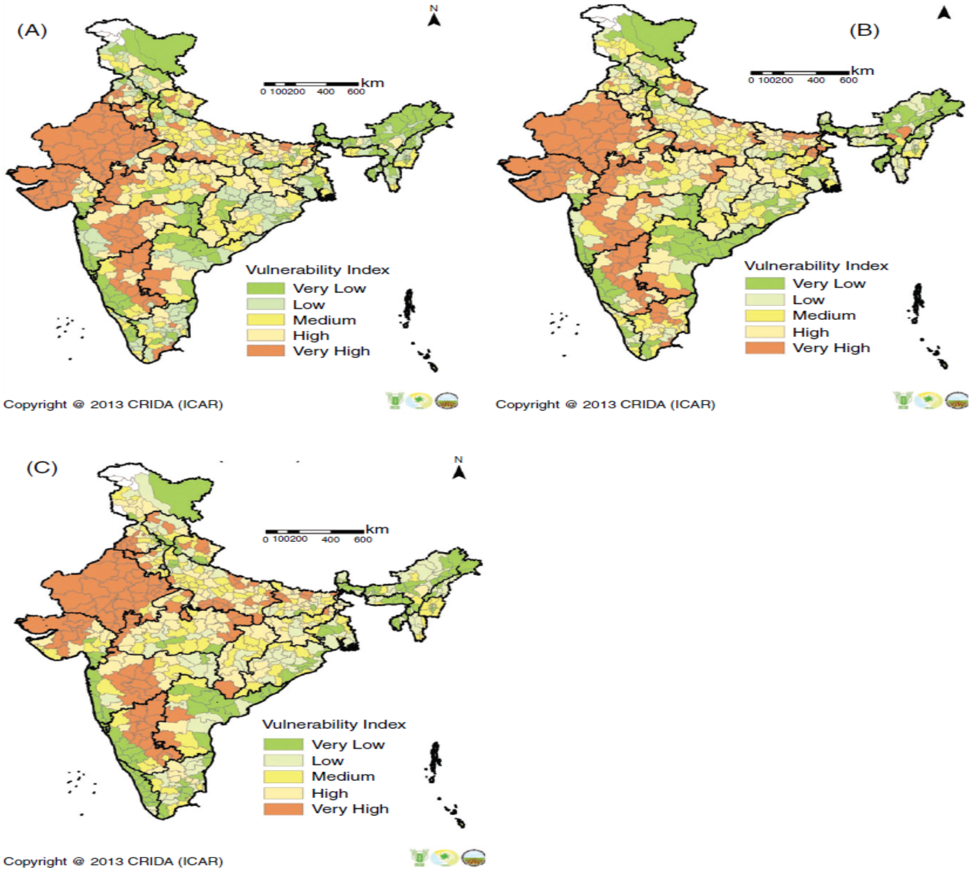
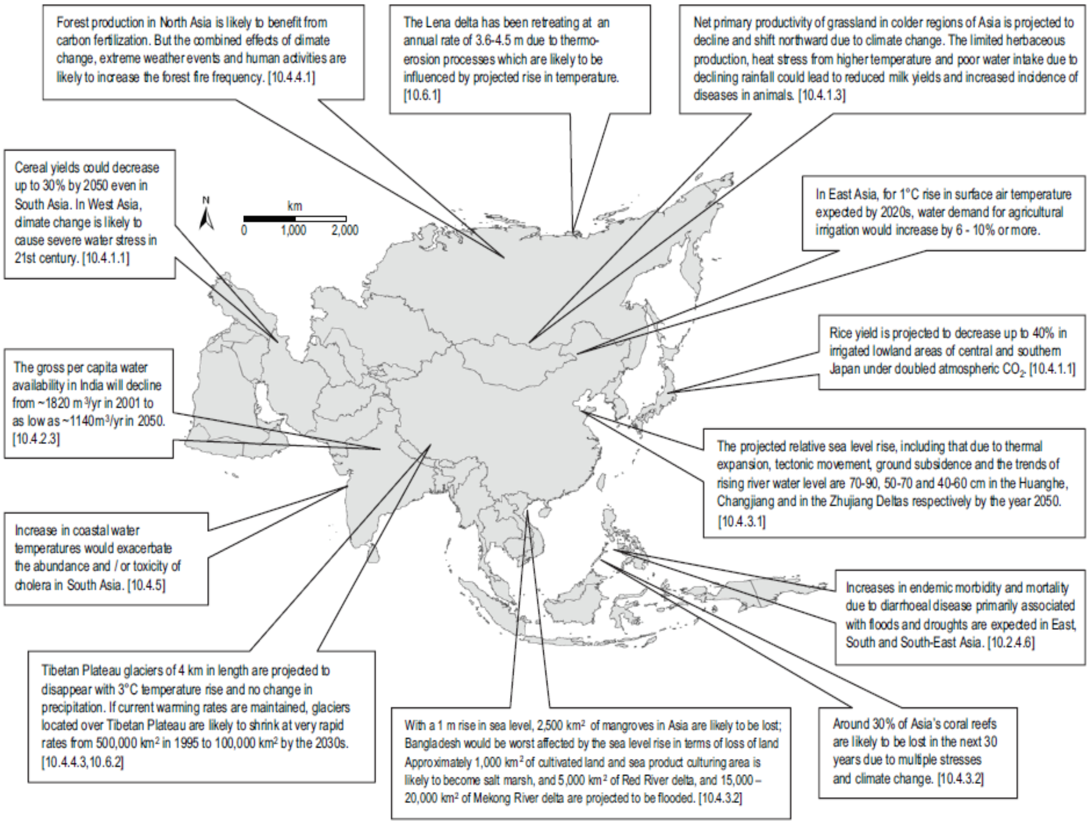


Fig. 3: District-level vulnerability of Indian agriculture to climate change: (A) present, (B) mid-century (2021–50), and (C) end of century (2071–98). Source: Rama Rao et al. (2013).

Research by Lobell et al. (2012) established that wheat production in northern India is particularly sensitive to temperatures exceeding 34°C. Earlier work by Lal et al. (2001) indicated that a 0.5°C rise in winter temperature alone could reduce wheat yields by approximately 0.45 tonnes per hectare. Easterling et al. (2007) noted that acute water stress combined with thermal strain would compound adverse effects on rice productivity. Global projections in the IPCC Fourth Assessment Report suggest that under various climate scenarios, 200 to 600 million additional people could face chronic hunger by 2080 (Yohe et al., 2007). Climate change is further expected to amplify economic drivers of food insecurity (Nira Ramachandran, 2014), with seasonal food shortages intensifying in the months before the monsoon sowing season. Urban food insecurity will also worsen, with climate-related risks concentrated among low-income populations in informal settlements susceptible to flooding, landslides, and other weather-related hazards (Nira Ramachandran, 2014). Climate scientist James Hansen has emphasized that sea-level rise will likely become one of the defining issues of the 21st century. Historical records show that sea levels rose by only 0.1 mm $yr^{-1}$ in the 19th century, accelerating to around 2 mm/year by the 1990s, with the current rate estimated at approximately 3.7 mm $yr^{-1}$ — equivalent to 37 cm per century (Chambers, 2003).



Forest production in North Asia is likely to benefit from carbon fertilization. But the combined effects of climate change, extreme weather events and human activities are likely to increase the forest fire frequency. [10.4.4.1]

The Lena delta has been retreating at an annual rate of 3.6-4.5 m due to thermo-erosion processes which are likely to be influenced by projected rise in temperature. [10.6.1]

Net primary productivity of grassland in colder regions of Asia is projected to decline and shift northward due to climate change. The limited herbaceous production, heat stress from higher temperature and poor water intake due to declining rainfall could lead to reduced milk yields and increased incidence of diseases in animals. [10.4.1.3]

Cereal yields could decrease up to 30% by 2050 even in South Asia. In West Asia, climate change is likely to cause severe water stress in 21st century. [10.4.1.1]

In East Asia, for 1°C rise in surface air temperature expected by 2020s, water demand for agricultural irrigation would increase by 6 - 10% or more.

Rice yield is projected to decrease up to 40% in irrigated lowland areas of central and southern Japan under doubled atmospheric $CO_2$. [10.4.1.1]

The gross per capita water availability in India will decline from ~1820 $m^3$/yr in 2001 to as low as ~1140$m^3$/yr in 2050. [10.4.2.3]

The projected relative sea level rise, including that due to thermal expansion, tectonic movement, ground subsidence and the trends of rising river water level are 70-90, 50-70 and 40-60 cm in the Huanghe, Changjiang and in the Zhujiang Deltas respectively by the year 2050. [10.4.3.1]

Increase in coastal water temperatures would exacerbate the abundance and / or toxicity of cholera in South Asia. [10.4.5]

Increases in endemic morbidity and mortality due to diarrhoeal disease primarily associated with floods and droughts are expected in East, South and South-East Asia. [10.2.4.6]

Tibetan Plateau glaciers of 4 km in length are projected to disappear with 3°C temperature rise and no change in precipitation. If current warming rates are maintained, glaciers located over Tibetan Plateau are likely to shrink at very rapid rates from 500,000 $km^2$ in 1995 to 100,000 $km^2$ by the 2030s. [10.4.4.3,10.6.2]

With a 1 m rise in sea level, 2,500 $km^2$ of mangroves in Asia are likely to be lost; Bangladesh would be worst affected by the sea level rise in terms of loss of land Approximately 1,000 $km^2$ of cultivated land and sea product culturing area is likely to become salt marsh, and 5,000 $km^2$ of Red River delta, and 15,000 – 20,000 $km^2$ of Mekong River delta are projected to be flooded. [10.4.3.2]

Around 30% of Asia's coral reefs are likely to be lost in the next 30 years due to multiple stresses and climate change. [10.4.3.2]

***Fig. 4: Hotspots of projected climate change impacts and vulnerabilities across Asia.***

FAO (2016) highlighted that shifts in climatic conditions under elevated $CO_2$ could diminish the nutritional quality of food crops by reducing concentrations of proteins and micronutrients such as zinc and iron. For India, where pulses serve as the primary protein source, such nutritional degradation could accelerate the prevalence of micronutrient deficiency — often termed 'hidden hunger'. Lal et al. (1998) and Kalra et al. (2003) corroborated that a 0.5°C winter temperature rise reduces Indian wheat yields by 0.45 t/ha, while Aggarwal (2003) projected 2–5% decreases in wheat and maize yield potential for a 0.5–1.5°C temperature increase. Studies from China indicate that a 2°C increase in mean air temperature could depress rain-fed rice yields by 5–12% (Lin et al., 2004).

Across South Asia, yield declines in non-irrigated wheat and rice become significant when temperatures exceed 2.5°C, translating into farm-level net revenue losses of 9–25% (Lal, 2007). Net cereal production across South Asian nations is projected to contract by 4–10% by end-of-century even under conservative climate scenarios (Lal, 2007). Rice production in Asia broadly could fall by 3.8% by the end of the 21st century owing to the compounded effects of $CO_2$ fertilization, heat stress, and water scarcity (Murdiyarso, 2000). In Bangladesh, rice and wheat production may decline by 8% and 32% respectively by 2050 (Faisal and Parveen, 2004). Under high-emission A1FI scenarios, crop yields across parts of Asia are projected to fall by 2.5–10% in the 2020s and 5–30% in the 2050s (Parry et al., 2004). Elevated $CO_2$ levels could reduce rice yields in central and southern Japan by up to 40% through heat-induced floret sterility (Nakagawa et al., 2003; Matsui and Omasa, 2002). In North Asia, a 30% increase in tropospheric ozone and a 20% decline in humidity are expected to reduce grain and fodder production by 26% and 9% respectively (Izrael, 2002).

## *Water Availability and Climate Change*

Water is the foundational input for agricultural production. Expanding irrigation infrastructure and strengthening water management are critical for improving rural livelihoods. Agriculture now competes with growing urban and industrial water demands. Smallholder farmers are especially dependent on groundwater, which is already being depleted across large parts of India, while wealthier farmers typically have greater access to canal systems. In India, Pakistan, Nepal, and Bangladesh, water shortfalls have been attributed to rapid urbanization and industrialization, population growth, and inefficient use — all compounded by climate change and its effects on water supply and quality. Kundzewicz and Doll (2009) highlighted the global significance of climate change impacts on groundwater, noting that between 1.5 and 3 billion people worldwide depend on groundwater as their primary drinking water source.

The IPCC (2008) projects that climate change over the coming century will significantly disrupt precipitation patterns, streamflow regimes, and coastal sea levels. Agricultural yields are expected to be severely affected over the next hundred years due to unprecedented rates of climatic change (Jarvis et al., 2010; Thornton et al., 2011). In arid and semi-arid regions, precipitation is projected to decline by more than 20% during the same period. Analysis by ISRO of 2,190 Himalayan glaciers found that roughly 75% are retreating, with an average contraction of 3.75 km over the past 15 years (Misra, 2013).

Stern (2007) warned that glacier melt from climate change could critically affect approximately 500 million people in the Himalaya–Hindu Kush region and 250 million in China who rely on glacial meltwater. Anthony Nyong (2005) projected that Sub-Saharan Africa could see rainfall decline by 10% by 2050, triggering major water shortages. This precipitation reduction would correspondingly diminish surface drainage by 17%, with regions currently receiving 500–600 mm/year facing drainage reductions of 30–50%.

AICRPAM–CRIDA projections indicate that wheat crop water requirements will increase from 423.7 mm in 1990 to 434.6 mm by 2020 and 447.9 mm by 2050, representing deviations of 2.6% and 5.8% respectively. Total volumetric water requirements will rise from 39,717.8 million cubic meters in 1990 to 41,990.4 million cubic meters by 2050.

Gupta and Deshpande (2004) projected that India's rapidly growing population will render the country water-scarce by 2050. Total water requirements by 2050 are estimated at 1,450 km$^3$, substantially exceeding projected available resources of 1,122 km$^3$ per year. Meeting this gap will require harnessing an additional 950 km$^3$ per year above the current 500 km$^3$. Irrigation return flows from surface and groundwater systems are expected to contribute 223 km$^3$ per year by 2050, while total recyclable wastewater is projected at 177 km$^3$ per year.

Aldaya et al. (2010) recommended that restoring soil quality to enhance 'green water' (soil moisture from precipitation) represents a cost-effective strategy, as it carries lower environmental externalities than expanding blue water (canal and groundwater) irrigation. Monaghan et al. (2013) demonstrated that precision irrigation, when integrated with regulated deficit irrigation (RDI) or partial root zone drying (PRD), can substantially optimize water use. Key challenges in scaling micro-irrigation include: (i) monitoring spatially variable soil moisture through electromagnetic induction and near-infrared sensing on unmanned aerial vehicles; (ii) assessing plant water status through high-resolution remote sensing; and (iii) implementing variable-rate water application systems.

Guo et al. (2002) used GIS-based modeling to demonstrate that runoff is more sensitive to changes in precipitation than to temperature increases, and that integrated water resource management can help mitigate climate impacts. Ma et al. (2008) found that climate change could reduce mean annual streamflow by 64%, with precipitation being the more sensitive driver compared to evapotranspiration. Alcamo et al. (2007) projected increasing water availability and more frequent high-runoff events in Russia, posing risks to food production. Mirza (2007) indicated that climate change will exacerbate flood and drought frequency in South Africa. Fischer et al. (2007) estimated that mitigation efforts could reduce climate impacts on agricultural water requirements by approximately 40%. De Silva et al. (2007) projected a 13–23% rise in paddy irrigation needs. Thomas (2008) and Eitzinger et al. (2003) further underscored the strong relationship between inter-annual climate variability, soil water balance, and crop production outcomes.

Holden and Brereton (2006) cautioned that while higher irrigation levels generally improve yields, farmers on heavier soils must manage runoff risks carefully. Gosain et al. (2006) projected heterogeneous changes in river basin runoff across India's sub-basins in the 2050s, with potential for severe drought conditions in some regions. Shukla et al. (2004) estimated that groundwater demand will rise to 980 million cubic meters (MCM) in the 2050s, requiring approximately 100 GWh of electricity per billion cubic meters pumped. Meeting this demand will necessitate intensive exploitation of both dynamic and static groundwater reserves. NIH (2008–09) reported that glaciers in Ladakh, Zanskar, and the Great Himalayan ranges of Jammu and Kashmir are broadly receding, with volume changes ranging from 3.6% to 97% and a majority of glaciers losing 17–25% of their mass.

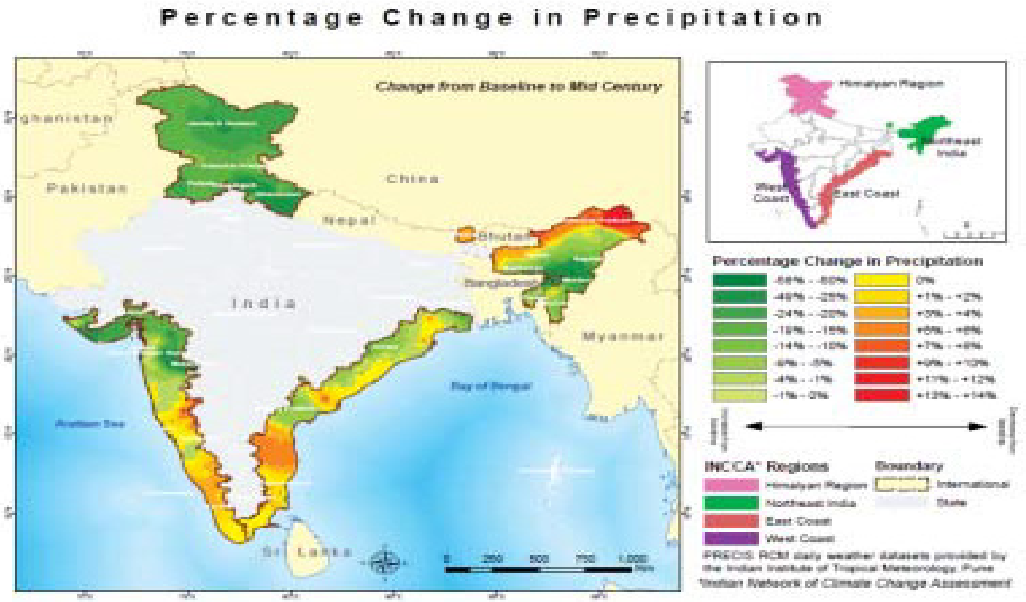


*Fig. 5 (a): Percentage change in precipitation towards the 2030s relative to the 1970s.*

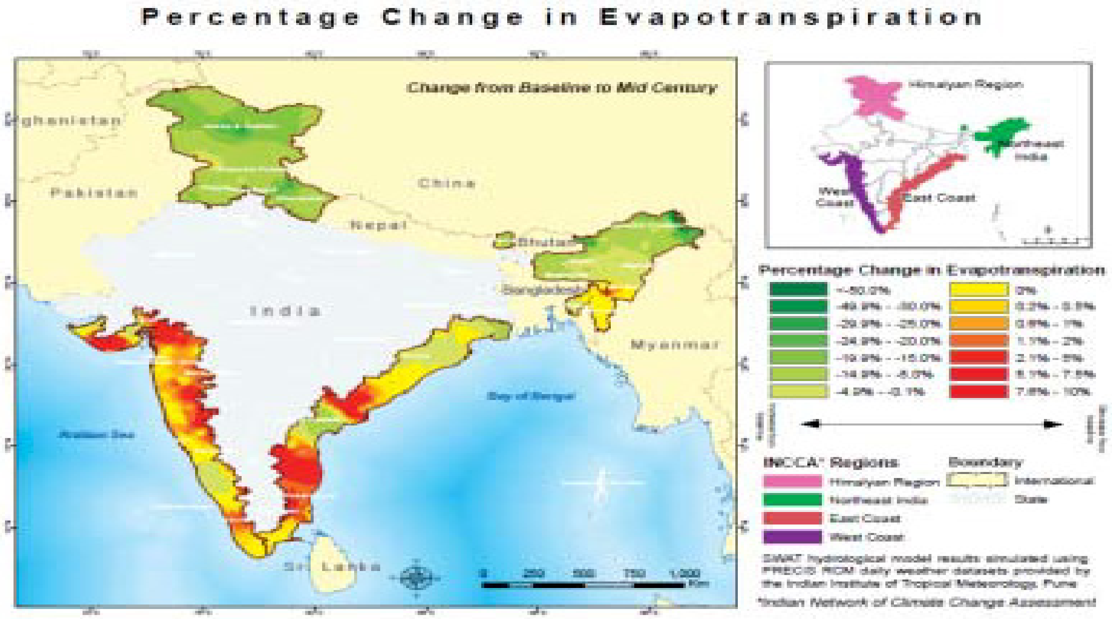


*Fig. 5 (b): Percentage change in evapotranspiration (crop water demand) towards the 2030s relative to the 1970s.*

Jain (2010) analyzed the effects of climate change on water balance components and found that water yield gains are highest in areas with lower evapotranspiration increases. Water yield in certain Indus River sub-basins may rise by as much as 50% in the 2030s. Annual rainfall in the Himalayan region is projected to fluctuate between 1268 ± 225.2 and 1604 ± 175.2 mm in the 2030s, with overall precipitation likely rising 5–13% compared to the 1970s. Although rain frequency is currently higher in eastern and northeastern India, projections for the 2030s indicate a broad decline in rainy day frequency across most of the country (Figs. 5a & 5b).

## CONCLUSION

Strengthening the resilience of agricultural systems to climate change is indispensable for ensuring universal access to food and water, particularly for smallholder and marginal farmers across Uttar Pradesh and India's resource-constrained rural regions. Agricultural productivity is jointly shaped by climate variability and its cascading effects on soil water balance and water use efficiency. While evidence of climate change impacts on agriculture is accumulating globally, countries like India face especially acute risks given their large agrarian populations, over-exploitation of natural resources, and limited adaptive capacity. Global warming will alter temperature and precipitation regimes in ways that directly affect soil moisture and groundwater recharge. Without proactive and planned adaptation strategies, the long-term consequences for the livelihood security of vulnerable communities could be profound. Accelerating investment in climate-smart agriculture, improving irrigation efficiency, and fostering pro-poor climate policies are therefore urgent priorities.

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