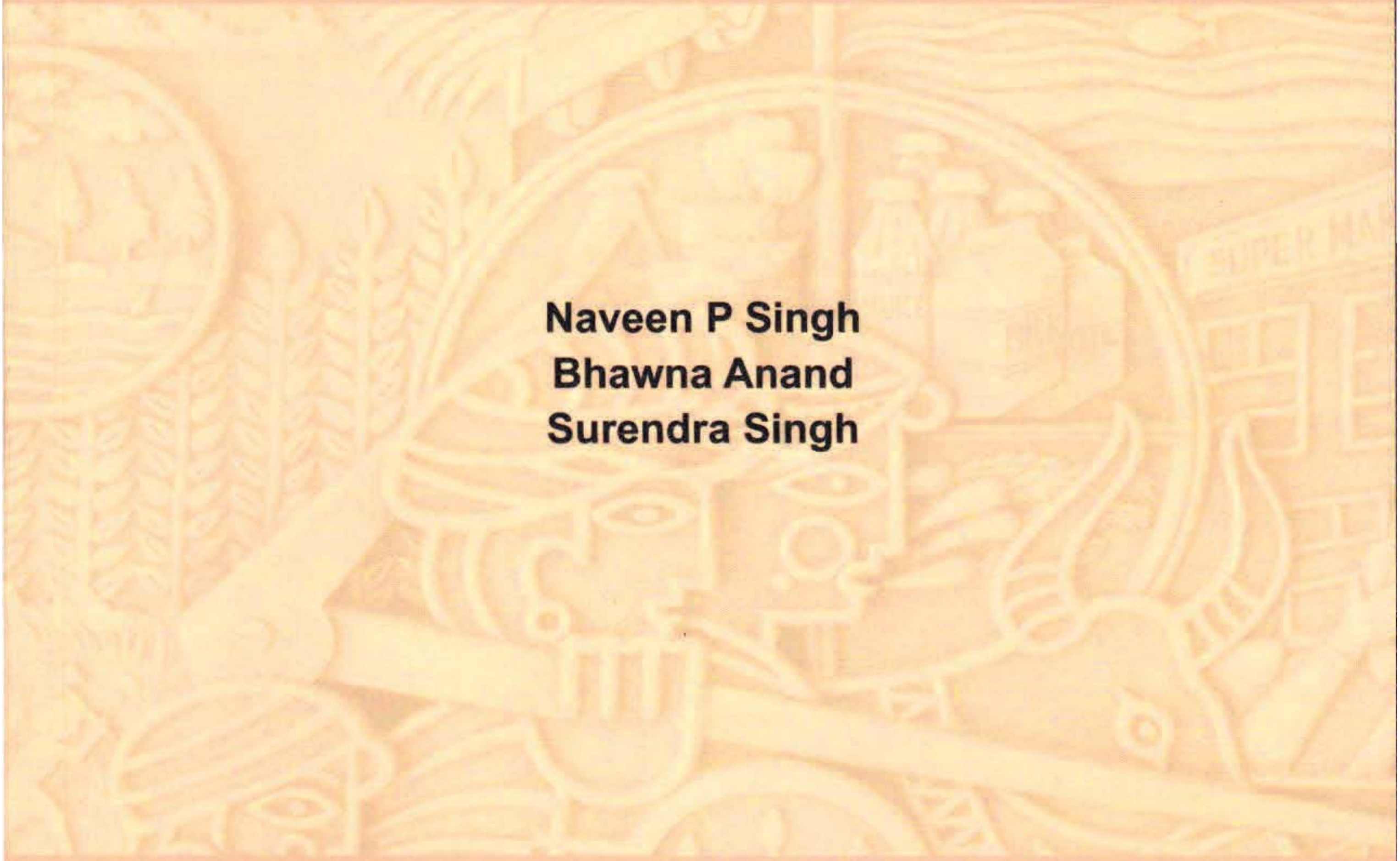
Policy Paper

35

Impact of Climate Change on Agriculture in India: Assessment for Agro-Climatic Zones



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Policy Paper 35

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Foreword

Despite the concerted efforts made during the post-green revolution period, India remains saddled with high rate of malnutrition and concerns of sustainability of agricultural systems. Beside the assurance of food security to meet the growing demands, the role of agriculture sector is crucial for livelihood sustenance and poverty alleviation. Among several factors that constrain the path to sustainable agriculture, climate change has emerged as the most formidable challenge, given that major tracts of the cropped area are still under rainfed conditions. There is now a great concern within the policy circle and scientific community to evolve dynamic response strategies to deal with this complex phenomenon.

Variability in climate and recurrence of extreme weather events, such as drought and floods, exacerbate the risks associated with food production and farm income. However, the impact of climate change and the consequent vulnerability vary across the regions. This is especially true in case of Indian sub-continent due to its wide variation across biophysical, socio-economic and agro-climatic characteristics. Thus, it is imperative to delineate the sensitivity of crops to changing climate at a spatially disaggregated scale.

This policy paper offers an insight into the potential impact of climate change on major *kharif* and *rabi* crop yields in different agro-climatic zones. It also provides useful inputs to formulate viable adaptation and mitigation strategies and policy options to combat the discernible effects of climate change on Indian agriculture. Constructive comments from the readers shall be useful to improve the research work in this area.

Suresh Pal
Director

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We hope that examining the impact of climate change on major crop yields in different agro-climatic zones will assist policy makers and development practitioners in identifying the vulnerable areas and in developing region-specific strategic priorities for mitigating the harmful effects of climatic variations on agricultural system.

Authors

Contents

Foreword *iii*

Acknowledgements *v*

List of Tables and Figures *ix*

Executive Summary *xi*

1. Introduction **1**

1.1 Climate Change Impact and Agriculture 1

1.2 Agro-Climatic Zones: Spread and Characteristics 6

2. Spatial and Temporal: Trend in Rainfall and Temperature **11**

2.1 Scouting the Pattern in Meteorological Variables 11

2.1.1 Studies on Temperature Pattern 11

2.1.2 Studies on Rainfall Pattern 12

2.2 Average Annual and Seasonal Rainfall and Temperature Across Agro-Climatic Zones 13

2.3 Trend in Annual and Seasonal Rainfall and Temperature Across Agro-Climatic Zones 13

3. Data and Methodology **19**

3.1 Data Sources 20

3.2 Methodology 21

3.2.1 Empirical Strategy 21

3.2.2 Future Climate Change Projections 22

4. Climate Change Impact and Futuristic Projections **24**

4.1 Impact of Climate Change on Crop Yields 24

4.1.1 Western Himalayan Region 24

4.1.2 Eastern Himalayan Region 24

4.1.3 Lower Gangetic Plains Region 26

4.1.4 Middle Gangetic Plains Region 28

4.1.5 Upper Gangetic Plains Region 28

4.1.6 Trans-Gangetic Plains Region 29

4.1.7 Eastern Plateau and Hills Region 32

4.1.8 Central Plateau and Hills Region 32

4.1.9 Western Plateau and Hills Region 35

4.1.10 Southern Plateau and Hill Region 35

4.1.11 East Coast Plains and Hills Region 38

4.1.12 West Coast Plains and Ghats Region 38

4.1.13 Gujarat Plains and Hills Region 40

4.1.14 Western Dry Region 42

4.2 Marginal Effects of Climate Change and Projected Change in Crop Yields 43

4.2.1 Marginal Impact and Projected Change for *kharif* Crop Yields 43

4.2.2 Marginal Impact and Projected Change for *rabi* Crop Yields 47

5 Conclusion and Way Forward **52**

References **54**

Appendices **63**

List of Tables and Figures

Tables

Table 1: Summary of projected impact of climate change on crop yield 4

Table 2: Spatial characteristics of Agro-climatic zones 9

Table 3: Average annual and seasonal rainfall and temperature, 1966-2011 14

Table 4: Trend in annual and seasonal rainfall and temperature, 1966-2011 17

Table 5: Projected changes in annual mean daily minimum and maximum temperature over India 23

Table 6: Regression estimates of climate and non-climatic factors on crop yields: Western Himalayan Region 25

Table 7: Regression estimates of climate and non-climatic factors on crop yields: Eastern Himalayan Region 26

Table 8: Regression estimates of climate and non-climatic factors on crop yields: Lower Gangetic Plains Region 27

Table 9: Regression estimates of climate and non-climatic factors on crop yields: Middle Gangetic Plains Region 29

Table 10: Regression estimates of climate and non-climatic factors on crop yields: Upper Gangetic Plains Region 30

Table 11: Regression estimates of climate and non-climatic factors on crop yields: Trans-Gangetic Plains Region 31

Table 12: Regression estimates of climate and non-climatic factors on crop yields: Eastern Plateau & Hills Region 33

Table 13: Regression estimates of climate and non-climatic factors on crop yields: Central Plateau & Hills Region 34

Table 14: Regression estimates of climate and non-climatic factors on crop yields: Western Plateau & Hills Region 36

Table 15: Regression estimates of climate and non-climatic factors on crop yields: Southern Plateau & Hills Region 37

Table 16: Regression estimates of climate and non-climatic factors on crop yields: East Coast Plains & Hills Region 39

Table 17: Regression estimates of climate and non-climatic factors on crop yields: West Coast Plains & Ghats Region 40

Table 18: Regression estimates of climate and non-climatic factors on crop yields: Gujarat Plains & Hills Region 41

Table 19: Regression estimates of climate and non-climatic factors on crop yields: Western Dry Region 42

Table 20: Marginal impacts (1966-2011) and projected change for *kharif* crop yields by 2030s, 2040s, 2050s and 2080s 44

Table 21: Marginal impacts (1966-2011) and projected change for *rabi* crop yields by 2030s, 2040s, 2050s and 2080s 48

Figures

Figure 1: Interaction between climate change and agriculture 2

Figure 2: Fifteen Agro-climatic zones of Planning Commission 7

Executive Summary

The harmful effects of climate change constraint the transition towards sustainable development across diverse ecosystems. It is now well established that agriculture sector is highly vulnerable to annual and seasonal variations in weather parameters. Changes in rainfall and temperatures (maximum and minimum) and sudden onset of extremes (dry spells, droughts, heat waves and floods) adversely affect crop growth leading to low level of productivity. Such climate-induced production risk not only deters food security and nutrition but also heightens the pressure on socio-economic stability of rural economies. However, the magnitude of climate impact on agricultural production and livelihood vary across the country's geographical landscape due to its diverse agro-climatic settings. Also, different location specific adaptation strategies and measures are adopted by the farmers premised on their economic and institutional capacity which are expected to shape the severity of climate impact. Several studies have been undertaken to quantify the potential impact of changes in climate variables on crop yields at national and regional/state level in the country. Nonetheless, uncertainty remains over the likely impact of changing climatic conditions on agriculture across homologous regions. Building on these considerations, this policy paper attempts to develop estimates of link between crop yield, climate variables and other socio-economic, infrastructural and technological factors for a 46-year period from 1966 to 2011, using Agro-climatic zones (ACZs) classification of the erstwhile Planning Commission, Government of India. Further, the study uses CORDEX South Asia multi-RCM reliability ensemble average estimate of projected changes in annual mean of daily minimum and maximum temperature over India under RCP 4.5 and 8.5 scenarios relative to the base 1976–2005 and assumed changes in rainfall for different time periods to project future impact on crop yields in each of the ACZs. To the best of our knowledge, such documentation of estimates of impact of climate over crop yields at ACZ level has not yet been conducted in India.

To understand the typography of the regions, we explored the major characteristic of 14 agro-climatic zones (excluding the island region), wherein it was observed that Southern Plateau & Hills and Eastern Plateau & Hills occupies a vast majority of geographical area while Lower Gangetic Plains covers the least. Middle Gangetic Plains (covering Bihar and parts of Uttar Pradesh) followed by Southern Plateau & Hills and Upper-Gangetic Plains were highly populated. Western Plateau & Hills had the largest net sown area of 19.67 Mha, followed by Southern Plateau & Hills (18.08 Mha)and Central Plateau & Hills (16.78 Mha). Trans-Gangetic Plains had the highest average food grain yield of 3.640 tonnes/ha, followed by Southern Plateau & Hills (2.720 tonnes/ha) and Lower Gangetic Plains (2.659 tonnes/ha).

During the period from 1966-2011, a rising trend was observed in both the mean maximum and minimum temperature, with relatively more pronounced changes in minimum temperature at both the annual and seasonal scale across the zones. Among the ACZs, Himalayan regions showed a strong increasing trend in both annual maximum and minimum temperature. In *kharif* season, Eastern Himalayan Region showed considerable warming. Except Trans-Gangetic Plains, Eastern Plateau & Hills, and Gujarat Plains & Hills, all other zones depicted rising trend in *kharif* maximum temperature. During *rabi* season, relatively strong increase in maximum temperature was observed in Western Himalayan Region, Middle Gangetic Plains, and Western Dry Region. Over the period, both Western and Eastern Himalayan Region experienced a negative trend in annual and *kharif* rainfall. The entire Gangetic Plains showed a decreasing trend in annual and *kharif* rainfall. A positive trend in annual and seasonal rainfall was observed in Southern Plateau & Hills (covering parts of Andhra Pradesh, Karnataka, and Tamil Nadu) and East Coast Plains & Hills.

The spatial and temporal assessments of the effects of climate change imply lowering of most of the *kharif* and *rabi* crop yields, but the relative magnitude of such effect vary by ACZs. Our results showed that rainfall had a positive influence on most of the crop yields, but was not sufficient enough to counterbalance the combined impacts of maximum and minimum temperature. Over the period 1966-2011, rice yield showed a high reduction in Eastern Himalayan Region (2.62%), Western Himalayan Region (2.34%) and Lower Gangetic Plains (1.17%). Maize yield was negatively impacted in Central Plateau & Hills, Western Dry Region, Trans-Gangetic and Upper Gangetic Plains. Sugarcane yield reduced by 9.91%, 8.02% and 3.66% in East Coast Plains & Hills, Middle Gangetic Plains and Western Plateau & Hills, respectively. Wheat yield showed a reduction in Western Dry Region, Eastern Himalayan Region, and Gangetic Plains. Rapeseed & mustard yield, with its strong climate tolerance capacity, showed a rise in East Coast Plains & Hills, Central Plateau & Hills, and Western Dry Region.

Our projections under RCP 4.5 indicate that rice yield will decline by 2.94% and 3.56% in Western and Eastern Himalayan Region in the near-term period. In Lower Gangetic Plains (parts of West Bengal), rice yield may decline up to 2% by 2040s. In both Eastern and Southern Plateau & Hills, rice yield is projected to reduce by about 1.7% during the mid-term period. The expected yield loss in case of sorghum is around 8% and 11% in Central Plateau & Hills by 2050s and 2080s, respectively. By 2030s, in Southern Plateau & Hills and West Coast Plains & Ghats, groundnut yield is expected to reduce by 1.96% and 1.82%, respectively. By 2080s, cotton yield is projected to decline up to 4% in Western Plateau & Hills. Pearl millet yield is likely to increase by 15.58% in Trans-Gangetic Plains, whereas it will reduce by 4.17% and 1.17% in Gujarat Plains & Hills and Western Dry Region by 2050s, respectively. Further, in Western Dry Region (parts of Rajasthan) wheat yield is projected to reduce by 7.17% in the long-term period. By 2050s wheat yield will decline by 4% and 2.57% in Eastern Himalayan Region and Trans-Gangetic Plains. In the long-term, rapeseed & mustard yield will increase in East Coast Plains & Hills, Central Plateau & Hills, and Western Dry Region. By 2050s, barley yield will reduce by 1.25% and 0.4% in Western Himalayan Region and Trans-Gangetic Plains, respectively.

The yield changes under RCP 8.5 temperature projections indicate that in the far future, maize yield is projected to increase by about 12% in Western Himalayan Region and Lower Gangetic Plains. In Western and Eastern Himalayan Region, rice yield is likely to reduce by 5.52% and 6.72% by 2050s, respectively. Rice yield in Lower Gangetic Plains (covering parts of West Bengal) is projected to decline by 4.87% by 2080s. The yield loss in case of pearl millet by 2080s is expected to be around 7% and 3% in Gujarat Plains & Hills and Western Dry Region, respectively. Under the mid and long-term period, cotton yield is expected to decline by 4.19% and 7.18%, in Western Plateau & Hills (covering parts of Maharashtra and Madhya Pradesh). By 2050s, finger millet yield will increase by 2.64% in West Coast Plains & Ghats. By the end of the century, sorghum yield is projected to decline by 19.08% in Central Plateau & Hills, and increase by about 18% in Western Plateau & Hills. In Middle Gangetic Plains and East Coast Plains & Hills, sugarcane yield is expected to decline by 21.17% and 24.79% by 2050s, respectively. The productivity of groundnut is projected to decline by 9.11% and 6.62% in Gujarat Plains & Hills and Southern Plateau & Hills, by 2080s. By the end of the century, wheat yield is projected to decline by 12.05% and 8.49% in Western Dry Region and Eastern Himalayan Region. Yield loss in case of barley was projected to be 0.54% and 1.63% in Trans-Gangetic Plains and Western Himalayan Region by 2050s. In the long-term, the rapeseed & mustard yield is expected to increase by around 11% to 12% in Central Plateau & Hills, West Coast Plains & Ghats, and Western Dry Region. By 2050s, linseed yield is expected to decline by 2.39% and 3.16% in Eastern and Southern Plateau & Hills, respectively.

The above analysis implies that the direct and near-term impact of climate change on crop yields will be smaller as compared to mid-and long-term projections. Further, changes in crop yields projected under RCP 8.5 were more pronounced compared to RCP 4.5, due to higher temperature projections under the former. Overall, Himalayan region, Gangetic Plains, Western Plateau and Coastal areas are some of the regions that appeared to be more vulnerable to current and future climatic changes.

The paper concludes that the underlying difference in agro-climatic settings, socio-economic conditions and adaptation measures leads to varying impact of climate change across ACZs. Hence, universal application of investment strategies for natural resource management and augmentation of agriculture productivity will only partially entail the desired target of reducing the climate-induced vulnerability and agriculture sustainability. Rather, comprehensive region-specific interventions should be emphasized, which when viewed from a dynamic perspective, helps mitigate the harmful effects of climate change on agriculture system in near to medium & long term.

1
Introduction

1.1 Climate change impact and agriculture

Climate change has emerged as the most potent global risk to the food security and agriculture-based livelihoods, impeding the path to sustainable development, especially in the developing nations. As per the Intergovernmental Panel on Climate Change (IPCC, 2018), greenhouse gas (GHG) accumulation owing to increased anthropogenic emissions has caused 1.0°C of global warming above pre-industrial levels, which is likely to reach 1.5°C between 2030 and 2052, causing greater frequency of extreme weather events (droughts, floods, and heat waves). For such a change in global climate, indigenous population and local communities dependent on agricultural or coastal livelihoods are highly susceptible to climatic aberrations. Over the past years, for different plausible scenarios scientific researches have well established the sensitivity of agriculture sector to the changing climatic conditions with concomitant implications for food security (Lobell & Field, 2007; Nelson et al. 2009; Lobell et al. 2011; Mishra et al., 2013). Agriculture production and productivity are directly influenced by changes in temperature, precipitation and carbon dioxide (CO_2) concentration in the atmosphere (Aggarwal, 2009; Falkenmark et al., 2009; Nelson et al., 2010). Temperature when exceed the critical physiological threshold adversely affects crop yield via increased heat stress on crops, water loss by evaporation and proliferation of weeds and pest (Singh et al., 2015). Also greater erraticism in the distribution of rainfall resulting in drought or flood like situations induces crop failures through higher runoff, soil erosion and loss of nutrients (Singh et al., 2015). There are evidences to support that elevated atmospheric carbon dioxide is expected to enhance water-use efficiency and accelerate plant photosynthesis (Tubiello & Ewert 2002; Kimball et al., 2002; Cline, 2007) leading to higher yields for some C3 crops. However, uncertainty still remains over the likely impact of CO_2 on crop yields due its complex interaction with variables like irrigation, fertilizer, rainfall, etc. and dynamic response of plant physiology. Agriculture also remains a major contributor to GHG emissions via crop cultivation, livestock, forestry and fisheries, the magnitude of which is further likely to increase in the future (FAO, 2016). Such dynamics of interaction between climate change and agriculture production and productivity, impacting farm income or profitability and food security has been schematized in Figure 1.

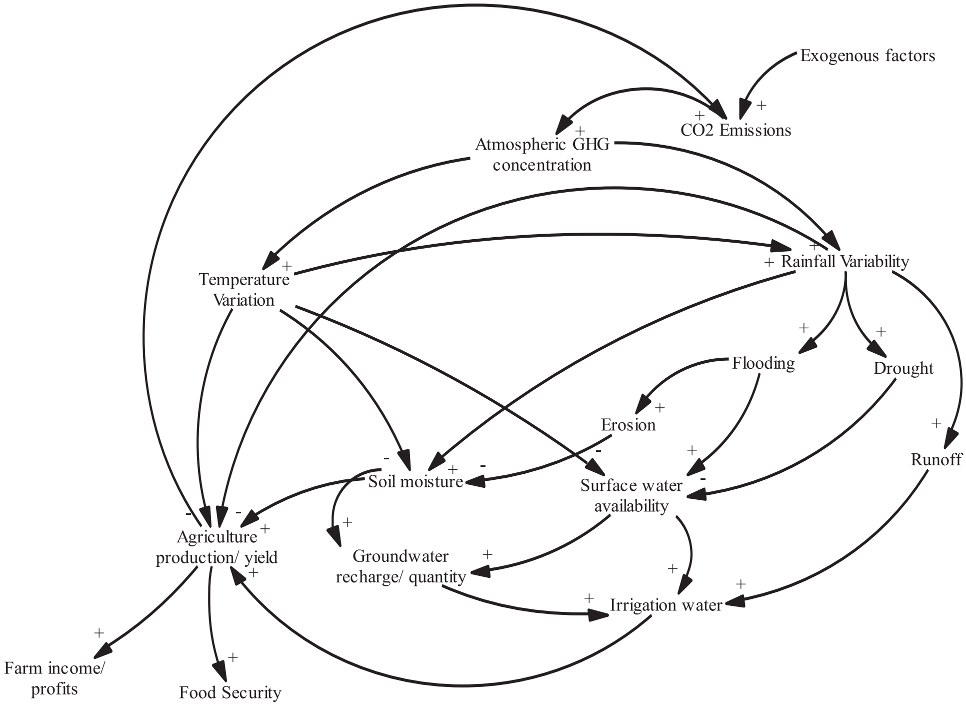

Figure 1: Interaction between climate change and agriculture

Source: Authors' schematization

Note: Causal relationships between variables are depicted with arrows from a cause to an effect. The polarities or direction of change (depicted as a '+' or '-') indicate how the cause' (arrow-tail variable) impacts the 'effect' (arrow-head variable). It must be noted that the signs are based on general perceptions of how a particular variable impacts other variable.

Based on geographical and technological aspects, crops in different regions behave differently to climate induced changes. For instance, Gornall et al., (2010) showed that a 2°C local warming in the mid-latitudes could increase wheat production by nearly 10 percent, whereas in low latitudes the same amount of warming may decrease yields by nearly the same amount. Several region specific adaptation strategies are employed and practiced at the farm level that helps to reduce climate vulnerability of crops. Such spatial disparities results in differential climate impacts and projections for different crop yields. However, it is important to note that impact of climate change on crop yields could be either positive or negative; nevertheless the past evidences generally postulate a negative effect of warming on crop production (Porter et al., 2014). Globally, during the period from 1980-2008, climate changes reduced yield of maize and wheat by 3.8% and 5.5%, respectively (Lobell et al., 2011). For South Asia, maize and sorghum yield are projected to reduce by 16% and 11% (Knox et al., 2012). The effect of climate change are expected to intensify overtime with negative effects becoming more prominent on agriculture beyond 2030 (FAO, 2016).

India, located close to the equator in the tropical region, is disproportionality at a higher risk to the climatic aberrations. The country has a diverse geographical and climatic condition which translates into differential regional impacts. Over the past decades a continuous rising trend has been observed in both the minimum and maximum temperature in India. Between 1901 and 2017, annual mean temperature in India has increased by 1.2°C (CSE, 2018) and is projected to increase more rapidly in the future (Kumar et al., 2011; Van Oldenborgh et al., 2018). In case of rainfall there are no clear long-term evidences of variations at the national level (Kothawale et al., 2010; Mondal et al., 2015) but regional analysis reveals a changing pattern of precipitation (Goswami et al., 2006; Jain & Kumar, 2012; Mallya et al., 2016). On the other side, prolonged breaks in southwest monsoon have exhibited an increased frequency of droughts (Udmale et al., 2015; Zhang et al., 2017, Choudhury & Sindhi, 2017) such that consecutive drought periods are being observed in different parts of the subcontinent. This poses enormous challenges for both food production and livelihoods of small scale farmers' who are already hapless with limited financial resources and access to infrastructure to invest in appropriate adaptation measures (Acharya, 2006; Khan et al., 2009; Jain et al., 2015; Patnaik & Das, 2017; Udamale et al., 2015).

Over the past years, substantial empirical work has been undertaken to examine and quantify the impact of climate on crop yields in India. Under different temperature and precipitation scenarios, a significant fall in the productivity of major crops like rice, wheat, maize, and millets have been observed in the country (Sanghi & Mendelsohn 2008; Guiteras 2009; Lobell et al. 2012; Auffhammer et al., 2012; Rao et al., 2014; Birthal et al., 2014a). For instance, during the period 1966–2002, rice yields decreased by around 5% to 10% (Auffhammer et al. 2011). In their district level analysis for the period 1971-2009, Rao et al. (2014) found reduction in *kharif* paddy yields by 411–859 kg/ha/°C rise. Padakandla (2016) showed that during 1981–2010, rice, tobacco and groundnut in Andhra Pradesh were significantly impacted by climate variations and crops grown in *rabi* season were more susceptible to changes in climate than those in *kharif* season. Moreover, studies on future projections also confirm fluctuations in major crop yields to climate change and variability (Table 1). Saseendran et al. (2000), reported continuous decline in rice yield for a rise in temperature up to 5°C and yield loss of 6% for every 1°C increment. By 2100, productivity of cereal crops like rice and wheat will be negatively impacted for 2-4°C increase in temperature and rise in the rate of precipitation (Mall et al., 2006).

Table 1: Summary of projected impact of climate change on crop yield

Region	Crop	Yield Impact (%)	Scenario	Reference
All India	Winter sorghum	-7, -11, -32	A2 2020, 2050, 2080	Srivastava et al. (2010)
	Irrigated rice	-4, -7, -10	A1B; A2; B1; B2 2020, 2050, 2080 +CO_2 MIROC; PRECIS/HadCM3	Kumar et al. (2013)
	Rainfed rice	–6, –2.5, –2.5		
	Monsoon maize	-21 to 0, –35 to 0, -35 to 0	A2 2020, 2050, 2080 HadCM3	Byjesh et al. (2010)
	Winter maize	–13 to +5, –50 to +5, –60 to –21		
	Rice	-2.5 to -7.1, -6.5 to -11.5, -5.9 to -15.4	2035, 2065, 2100	Birthal et al. (2014a)
	Maize	0.2 to -1.20, 0.0 to -3.7, 0.4 to -4.2		
	Wheat	-0.5 to -8.3, -3.5 to 15.4, -8.2 to -22.0		
	Wheat	-6 to -23 and -15 to -25	2050 and 2080	Kumar et al. (2014)
	Pearl millet	0.63-1.15	2010-2039	Gupta et al. (2014)
	Sorghum	-0.55 to -1.42		
	Soybean	-10 and -20	2100	Mall et al. (2004)
Northeast India	Irrigated rice	–10 to +5	A1B 2030 +CO_2 PRECIS/HadCM3	Kumar et al. (2011)
	Rainfed rice	–35 to +5		
	Maize	up to –40		
	Wheat	up to –20		
Coastal India	Irrigated rice	–10 to +5		
	Rainfed rice	–20 to +15		
	Irrigated maize	–50 to –15		
	Rainfed maize	–35 to +10		
Western Ghats	Irrigated rice	–11 to +5		
	Rainfed rice	–35 to +35		
	Maize	up to –50		
	Sorghum	up to –50		
Northwest India	Wheat	Rainfed: 29–37 Irrigated: 16–28 under	Modified climate (T_{max} + 1.0 °C, T_{min} + 1.5 °C, 2 × CO_2)	Attri and Rathore. (2003)

Gomti River basin, Uttar Pradesh	Rice	5.5-6.7, 16.6-20.2 and 26-33.4	A2, A1B and B1, 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099) MIROC 3.2	Abeysingha et al. (2016)
	Wheat	13.9-15.4, 23.6-25.6 and 25.2-27.9		
Tamil Nadu	Rice	-10	RegCM4, 2100	Saravana kumar et al. (2015)
	Sorghum	-9		
Bihar	Wheat	-11.1 to 2.7, -22.3 to -3.6 and –39.5 to -14.1	HADCM3 A2 scenario 2020, 2050 and 2080 (elevated CO_2)	Haris et al. (2013)
	Winter maize	8.4 to 18.2, 14.1 to 25.4 and 23.6 to 76.7		
West Bengal	Wet-season rice	-20 and -27.8	CGSM-InfoCrop, 2025 and 2050	Banerjee et al. (2016)
	Mustard	-20 to -33.9 and up to -40		
Indian Ganga basin	Rice	-43.2 and -24.8	2011–2040, REMO and HadRM3	Mishra et al. (2013)
	Wheat	-20.9 and -17.2		
North-Western Indo Gangetic plain	Wheat	-8 to -22	2050	Kumar et al. (2014)
Central Indo-Gangetic plain/ Eastern Indo-Gangetic plain		-24		
Rajasthan and Madhya Pradesh		-25		

Note: $+CO_2$ = with CO_2 effects; HadCM3, Hadley Centre Climate Prediction Model 3; HadRM3, Met Office Hadley Centre Regional Climate Model; MIROC, Model for Interdisciplinary Research on Climate; PRECIS, Providing Regional Climates for Impact Studies; CGSM, Crop growth simulation model; RegCM4, Regional Climate Model version 4; REMO, Max Planck Institute Regional Model.

Using CERES-wheat dynamic simulation model and climate change scenarios, Attri & Rathore (2003) projected an increase in wheat yield between 29% to 37% and 16% to 28% under rainfed and irrigated conditions, respectively, especially in northwest India. However, an increase in temperature by 3°C or more is likely to offset the positive effects of evaluated CO_2. There is a probability of 10% to 40% crop loss in India by 2080-2100 due to global warming (Aggarwal, 2008). Further, high losses in crop yield ranging from 30% to 40% have been projected by 2080, both with and without carbon fertilization (Cline, 2007). Studies done at the Indian Agricultural Research Institute (IARI) indicated the possibility of wheat yield loss of 4 to 5 million tonnes with every 1°C rise in temperature (Kalra et al., 2007). Further yields of wheat, soybean, mustard, groundnut, and potato are expected to decline by 3% to 7% for 1°C rise in temperature (Aggarwal, 2009). In another study, Srivastava et al. (2010) projected a reduction of 14% in monsoon sorghum in central and south-west zone and 2% in south-central zone by 2020 scenarios. However, appropriate adaptations could minimize such impact to about 10%, 2% and 3% in central, southcentral and southwest zones, respectively. Indian mustard is predicted to have lower yields under both rainfed and irrigated conditions (Boomiraj et al., 2010). Integrating 'Soil and Water Assessment Tool (SWAT)', a widely used hydrological model and climate change scenario generated from MIROC (HiRes) global climate model, Abeysingha et al., (2016) showed an increase of 5.5% to 6.7%, 16.6% to 20.2%, and 26% to 33.4% in mean annual rice yield and of 13.9% to 15.4%, 23.6% to 25.6%, and 25.2% to 27.9% in mean annual wheat yield in the Gomti River basin, during 2020s, 2050s, and 2080s, respectively.

Most of the previous assessments extrapolated climate impact on crop yields at a national/ state level, but there still remains a considerable uncertainty over the likely impact of change in climate parameters on crop yields for homologous environments. Hence, there is a dire need to get empirics related to the impact of climate change for major crops at agro-climatic zone level so that location specific R&D and dynamic, diversified and flexible interventions having local contexts (Singh et al., 2014; 2019) can be suggested. Thus, the present study examined the impact of climate change on major *kharif* and *rabi* crop yields, across agro-climatic zones (ACZs) delineated by the erstwhile Planning Commission of the Government of India (1989) for a 46 year period from 1966 to 2011. Further, the study projects the likely changes in crop yields across the ACZ for different time periods.

1.2 Agro-climatic zones: Spread and characteristics

Regional heterogeneity across Indian geographical landscape significantly influences the growth and development of agriculture system, leading to the inter/intra-regional disparities in rural income and technology adoptions (Basu & Guha, 1996). In the course of changing climatic conditions and depletion of natural resources base, sustainability of agriculture postulates developing effective technological and differentiated mechanisms that address region-specific farm-level issues. This requires spatially disaggregated plans for homogeneous regions (agro-climatic zones) that bring synergy between the core components of technology for resource-use efficiency.

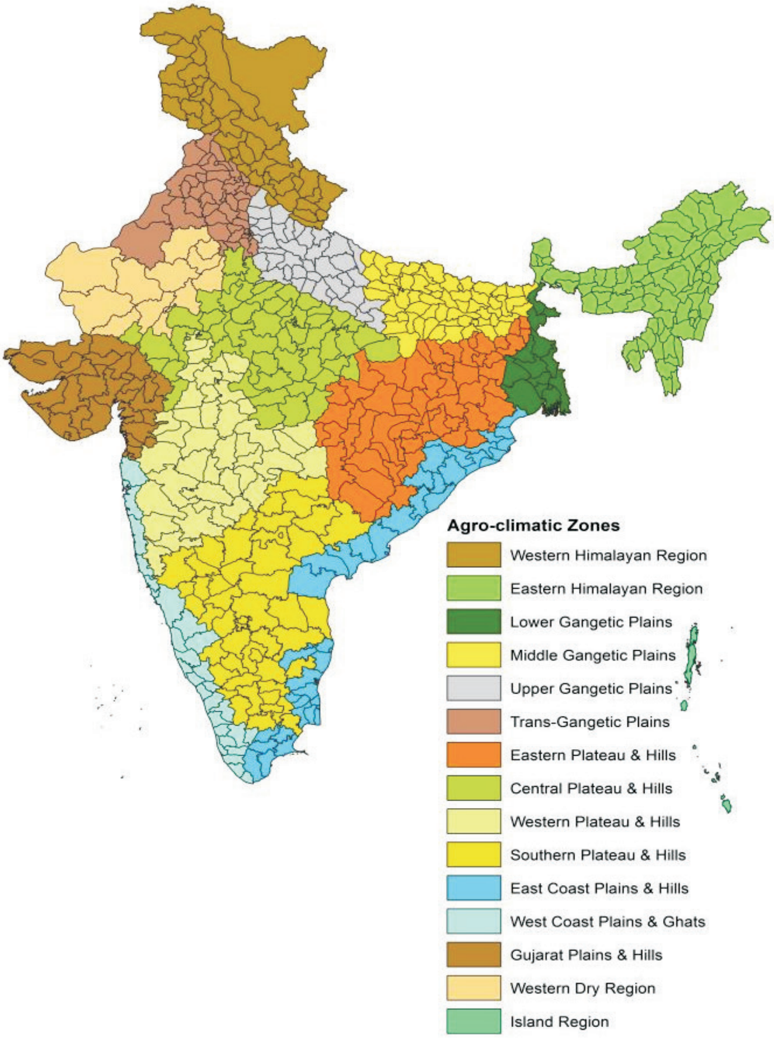

Figure 2: Fifteen Agro-climatic zones of Planning Commission
(map not to be scaled)

The genesis of regionalization of national agriculture economy by Planning Commission goes back to 1964 which resulted in retrenchment of 15 resource development regions/ agro-climatic zones, with 14 regions in the mainland and the islands of Bay of Bengal and the Arabian Sea (Figure 2). The sub-regionalization exercise was undertaken with the prime objective of internalizing the resource development potentials and physical distinction across states/ regions in the country into the developmental policy and programme formulation and implementation (Chand & Puri, 1983). Moreover, as laid down by the Government of India (1989), the agro-climatic regional planning aims:

a) to attempt a broad demand-supply balance of major commodities at the national level based on a careful analysis of the potential and prospects of various zones.

b) to maximize the net income of the producers,

c) to generate additional employment for the benefit of the landless labourers',

d) to provide scientific and sustainable use of natural resources particularly land, water and forest, in the long run.

The segregation of cultivable land into agronomically homologous regions was intrinsically dictated by the principal attributes of the agriculture economy, namely, soil properties, climate, rainfall and temperature regimes, and water availability, including the state of aquifers (Alagh, 1990). Table 2, depicts the spatial characteristic of ACZs where it was found that Southern Plateau & Hills (comprising parts of Andhra Pradesh, Karnataka, and Tamil Nadu) with 12.38% and Eastern Plateau & Hills with 11.50% covered the largest geographical area among the ACZs. On the other spectrum, Lower Gangetic Plains (parts of West Bengal) had the lowest area coverage. In terms of population, Middle Gangetic Plains, comprising Bihar and parts of Uttar Pradesh, was the most populated, while Western Himalayan Region had the lowest population. Western Plateau & Hills had the largest net sown area of 19.67 million hectares, followed by Southern and Central Plateau & Hills. Of the total gross cropped area, 27.59, 25.13 and 20.47 million hectares were occupied by Central, Western, and Southern Plateau & Hills, respectively. Among the ACZs, Trans-Gangetic Plains (3.64 tonnes) followed by Southern Plateau & Hills (2.72 tonnes) and Lower Gangetic Plains (2.65 tonnes) recorded the highest average food grain yield per hectare during 2016-17.

Table 2. Spatial characteristics of Agro-climatic zones

Agro-climatic zone	Climate	Area$^{\$}$ (sq. km) 2011	Population* (Millions) 2011	Net sown area (Mha) 2016-17	Gross sown area (Mha) 2016-17	Food grains yield (Ton/ha) 2016-17	States@
Western Himalayan Region	Cold Arid to Humid	331392 (10.08)	29.492 (2.44)	1.995	3.203	2.178	Himachal Pradesh (12,16.80), Jammu & Kashmir^{w} (22, 67.06), Uttarakhand (13,16.14)
Eastern Himalayan Region	Per Humid to Humid	274942 (8.36)	54.310 (4.49)	4.916	5.972	1.828	Arunachal Pradesh (16, 30.46), Assam (27, 28.53), Manipur (9, 8.12), Meghalaya (7, 8.16), Mizoram (8, 7.67), Nagaland (11, 6.03), Sikkim (4, 2.58), Tripura (4, 3.81), West Bengal (3, 4.64)
Lower Gangetic Plains Region	Moist Sub Humid to Dry Sub Humid	69730 (2.12)	79.807 (6.59)	4.204	8.501	2.659	West Bengal (15, 100)
Middle Gangetic Plains Region	Moist Sub Humid to Dry Sub Humid	163793 (4.98)	169.736 (14.02)	9.704	14.580	1.590	Uttar Pradesh (23, 42.51), Bihar (38, 57.49)
Upper Gangetic Plains Region	Dry Sub-Humid to Semi-Arid	141881 (4.32)	124.493 (10.28)	9.590	15.288	2.345	Uttar Pradesh (41, 100)
Trans Gangetic Plains Region	Extreme Arid to Dry Sub-Humid	147044 (4.47)	77.045 (6.36)	10.626	17.865	3.640	Chandigarh (1, 0.08), Delhi (9,1.01), Haryana (21, 30.07), Punjab (20, 34.25), Rajasthan (3, 34.60)
Eastern Plateau & Hills Region	Moist Sub-Humid to Dry Sub-Humid	378178 (11.50)	91.990 (7.60)	10.461	10.967	1.560	Chhattisgarh (18, 35.75) Jharkhand (24, 21.08), Madhya Pradesh (5, 8.58), Maharashtra (3, 6.28), Odisha (17, 26.66), West Bengal (1, 1.66)

Agro-climatic zone	Climate	Area$^{\$}$ (sq. km) 2011	Population* (Millions) 2011	Net sown area (Mha) 2016-17	Gross sown area (Mha) 2016-17	Food grains yield (Ton/ha) 2016-17	States@
Central Plateau & Hills Region	Semi-Arid to Dry Sub-Humid	334700 (10.18)	86.527 (7.15)	16.784	27.595	1.947	Madhya Pradesh (31, 58.58), Rajasthan (18, 32.63), Uttar Pradesh (7, 8.79)
Western Plateau & Hills Region	Semi-Arid	332979 (10.13)	101.767 (8.40)	19.666	25.132	1.561	Madhya Pradesh (14, 23.94), Maharashtra (25, 76.06)
Southern Plateau & Hills Region	Semi-Arid	407014 (12.38)	132.852 (10.97)	18.082	20.473	2.720	Andhra Pradesh (15, 47.96), Karnataka (23, 37.10), Tamil Nadu (13, 14.94)
East Coast Plains & Hills Region	Semi-Arid to Dry Sub-Humid	199900 (6.08)	942.808 (7.79)	7.205	8.584	2.076	Andhra Pradesh (8, 39.93), Odisha (13, 27.45) Puducherry (4, 0.25), Tamil Nadu (17, 32.37)
West Coast Plains & Ghats Region	Dry Sub-Humid to Per Humid	118634 (3.61)	75.722 (6.25)	4.299	6.860	1.366	Goa (2, 3.12), Karnataka (7, 34.39), Kerala (14, 32.75) Maharashtra (6, 25.90, Tamil Nadu (2, 3.84)
Gujarat Plains & Hills Region	Arid to Dry Sub-Humid	196846 (5.99)	61.026 (5.04)	7.931	12.238	2.036	Gujarat (26, 99.69), Dadra & Nagar Haveli (1, 0.25), Daman & Diu (2, 0.06)
Western Dry Region	Arid to Extremely Arid	182157 (5.54)	31.354 (2.59)	9.727	12.970	1.962	Rajasthan (12, 100)

Source: Authors Estimation. Census of India (2011), Singh (2006), NICRA District Agricultural Contingency Plans, Directorate of Economics and Statistics, Ministry of Agriculture and Farmers' Welfare.

Note: As per Census 2011, total geographical area of India: 3287469 sq. km, total population: 1210854977 persons and total districts: 640

W includes illegal occupied J&K area by Pakistan and China.

$ Figures in the parentheses includes percentage share of ACZ in the total geographical area of the country.

* Figures in the parentheses includes percentage share of ACZ in the total population of the country.

@ Figure in the parenthesis represents (number of districts, total percentage area of state under ACZ)

2

Spatial and Temporal Trend in Rainfall and Temperature

2.1 Scouting the pattern in meteorological variables

2.1.1 Studies on temperature pattern

Several studies that attempted to analyse the variability/trend in meteorological variables in the country reported a rising trend in mean surface temperatures which differ in seasonal and regional distribution (Hingane et al., 1985; Srivastava et al., 1992; Rupa Kumar et al., 1994; De & Mukhopadhyay, 1998; Pant et al., 1999; Singh & Sontakke, 2002; Singh et al., 2001; Kothawale & Rupa Kumar, 2005; Kothawale et al., 2010; Jayaraman & Murari, 2014; Rao et al., 2014; Mondal et al., 2015). Hingane et al. (1985), reported a warming trend in mean annual temperature in India for 1901-1982. Pant & Kumar (1997), analysed seasonal and annual air temperature series for 1881-1997 and showed that there is a significant warming trend of 0.57°C per 100 years. In their study, Kothawale & Rupa Kumar (2005) found a significant warming trend of 0.05°C/10 years during the period from 1901-2003, mostly due to the rise in maximum temperature, while a relatively accelerated warming of 0.22°C/10 years was observed during 1971-2003 due to increase in both maximum (0.20°C/10 years) and minimum temperatures (0.21°C/10 years). An overall rise of about 0.6°C to 0.8°C in mean annual temperatures for India during 1850–2010 was observed by Jayaraman & Murari, (2014). Paul et al. (2015), revealed an increasing trend in mean monthly temperature for the period of 1901-2002 in all the four agro-climatic zones (arid, humid, semi-arid temperate and semi-arid tropic). In spatial and temporal analysis of temperature for 107 years (1901-2007), Mondal et al. (2015), concluded a significant increasing trend in both maximum and minimum temperature, with stronger intensity of maximum temperature during the period. Across the regional scales, a significant rise in annual minimum temperature was found in east and west coasts and interior peninsula, while increase in the maximum temperature was highest in the Western Himalayan Region. Similarly, Bhutiyani et al. (2007), found increasing trend in maximum, minimum, mean, and diurnal temperature ranges over the north-western Himalayan region during the 20th century.

2.1.2 Studies on rainfall pattern

The studies examining trend in rainfall at spatial and temporal scales are segregated over conjectures. Owing to high spatial variability in rainfall, over a longer period of time some studies found no significant trend in annual and summer monsoon for the country as a whole, although some inter-decadal variability has been reported (Mooley & Parthasarathy, 1984; Thapliyal & Kulshrestha, 1991; Pant & Kumar, 1997; Pant et al., 1999; Stephenson et al., 2001). Using observed data for a 131-year period (1971–2001), Kripalani et al. (2003) found random fluctuations in annual rainfall and distinct alternate epochs (lasting approximately three decades) of above-and below-normal rainfall for decadal rainfall. They also concluded that this inter-annual and decadal variability appears to have no relationship to global warming. In their study Dash et al. (2007), reported a decreasing trend in monsoon rainfall and an increasing trend in pre-monsoon and post-monsoon for the period 1871–2002. For the period 1871-2011, a decrease in annual rainfall (-0.04mm/year) and monsoon rainfall (-0.23mm/year) for the entire sub-continent was reported by Mondal et al., (2015). In a recent study, Kothawale & Rajeevan et al. (2017), found a very weak decreasing trend of -0.18 mm/year and -0.17 mm/year for the periods 1871-2016 and 1981-2016 for monsoon rainfall in the country, respectively. Significant changes in rainfall have been found at the regional/ sub-divisional scale (Chaudhary & Abhyankar, 1979; Kumar et al., 2005; Dash et al., 2007; Kripalani et al., 2003; Singh & Sontakke, 2002; Goswami et al., 2006; Kumar & Jain, 2009; Jain & Kumar, 2012; Mallya et al., 2016). Rupa Kumar et al. (1992) found significant increasing trend in monsoon seasonal rainfall along the west coast, north Andhra Pradesh, and northwest India while significant decreasing trend was found over east Madhya Pradesh and adjoining areas, northeast India and parts of Gujarat and Kerala. Roxy et al. (2015), demonstrated a significant weakening trend in summer rainfall during 1901–2012 over the central-east and northern regions of India. Studies also indicate an increased frequency of extreme precipitation and decrease in the number of rainy days and total annual precipitation in the country. Using daily rainfall data from 1951 to 2000, Goswami et al., (2006) showed a significant rising trend in the frequency and magnitude of extreme rainfall event over central India during the monsoon season. Variability and long-term trends of extreme rainfall events over central India were examined by Rajeevan et al. (2008) using 104 years (1901–2004) of high-resolution daily grided rainfall data. They found a statistically-significant, long-term trend of 6% per decade in the frequency of extreme rainfall events. According to them, the increasing trend of extreme rainfall events in the last five decades could be associated with the increasing trend of sea surface temperatures and surface latent heat flux over the tropical Indian Ocean.

2.2 Average annual and seasonal rainfall and temperature across Agro-climatic zones

A wide variation was found in the distribution of rainfall across the ACZs (Table 3). It was observed that Eastern Himalayan Region (comprising north-eastern states and parts of West Bengal), followed by the West Coast Plains & Ghats received the highest amount of annual rainfall, whereas Western Dry Region (parts of Rajasthan) and Trans-Gangetic Plains received the lowest. During *kharif* season, zones such as West Coast Plains & Ghats, Eastern Himalayan Region, and Lower Gangetic Plains received the highest amount of rainfall of 1816 mm, 1713 mm, and 1120 mm, respectively. On the other hand, Western Dry Region, Southern Plateau & Hills, and Trans-Gangetic Plains received the lowest amount of rainfall. East Coast Plains & Hills and West Coast Plains & Ghats recorded the maximum amount of rainfall during the *rabi* season.

The annual minimum temperature was the lowest in Western Himalayan Region, comprising high altitude states of Himachal Pradesh, Jammu & Kashmir, and Uttarakhand. On the other hand, East Coast Plains & Hills, Southern Plateau & Hills, and Lower Gangetic Plains recorded the highest annual minimum temperature among the ACZs. Arid and semi-arid regions such as Western Dry Region and Western Plateau & Hills recorded the highest annual maximum temperature. Further, it was observed that minimum temperature during *kharif* season remained in the range of 21°C to 26°C. West Coast Plains & Ghats, followed by the Himalayan regions, had the lowest degree of *kharif* maximum temperature of about 29°C and 30°C, respectively. In *rabi* season, the highest minimum temperature of 20.22°C was observed in East Coast Plains & Hills, followed by Southern Plateau & Hills (comprising parts of Andhra Pradesh, Karnataka, and Tamil Nadu) at 19.49°C.

2.3 Trend in annual and seasonal rainfall and temperature across Agro-climatic zones

The spatial and temporal assessment indicates a significant rising trend in both the minimum and maximum temperature, though the magnitude of such trend vary by ACZs. A significant increasing trend in annual maximum (0.020°C/year) and minimum temperature (0.035°C/year) was observed for Western Himalayan Region. This was followed by Eastern Himalayan Region where annual minimum temperature recorded an increasing trend of 0.028°C/year and Western Dry Region where a rise

Table 3: Average annual and seasonal rainfall and temperature, 1966-2011

Agro-Climatic Zone	Annual			*Kharif*			*Rabi*		
	Rainfall (mm)	MinT (°C)	MaxT (°C)	Rainfall (mm)	MinT (°C)	MaxT (°C)	Rainfall (mm)	MinT (°C)	MaxT (°C)
Western Himalayan Region	1158.21 (13.50)	14.18 (0.14)	26.27 (0.18)	830.98 (12.63)	21.13 (0.16)	30.62 (0.17)	233.8657 (5.09)	8.39 (0.12)	21.50 (0.17)
Eastern Himalayan Region	2463.50 (34.43)	18.40 (0.05)	27.86 (0.06)	1713.33 (29.36)	23.55 (0.05)	30.09 (0.06)	290.64 (4.87)	14.39 (0.04)	25.78 (0.06)
Lower Gangetic Plains Region	1485.36 (18.07)	21.21 (0.05)	31.55 (0.05)	1120.22 (14.80)	25.47 (0.03)	32.53 (0.04)	199.79 (5.77)	17.19 (0.07)	29.24 (0.04)
Middle Gangetic Plains Region	1113.14 (10.35)	19.45 (0.02)	32.08 (0.02)	961.08 (8.80)	25.61 (0.02)	34.12 (0.03)	93.22 (2.04)	13.93 (0.02)	28.40 (0.02)
Upper Gangetic Plains Region	878.24 (8.21)	18.87 (0.02)	32.28 (0.02)	773.76 (7.46)	25.98 (0.02)	35.26 (0.02)	78.50 (1.48)	12.54 (0.02)	27.86 (0.02)
Trans Gangetic Plains Region	672.73 (11.40)	18.26 (0.02)	31.90 (0.03)	540.63 (9.62)	26.15 (0.03)	36.49 (0.04)	97.94 (2.44)	11.46 (0.03)	26.69 (0.03)
Eastern Plateau & Hills Region	1324.19 (8.40)	19.95 (0.03)	31.42 (0.04)	1116.76 (7.20)	23.78 (0.02)	31.72 (0.04)	140.01 (2.82)	15.95 (0.04)	28.98 (0.05)
Central Plateau & Hills Region	916.80 (6.89)	19.13 (0.01)	32.00 (0.05)	840.07 (6.55)	24.24 (0.02)	32.85 (0.04)	66.15 (1.33)	13.98 (0.03)	29.00 (0.06)

Western Plateau & Hills Region	929.05 (9.41)	19.95 (0.02)	32.91 (0.03)	814.98 (9.04)	22.97 (0.02)	31.63 (0.04)	95.14 (1.90)	16.46 (0.04)	31.72 (0.03)
Southern Plateau & Hills Region	843.24 (7.27)	21.41 (0.03)	32.23 (0.04)	29.25 (6.98)	22.70 (0.04)	31.20 (0.05)	234.91 (4.62)	19.49 (0.03)	31.28 (0.03)
East Coast Plains & Hills Region	1100.96 (12.74)	22.38 (0.05)	31.34 (0.07)	600.91 (12.47)	24.31 (0.06)	31.92 (0.09)	405.62 (8.98)	20.22 (0.06)	29.79 (0.06)
West Coast Plains & Ghats Region	2417.93 (31.01)	20.60 (0.05)	30.36 (0.10)	1816.43 (33.29)	21.56 (0.07)	29.08 (0.10)	406.12 (8.39)	19.10 (0.06)	29.99 (0.08)
Gujarat Plains & Hills Region	861.77 (17.49)	19.95 (0.05)	32.17 (0.09)	822.18 (17.23)	23.97 (0.07)	31.69 (0.10)	34.38 (1.60)	16.14 (0.05)	31.03 (0.09)
Western Dry Region	427.54 (9.00)	18.77 (0.03)	33.08 (0.04)	379.96 (8.64)	25.43 (0.04)	35.53 (0.06)	28.90 (1.26)	12.63 (0.05)	29.33 (0.06)

Note: Figures in the parenthesis are the standard error
kharif season (June-September) and *rabi* season (October-March)

of 0.018°C/year was recorded in annual maximum temperature. However, a low positive significant trend in annual maximum temperature was observed in Eastern Plateau & Hills, whereas a similar trend in case of annual minimum temperature was seen for Gujarat Plains & Hills. During *kharif* season, a notable warming trend of 0.026°C/year in minimum temperature and 0.018°C/year in maximum temperature was observed in Eastern Himalayan Region. Further, as shown in Table 4, except Trans-Gangetic Plains, Eastern Plateau & Hills and Gujarat Plains & Hills, *kharif* maximum temperature showed a rising trend in all other zones. On the other spectrum, minimum temperature during *kharif* season showed a low warming trend in Middle-Gangetic Plains (0.003°C/year), Trans-Gangetic Plains (0.004°C/year) and West Coast Plains & Ghats (0.007°C/year). Himalayan regions depicted a high increasing trend (0.042°C/year and 0.033°C/year) in minimum temperature during the *rabi* season. A strong rising trend was observed in Western Himalayan Region (0.027°C/year), followed by Middle-Gangetic Plains (Bihar and parts of Uttar Pradesh) and Western Dry Region (covering parts of Rajasthan) during *rabi* season. Overall, in analysing temperatures at a spatially-disaggregated level, it may be construed that the warming trend in average annual and seasonal minimum temperature was more pronounced than the maximum temperature across most of the ACZs.

During the period 1966-2011, a significant negative trend in annual rainfall was observed for both the Western (-3.93mm/year) and Eastern (-3.814mm/year) Himalayan Region. The entire Gangetic Plains Region showed a decreasing trend in annual rainfall, with the maximum decline observed in Upper Gangetic Plains (covering parts of Uttar Pradesh). Further, a significant negative trend of -2.432mm/year in annual rainfall was also seen in Central Plateau & Hills (comprising parts of Madhya Pradesh, Rajasthan, and Uttar Pradesh) and -0.288mm/year in Western Dry Region. On the other hand, zones such as Eastern, Western, Southern Plateau & Hills, East Coast Plains & Hills, West Coast Plains & Ghats, and Gujarat Plains & Hills showed an increasing trend in the annual rainfall. In the *kharif* season, a strong declining trend in rainfall was observed in Eastern Himalayan Region (-3.762mm/year), followed by Upper Gangetic Plains (-3.134mm/year) and Western Himalayan Region (-2.794mm/year). The Gujarat Plains & Hills, Eastern Plateau & Hills, East Coast Plains & Hills, Western Plateau & Hills, and Southern Plateau & Hills depicted a significant positive trend in *kharif* rainfall. A non-significant, increasing trend in *rabi* rainfall was observed in zones such as Lower Gangetic Plains (0.156mm/year), East Coast Plains & Hills (0.232mm/year), and Western Dry Region (0.017mm/year). West Coast Plains & Ghats (comprising Goa, Kerala and parts of Karnataka, Maharashtra, and Tamil Nadu) showed a strong increasing trend of 2.591mm/year in *rabi* rainfall.

Table 4: Trend in rainfall and temperature, 1966-2011

Agro-Climatic Zone	Annual			*Kharif*			*Rabi*		
	Rainfall (mm)	MinT (°C)	MaxT (°C)	Rainfall (mm)	MinT (°C)	MaxT (°C)	Rainfall (mm)	MinT (°C)	MaxT (°C)
Western Himalayan Region	-3.9378*** (0.7472)	0.0355*** (0.0012)	0.0200*** (0.0015)	-2.7948*** (0.6703)	0.0204*** (0.0011)	0.0043*** (0.0015)	-0.9950*** (0.2873)	0.0424*** (0.0014)	0.0275*** (0.0019)
Eastern Himalayan Region	-3.8147*** (1.3555)	0.0287*** (0.0010)	0.0163*** (0.0010)	-3.7629*** (1.0546)	0.0264*** (0.0009)	0.0186*** (0.0010)	-0.3024 (0.3218)	0.0334*** (0.0013)	0.0177*** (0.0013)
Lower Gangetic Plains Region	-1.4907 (1.1582)	0.0244*** (0.0014)	0.0071*** (0.0016)	-1.7468* (0.9650)	0.0192*** (0.0015)	0.0036*** (0.0017)	0.1562 (0.4048)	0.0285*** (0.0016)	0.0099*** (0.0017)
Middle Gangetic Plains Region	-1.2362*** (0.6159)	0.0243*** (0.0009)	0.0144*** (0.0010)	-0.7386 (0.5639)	0.0038*** (0.0013)	0.0034** (0.0014)	-0.7572*** (0.1446)	0.0297*** (0.0010)	0.0227*** (0.0012)
Upper Gangetic Plains Region	-3.4057*** (0.5003)	0.0211*** (0.0007)	0.0107*** (0.0009)	-3.1343*** (0.4680)	0.0190*** (0.0009)	0.0094*** (0.0012)	-0.4441*** (0.1045)	0.0210*** (0.0009)	0.0110*** (0.0011)
Trans Gangetic Plains Region	-0.1965 (0.5024)	0.0229*** (0.0011)	0.0120*** (0.0011)	-0.2353 (0.4826)	0.0040*** (0.0016)	-0.0016 (0.0015)	-0.2007 (0.1244)	0.0278*** (0.0016)	0.0139*** (0.0014)
Eastern Plateau & Hills Region	1.7703*** (0.5770)	0.0144*** (0.0008)	0.0045*** (0.0009)	1.7431*** (0.5055)	0.0051*** (0.0010)	-0.0044 (0.0013)	-0.3174* (0.1901)	0.0210*** (0.0010)	0.0107*** (0.0010)
Central Plateau & Hills Region	-2.4320*** (0.3961)	0.0199*** (0.0006)	0.0163*** (0.0007)	-2.0376*** (0.3880)	0.0153*** (0.0010)	0.0117*** (0.0011)	-0.4735*** (0.0919)	0.0222*** (0.0008)	0.0193*** (0.0009)

Agro-Climatic Zone	Annual			*Kharif*			*Rabi*		
	Rainfall (mm)	MinT (°C)	MaxT (°C)	Rainfall (mm)	MinT (°C)	MaxT (°C)	Rainfall (mm)	MinT (°C)	MaxT (°C)
Western Plateau & Hills Region	1.0617** (0.5378)	0.0118*** (0.0006)	0.0110*** (0.0006)	1.2148** (0.5234)	0.0020** (0.0010)	0.0013 (0.0010)	-0.0783 (0.1299)	0.0184*** (0.0009)	0.0179*** (0.0009)
Southern Plateau & Hills Region	1.4263*** (0.4064)	0.0157*** (0.0005)	0.0150*** (0.0005)	0.9021*** (0.3275)	0.0105*** (0.0008)	0.0098*** (0.0008)	0.4233*** (0.2145)	0.0201*** (0.0006)	0.0195*** (0.0006)
East Coast Plains & Hills Region	2.6227*** (0.6880)	0.0166*** (0.0008)	0.0143*** (0.0008)	1.7288*** (0.4319)	0.0144*** (0.0010)	0.0125*** (0.0010)	0.2327 (0.4548)	0.0188*** (0.0009)	0.0163*** (0.0009)
West Coast Plains & Ghats Region	0.5458 (1.1999)	0.0108*** (0.0007)	0.0118*** (0.0007)	-2.2155** (1.1063)	0.0073*** (0.0009)	0.0100*** (0.0012)	2.5912*** (0.3787)	0.0146*** (0.0009)	0.0150*** (0.0008)
Gujarat Plains & Hills Region	2.7633*** (0.8554)	0.0071*** (0.0008)	0.0067*** (0.0008)	2.9252*** (0.8589)	-0.0005 (0.0011)	-0.0011 (0.0011)	-0.1377 (0.1150)	0.0109*** (0.0011)	0.0108*** (0.0011)
Western Dry Region	-0.2888 (0.5573)	0.0216*** (0.0014)	0.0186*** (0.0014)	-0.3618 (0.5447)	0.0153*** (0.0019)	0.0121*** (0.0020)	0.0176 (0.0892)	0.0231*** (0.0016)	0.0202*** (0.0019)

Note: Trend has been estimated incorporating district-fixed effects

Stationarity was tested using panel unit root tests for the climatic variables; rainfall and temperatures (maximum and minimum) series were found to be stationary at levels.

Figures in the parenthesis are robust standard errors

Significance level: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

3

Data and Methodology

There have been continuous methodological improvements for estimating the impact of climate variables (temperatures and rainfall) on agriculture systems. Each method has been developed systematically to address some of the limitations of the former. In literature, three approaches have been widely used for analysing the economic effects of climate change on crop productivity: (i) Production function method, (ii) Ricardian model, and (iii) Panel data approach.

Production function method, also known as crop modelling or agronomic-economic model, is a laboratory-type setup wherein under controlled experimental conditions, crops are exposed to a varied degree of climate scenarios and carbon dioxide levels, keeping farm level adaptations constant, to study how change in rainfall, temperature and carbon dioxide precisely affect crops (Rosenzweig & Parry, 1994; Rao and Sinha, 1994; Lal et al., 1998; Mathauda et al., 2000). Yield changes are then incorporated in economic models to predict output and net revenue. Since the approach does not reflect the farmer's adaptive behaviour to changing climatic conditions, it is likely to produce climate estimates that are downward biased (Deschenes & Greenstone, 2007). In an alternative to crop simulation models, Mendelsohn et al., (1994) advocated the cross-sectional Ricardian approach, which measures the impact of climate change on the net rent or value of agriculture land while integrating farmers' compensatory responses pertaining to the changes in both crop and input decisions. This method is similar to the hedonic price method of environmental valuation and explains regional differences in land values or productivity due to differences in climatic factors. However, the major lacuna with Ricardian approach is the omitted variable bias. This can occur if the critical farm variables (soil type, irrigation, and population density) correlated with climate are omitted from the regression model, leading to estimates that are not only biased but also inconsistent in nature. Hence, to obtain consistent estimates, the approach requires that all unobserved factors influencing farmland value are orthogonal to climate (Deschenes & Greenstone, 2007). In the recent years, several researchers have also used the panel data approach (Kelly et al. 2005; Deschenes & Greenstone, 2007;

Guiteras, 2007; Burke et al., 2015) to capture the effects of year-to-year change in climate variables on agriculture output by controlling for time-invariant un-observables (e.g. soil and water quality) that may be correlated with climate and dependent variable, thereby reducing the possibility of an omitted variable bias. Besides, the approach accounts for short-term adaptations by the farmers in estimating the climate change impact.

3.1 Data sources

The study uses the panel data approach to examine the impact of climate on crop yields across different regions. A comprehensive district-level panel for the period 1966-2011, covering 301[1] districts in the country spread across 14 agro-climatic zones (excluding island region) was constructed. The crop yields and certain non-climatic variables were paired with the climate parameters (rainfall and temperature) to develop this large-scale panel which allows inter-temporal and spatial assessment while controlling for district-specific factors and time trend. The data on crop area (ha) and production (tonnes) and non-climatic factors such as irrigated area (ha) road length (km/000 sq. km), rural literates (no.), tractors (no./ha), pump sets (no./ha), and fertilizer consumption (tonnes/ha) were compiled from the database maintained by International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) under the Village Dynamics Studies in Asia (VDSA) project. There are two major cropping seasons in India, *kharif* and *rabi*. *Kharif* cultivation starts during the months of June-July, where crops such as rice, sorghum, maize, pearl millet, and groundnut are sown, which are then harvested during the months of September-October. While *rabi* crops such as wheat, chickpea, barley, and rapeseed & mustard are sown in the months of October-November and are harvested during March-April. The selection of the crops for the study was based on their respective area coverage under each of the ACZs. Hence the dominant crops in the ACZ were selected for assessment. The data on rainfall and temperature (minimum and maximum) was obtained from the India Meteorological Department (IMD), Government of India and later aggregated into the annual district metrics for the entire crop growing period. For the study, crop growing period is taken as an amalgamation of sowing, germination and harvesting months as shown in the appendix Table A1.

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[1] ICRISAT-VDSA database contains information for 311 districts spread across 19 states of India from 1966-67 to 2011-12 with 1966 district boundaries. Due to paucity of data on certain variables, a total of 301 districts were finally selected for the study.

3.2 Methodology

3.2.1 Empirical strategy

The present study used the following model to assess the impact of climate change on crop yields in each of the ACZ:

$$\log y_{dt} = c + \alpha_d + \partial t + \gamma \log X_{dt} + \beta \log W_{dt} + \varepsilon_{dt} \quad \dots (1)$$

where y_{dt} represents crop yield, W_{dt} is a vector of climate variables (rainfall, maximum and minimum temperature), X_{dt} denotes non-climatic factors (irrigated area, road length, rural literates, tractors, fertilizer consumption and pump sets) and ε_{dt} is the error term for the d^{th} district during the t^{th} time period. The model includes district-level fixed effects (α_d) which controls for unobserved district-specific heterogeneity due to time-invariant factors that influence dependent variable. In their analysis, Deschênes & Greenstone (2007), Guiteras, (2009), Kala et al., (2012), Saravanakumar (2015) and Birthal et al., (2014 a,b) all have added entity fixed effects to eliminate the omitted variable bias. Further, a time trend is incorporated in the model as a proxy to absorb the technological effects and other farm-level adaptations.

To ensure robustness of the applied panel regression certain residual diagnostics were employed. We tested for first-order autocorrelation in the residuals of a linear panel-data using the Woolridge test (2002). Homoscedasticity of error process across cross-sectional units was investigated through modified Wald test (Greene, 2000). Interestingly, we found autocorrelation in most of the cases across ACZs. However, there was no incidence of error exhibited group-wise heteroscedasticity, possibly due to the inclusion of trend component in the model which corroborates with the findings of Banerjee (1999) as to how common trend in the panel imparts homogeneity across the cross-sectional units. Based on the above verifications, we applied feasible generalized least squares (FGLS) method with corrections for autocorrelation to estimate model (1) under the assumptions that within panels, there is AR (1) autocorrelation and the coefficient of the AR (1) process is common to all the panels. However, it is important to note that FGLS is feasible and tends to produce efficient and consistent estimates of standard errors, provided that $N < T$; i.e. panel time dimension (T), is larger than the cross-sectional dimension (N) (Kmenta, 1986; Beck & Katz, 1995; Hoechle, 2007). In our case, this assumption was satisfied as under each ACZ, number of districts, representing the cross-sectional units (N) were less than the time period of 46 years.

Marginal effects

The marginal effect of the climate parameters were calculated at their mean values from the regression coefficients. In model (1), the regression coefficient measures elasticity, i.e. proportionate change in crop yield to proportionate change in the independent variable. Thus, the combined marginal effect of climate variables, viz. rainfall, minimum and maximum temperature on crop yield were quantified using equation (2).

$$\frac{dy}{dc} = \left(\beta_{MT} * \left[\frac{\bar{Y}}{\overline{MT}} \right] + \beta_{MNT} * \left[\frac{\bar{Y}}{\overline{MNT}} \right] + \beta_{R} * \left[\frac{\bar{Y}}{\overline{R}} \right] \right) \quad \text{……..(2)}$$

Where, $\frac{dy}{dc}$ is combined marginal effect of change in climate variables on the crop yield, β denotes coefficients which are determined from the model, $\overline{MT}$ is mean maximum temperature, $\overline{MNT}$ is mean minimum temperature, $\overline{R}$ is mean rainfall, and $\overline{Y}$ is the mean crop yield during the period in an ACZ.

3.2.2 Future climate change projections

We used CORDEX South Asia multi-RCM reliability ensemble average estimate of projected changes in annual mean of daily minimum and maximum temperature over India for the 30-year future periods: near-term (2016-2045), mid-term (2036-2065) and long-term (2066-2095) changes in future climate over India under RCPs[2] 4.5 and 8.5 scenarios relative to the base 1976–2005 to project the changes in crop yields. For RCP 4.5 and 8.5, an increase of less than 2°C was observed for both the mean minimum and maximum temperature under the near-term period (Table 5). The mid-term warming in annual minimum temperature is projected to be in the range of 2.14 to 2.60°C while for the maximum temperature it is around 1.81 to 2.30°C. Under the RCP 4.5 minimum and maximum temperature surpasses 2°C by the end of the 21st century. In the far future minimum temperature is projected to increase beyond 4°C for RCP 8.5 with high degree of certainty. Moreover, it was observed that the magnitude of changes in all India annual minimum temperature exceeds the changes estimated for the maximum temperature.

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[2] The Representative Concentration Pathways (RCPs) used by IPCC in its Fifth Assessment Report (AR5, 2014) describes the future trend in greenhouse gases concentration in the atmosphere due to human activities. The pathway delineates four future climate scenarios of RCP2.6, RCP4.5, RCP6.0 and RCP8.5, premised on different emission levels, energy use and socio-economic circumstances. For impact assessment we focused on RCPs 4.5 and 8.5 representing moderate and worst-case (business-as-usual) scenario, thus producing estimates and policy implications for future adaptation planning.

Table 5: Projected changes in annual mean daily minimum and maximum temperature over India

Variable	Scenarios	Near-term (2030s)	Mid-term (2050s)	Long-term (2080s)
Minimum temperature	RCP 4.5	1.36 ± 0.18 (13.2%)	2.14 ± 0.28 (13.1%)	2.63 ± 0.38 (14.4%)
	RCP 8.5	1.50 ± 0.16 (10.7%)	2.60 ± 0.23 (8.8%)	4.43 ± 0.34 (7.7%)
Maximum temperature	RCP 4.5	1.26 ± 0.20 (15.9%)	1.81 ± 0.27 (14.9%)	2.29 ± 0.36 (15.7%)
	RCP 8.5	1.36 ±0.16 (11.8%)	2.30 ±0.31 (13.5%)	3.94 ± 0.45 (11.4%)

Source: Climate Change over India: An Interim report (2017). Centre for Climate Change Research, ESSO-IITM, Ministry of Earth Sciences, Govt. of India.

Note: Figure in the parenthesis indicate the associated uncertainty range

In addition to the three time periods considered, the study also assumed another *near-to-mid-term* period of 2040s (2026-2055) as an average of the projections made for near-term (2016-2045) and mid-term (2036-2065) periods, respectively. Further, a variation of 5%, 7%, 10% and 12% in rainfall were assumed for 2030s, 2040s, 2050s and 2080s. The direction of rainfall anomaly (positive or negative) in each of the ACZ was based on their respective rainfall trend during the period 2001-2011 (Table A2). The projected impact of climate change on crop yield expressed as percentage change was calculated using equation (3),

$$\Delta Y = \left(\frac{\partial Y}{\partial R}\right) * \Delta R + \left(\frac{\partial Y}{\partial T}\right) * \Delta T * 100 \qquad \text{....(3)}$$

Where, ΔY denotes change in crop yield, ΔR in rainfall and ΔT in temperature and $\left(\frac{\partial Y}{\partial R}\right)$ and $\left(\frac{\partial Y}{\partial T}\right)$ are their marginal effects estimated from the model.

4

Climate Change Impact and Futuristic Projections

4.1 Impact of climate change on crop yields

This section estimates the impact of climate variables (rainfall and temperatures) and non-climatic factors (irrigated area, road length, literacy, pumpsets, tractors and fertilizers consumption) on crop yields during the period 1966-2011 across ACZs.

4.1.1 Western Himalayan Region

Western Himalayan Region spreads over the states of Himachal Pradesh, Jammu & Kashmir and Uttarakhand and covers 10.08% of the total geographical area of India. The climate in the region ranges from cold arid to humid with mean temperature varying from 14°C to 27°C and average annual rainfall of 1158mm. Wheat, rice, barley and maize are some of the major crops grown in this zone.

The estimated results presented in Table 6, showed that temperature negatively impacts rice yield, while rainfall has a positive impact. A rise in minimum temperature lowers maize and wheat yields whereas rise in maximum temperature negatively impacts rice and barley yields. Irrigation significantly and positively impacted all the crop yields except wheat. Higher fertilizer consumption increases yield of rice, wheat and barley but significantly lowers that of maize in Western Himalayan Region.

4.1.2 Eastern Himalayan Region

All the north-eastern states and northern part of West Bengal, spread over an area of 274,942 sq. km, form the Eastern Himalayan Region. The zone has climatic conditions that vary from per-humid to humid, with mean annual rainfall of 2643 mm. The mean maximum temperature in the region remains around 27.86°C while mean minimum temperature is about 18.40°C. The important crops grown in this zone are rice, maize, wheat and rapeseed.

The assessment of climate impact for Eastern Himalayan Region revealed that a rise in maximum temperature lowers all the crop yields

(Table 7). Higher minimum temperature had a harmful impact on rice, wheat, and rapeseed & mustard yields while it benefits maize yield. Higher rainfall positively affects yield of rice, maize, and rapeseed & mustard whereas it reduces that of wheat. Both irrigation and fertilizer consumption benefits productivity of rice, maize, and rapeseed across the zone.

Table 6. Regression estimates of climate and non-climatic factors on crop yields: Western Himalayan Region

Variables	Rice	Maize	Wheat	Barley
Ln Rainfall	0.0382*** (0.0068)	0.0125 (0.0117)	-0.0017 (0.0029)	0.0053 (0.0054)
Ln Min Temp	-0.3770*** (0.1403)	-0.0595 (0.1667)	-0.0372* (0.0190)	0.0491 (0.0354)
Ln Max Temp	-0.2745 (0.1697)	1.1964*** (0.2508)	0.0012 (0.0720)	-0.3428*** (0.1185)
Ln Irrigation	0.2810*** (0.0285)	0.2354*** (0.0377)	-0.0640*** (0.0107)	0.1623*** (0.0104)
Ln Fertilizer	0.0017 (0.0022)	-0.0114*** (0.0027)	0.0002 (0.0011)	0.0019 (0.0019)
Ln Road length	0.0019 (0.0016)	-0.0063*** (0.0019)	-0.0008 (0.0008)	-0.0008 (0.0014)
Ln Ruliteracy	-0.0043 (0.0049)	0.0185*** (0.0060)	0.0025 (0.0025)	0.0077* (0.0042)
Ln Tractors	-0.0020 (0.0026)	0.0042* (0.0023)	0.0003 (0.0012)	0.0016 (0.0018)
Ln Pumpset	0.0034 (0.0030)	0.0011 (0.0029)	-0.0007 (0.0014)	-0.0013 (0.0022)
Time	0.0095*** (0.0005)	0.0085*** (0.0004)	0.0075*** (0.0002)	0.0053*** (0.0003)
Constant	-20.6613*** (0.9824)	-21.1332*** (0.9018)	-13.9598*** (0.3489)	-10.0058*** (0.6930)
District fixed effects	Yes	Yes	Yes	Yes
Observations	629	629	628	629
Wald chi^2(25)	3988.85***	3506.74***	5408.5***	387.5***
F(1, 15)[1]	391.794***	7015.309***	7.627**	0.14
chi^2 (16)[2]	9.06	2.34	0.90	5.11

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2]Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
Figures within the parentheses are standard errors.
Dependent variable, i.e., crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

Table 7. Regression estimates of climate and non-climatic factors on crop yields: Eastern Himalayan Region

Variables	Rice	Maize	Wheat	Rapeseed & mustard
Ln Rainfall	0.0160 (0.0130)	0.0082 (0.0206)	-0.0081** (0.0037)	0.0148 (0.0130)
Ln Min Temp	-0.4568*** (0.1688)	0.4153*** (0.1548)	-0.1171*** (0.0445)	-0.0659 (0.1266)
Ln Max Temp	-0.2768 (0.2117)	-0.1807 (0.2345)	-0.0828 (0.0755)	-0.3037 (0.2943)
Ln Irrigation	0.1576*** (0.0253)	0.2029*** (0.0407)	-0.0274*** (0.0099)	0.0689*** (0.0210)
Ln Fertilizer	0.0025 (0.0021)	0.0015 (0.0020)	-0.0006 (0.0009)	0.0027 (0.0025)
Ln Road length	-0.0021 (0.0032)	0.0065* (0.0039)	-0.0011 (0.0016)	-0.0050 (0.0049)
Ln Ruliteracy	-0.0052 (0.0038)	-0.0044 (0.0034)	0.0000 (0.0016)	0.0020 (0.0042)
Ln Tractors	-0.0036 (0.0027)	-0.0058** (0.0024)	-0.0005 (0.0012)	0.0014 (0.0032)
Ln Pumpset	-0.0037 (0.0040)	0.0150*** (0.0039)	0.0009 (0.0019)	-0.0093* (0.0050)
Time	0.0115*** (0.0004)	0.0093*** (0.0003)	0.0070*** (0.0002)	0.0133*** (0.0004)
Constant	-24.2496*** (0.8781)	-19.7975*** (0.8577)	-13.0273*** (0.3303)	-25.9038*** (1.0631)
District fixed effects	Yes	Yes	Yes	Yes
Observations	548	548	548	548
Wald chi^2(22)	2761.07***	2232.37***	4031.65***	2953.83***
F(1,12)[1]	151.85***	2506.844***	6.999**	2135.548
chi^2 (13)[2]	1.82	1.30	0.87	1.09

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2] Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

4.1.3 Lower Gangetic Plains Region

Lower Gangetic Plains comprise parts of West Bengal state. The zone occupies 2.12% of the country's area and has moist sub-humid to dry sub-humid climate. The mean temperature varies from 21.21°C to 31.55°C and the region receives an annual rainfall of 1485 mm. Besides rice which is the principal crop cultivated in the zone wheat, maize, mustard, sugarcane and rapessed & mustard are also grown.

Table 8. Regression estimates of climate and non-climatic factors on crop yields: Lower Gangetic Plains Region

Variables	Rice	Maize	Wheat	Rapeseed & mustard
Ln Rainfall	0.0311*** (0.0113)	-0.0390** (0.0177)	-0.0183*** (0.0033)	0.0356*** (0.0083)
Ln Min Temp	0.0500 (0.1023)	0.5641*** (0.1186)	-0.0283 (0.0386)	-0.0022 (0.0867)
Ln Max Temp	-0.4864*** (0.1476)	0.1380 (0.1991)	-0.0899 (0.0785)	-0.5074** (0.2189)
Ln Irrigation	0.0797*** (0.0134)	-0.1300*** (0.0355)	-0.0296*** (0.0073)	0.0924*** (0.0129)
Ln Fertilizer	0.0072 (0.0049)	0.0203*** (0.0063)	-0.0023 (0.0028)	-0.0292*** (0.0064)
Ln Road length	-0.0032*** (0.0015)	0.0003*** (0.0020)	0.0009 (0.0009)	-0.0021 (0.0020)
Ln Ruliteracy	-0.0602*** (0.0143)	-0.0216 (0.0178)	0.0036 (0.0079)	0.0340* (0.0181)
Ln Tractors	0.0007 (0.0020)	0.0011 (0.0026)	0.0024** (0.0012)	-0.0022 (0.0025)
Ln Pumpset	-0.0086*** (0.0020)	0.0019 (0.0025)	0.0008 (0.0012)	-0.0036 (0.0025)
Time	0.0127*** (0.0002)	0.0100*** (0.0003)	0.0067*** (0.0001)	0.0137*** (0.0003)
Constant	-24.0286*** (0.7591)	-21.7176*** (0.8990)	-12.8414*** (0.3907)	-26.2943 (0.9605)
District fixed effects	Yes	Yes	Yes	Yes
Observations	356	356	356	356
Wald chi^2(17)	6542.28	2207.28***	4365.7***	5105.89***
F(1,7)[1]	366.438***	1759.775***	0.955	1133.817***
chi^2 (8)[2]	1.51	2.28	1.61	0.73

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2] Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

As shown in Table 8, in case of rice the positive effects of rainfall and minimum temperature are offset by the strong negative impact of maximum temperature. Higher rainfall significantly reduces the yield of maize and wheat. Higher irrigation coverage was beneficial for rice and rapeseed & mustard in the region. Fertilizer consumption increases the yield of rice and maize. A rise in maximum temperature adversely impacts rice, wheat, and rapeseed & mustard yields. Rainfall significantly impacted all the crop yields in the zone but had a harmful effect on the yield of maize and wheat.

4.1.4 Middle Gangetic Plains Region

Middle Gangetic Plains covers the entire state of Bihar and parts of Uttar Pradesh with the total geographical area of 163,793 sq. km. The climate in the zone is characterized as moist sub-humid to dry sub-humid conditions with an average annual rainfall of 1113 mm. The mean minimum temperature in the zone is 19.45°C while the mean maximum temperature remains around 32.08°C. Rice, maize, sugarcane, pigeon pea, wheat, groundnut, and lentil are the commonly grown crops in the Middle Gangetic Plains.

The estimated regression results as shown in Table 9, reveals that higher temperature lowers the yield of rice, sugarcane, and wheat. The effect of minimum temperature was stronger on sugarcane yield while in case of rice and wheat, the magnitude of maximum temperature dominates. Except maize yield, higher rainfall positively affected all other crop yields in the region. Irrigation variable was found to be significant and positively impacted the yield of rice, maize, rapeseed, and barley.

4.1.5 Upper Gangetic Plains Region

Upper Gangetic Plains comprise some of the districts of Uttar Pradesh and covers 4.32% of the total geographical area. The climate in the zone ranges from dry sub-humid to semi-arid and the area receives an average annual rainfall of 878 mm. The mean temperature ranges from 18°C to 32°C. Rice, maize, sorghum, pearl millet, wheat, rapeseed & mustard, and sugarcane are the major crops grown in the zone.

As depicted in Table 10, higher rainfall leads to higher yield of maize, sorghum, wheat, barley, and rapeseed & mustard while it reduces rice and sugarcane yields. Rise in minimum temperature had a harmful effect on most of the crop yields, except for maize and rapeseed & mustard. On the other hand, maximum temperature adversely impacted rice, maize, and wheat. In the Upper Gangetic Plains, fertilizer consumption significantly lead to higher yield in case of rice, maize, barley, and rapeseed & mustard. Higher irrigation benefits most of the crop yields, except maize, for which the respective coefficient is also insignificant.

Table 9. Regression estimates of climate and non-climatic factors on crop yields: Middle Gangetic Plains Region

Variables	Rice	Maize	Sugarcane	Wheat	Rapeseed & mustard	Barley
Ln Rainfall	0.0081 (0.0056)	-0.0426*** (0.0080)	0.0132** (0.0060)	0.0005 (0.0014)	0.0299*** (0.0044)	0.0058** (0.0026)
Ln Min Temp	-0.0193 (0.0517)	0.0424 (0.0631)	-0.1973** (0.0638)	-0.0107 (0.0269)	0.2024*** (0.0623)	0.0549 (0.0397)
Ln Max Temp	-0.0356 (0.0345)	0.0026 (0.0365)	-0.0840 (0.0653)	-0.0245 (0.0247)	0.0825 (0.0615)	-0.0787** (0.0335)
Ln Irrigation	0.8584*** (0.0324)	0.3386*** (0.0275)	-0.0651** (0.0289)	-0.0601*** (0.0158)	0.0898*** (0.0194)	0.2680*** (0.0105)
Ln Fertilizer	-0.0012 (0.0008)	0.0012 (0.0009)	-0.0005 (0.0010)	-0.0013*** (0.0005)	-0.0019 (0.0013)	-0.0015** (0.0007)
Ln Road length	-0.0008 (0.0006)	-0.0001 (0.0006)	-0.0003 (0.0008)	0.0000 (0.0004)	-0.0006 (0.0009)	-0.0005 (0.0005)
Ln Ruliteracy	-0.0023 (0.0060)	0.0171*** (0.0061)	-0.0269** (0.0123)	-0.0002 (0.0040)	-0.0191** (0.0089)	-0.0024 (0.0055)
Ln Tractors	0.0127*** (0.0025)	-0.0089*** (0.0025)	0.0177*** (0.0047)	-0.0016 (0.0017)	0.0242*** (0.0037)	0.0023 (0.0023)
Ln Pumpset	-0.0032 (0.0034)	-0.0374*** (0.0037)	0.0009 (0.0053)	-0.0088*** (0.0024)	0.0520*** (0.0053)	-0.0008 (0.0031)
Time	-0.0001 (0.0006)	0.0093*** (0.0004)	0.0096*** (0.0008)	0.0082*** (0.0003)	0.0101*** (0.0006)	0.0087*** (0.0004)
Constant	-3.2343*** (1.0156)	-19.0546*** (0.7032)	-16.1836*** (1.4902)	-15.3907*** (0.5117)	-21.5207*** (1.1701)	-17.6718*** (0.7187)
District fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	966	966	966	966	966	966
Wald chi^2(31)	15165.47***	8245.17***	1270.86***	7874.34***	7225.18***	968.38***
F(1, 21)[1]	4755.252***	16622.367***	5236.268***	73.021***	4953.658***	0.002
chi^2 (22)[2]	0.42	4.31	2.38	0.76	1.00	1.90

Note: [1]Woolridge test for autocorrelation in panel data (H$_0$: no first order auto correlation) and [2] Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

4.1.6 Trans-Gangetic Plains Region

Trans-Gangetic Plains comprises states of Haryana, Punjab, and parts of Rajasthan as well as the Union Territories of Delhi and Chandigarh. The zone occupies an area of 147,044 sq. km and is characterized with extreme arid to dry sub-humid climatic conditions. The mean minimum temperature in the region remains at 18.26°C, while the maximum at 31.90°C with annual average rainfall of 673mm, the lowest precipitation across the ACZs. Wheat, rice, cotton, maize and sugarcane are some of the major crops grown in the zone.

Table 10. Regression estimates of climate and non-climatic factors on crop yields: Upper Gangetic Plains Region

Variables	Rice	Sugarcane	Maize	Sorghum	Wheat	Barley	Rapeseed & mustard
Ln Rainfall	-0.0140*** (0.0037)	-0.0177*** (0.0039)	0.0350*** (0.0054)	0.0060 (0.0074)	0.0004 (0.0011)	0.0072*** (0.0020)	0.0127*** (0.0032)
Ln Min Temp	-0.0104 (0.0184)	-0.0243** (0.0110)	0.0122 (0.0136)	-0.0594** (0.0295)	-0.0039 (0.0046)	-0.0025 (0.0056)	0.0178 (0.0123)
Ln Max Temp	-0.0106 (0.0148)	0.0377 (0.0230)	-0.0316*** (0.0116)	0.0013 (0.0363)	-0.0053 (0.0073)	0.0055 (0.0105)	0.0408*** (0.0135)
Ln Irrigation	0.8030*** (0.0287)	-0.0069 (0.0263)	0.2628*** (0.0218)	0.1935 (0.1375)	0.0033 (0.0190)	0.2902*** (0.0094)	0.1063*** (0.0148)
Ln Fertilizer	0.0108*** (0.0029)	0.0224*** (0.0041)	-0.0539*** (0.0028)	-0.0600*** (0.0098)	-0.0144*** (0.0024)	0.0128*** (0.0027)	0.0788*** (0.0041)
Ln Road length	-0.0013** (0.0006)	-0.0001 (0.0006)	-0.0007 (0.0006)	0.0028 (0.0020)	-0.0006 (0.0004)	-0.0006 (0.0005)	-0.0007 (0.0010)
Ln Ruliteracy	0.0016 (0.0057)	-0.0041 (0.0113)	-0.0050 (0.0049)	-0.0109 (0.0171)	-0.0051 (0.0038)	0.0015 (0.0053)	0.0061 (0.0074)
Ln Tractors	0.0170*** (0.0021)	0.0081** (0.0036)	-0.0110*** (0.0018)	-0.0739*** (0.0063)	-0.0050*** (0.0014)	0.0033* (0.0020)	0.0290*** (0.0028)
Ln Pumpset	0.0132*** (0.0026)	0.0053 (0.0043)	-0.0127*** (0.0022)	-0.0658*** (0.0078)	-0.0028 (0.0017)	0.0024 (0.0024)	0.0361*** (0.0034)
Time	-0.0009* (0.0005)	0.0058*** (0.0008)	0.0148*** (0.0004)	0.0139*** (0.0012)	0.0087*** (0.0003)	0.0080*** (0.0004)	0.0029*** (0.0006)
Constant	-1.8791** (0.8920)	-9.9467*** (1.5606)	-29.5775*** (0.7795)	-26.3545*** (2.2623)	-16.3380*** (0.5045)	-16.6363*** (0.7171)	-7.5739*** (1.1925)
District fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1253	1253	1253	1253	1248	1253	1225
Wald chi^2(39)	18821.49***	1499.96	15945.22***	328.38***	9864.12***	1343.23***	10519.42***
F(1, 29)[1]	250.706***	5461.417***	3719.391***	529.949***	43.646***	12.431***	2886.572***
chi^2 (30)[2]	1.08	1.35	4.80	3.01	1.29	3.18	2.96

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2] Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.

Significance level: * p <0.10, ** p <0.05, *** p< 0.01

Figures within the parentheses are standard errors.

Dependent variables i.e. crop yield is in logarithmic form.

District dummies were incorporated but the estimated coefficients are not shown.

Table 11. Regression estimates of climate and non-climatic factors on crop yields: Trans-Gangetic Plains Region

Variables	Rice	Cotton	Pearl millet	Maize	Sugarcane	Wheat	Barley	Rapeseed & mustard
Ln Rainfall	0.0138***	0.0343***	0.0900***	0.0156**	-0.0101**	-0.0091***	0.0073***	0.0190***
	(0.0044)	(0.0122)	(0.0105)	(0.0072)	(0.0050)	(0.0017)	(0.0028)	(0.0049)
Ln Min Temp	0.0042	-1.4053***	0.1244	-0.3388***	-0.2114***	-0.1517***	0.0092	0.6562***
	(0.0875)	(0.2625)	(0.1909)	(0.0963)	(0.0741)	(0.0333)	(0.0530)	(0.0867)
Ln Max Temp	-0.1421	1.3000***	0.9224***	0.2945***	-0.2135	0.1125**	-0.1112	-0.5055***
	(0.0958)	(0.3479)	(0.1998)	(0.1069)	(0.1297)	(0.0481)	(0.0731)	(0.1231)
Ln Irrigation	0.8285***	0.5298***	-0.0639**	0.2379***	-0.1027***	-0.0643***	0.2701***	0.0478**
	(0.0372)	(0.1080)	(0.0257)	(0.0343)	(0.0309)	(0.0148)	(0.0130)	(0.0209)
Ln Fertilizer	0.0018	-0.0134**	-0.0043	-0.0165***	0.0053***	0.0001	0.0044***	0.0241***
	(0.0015)	(0.0052)	(0.0032)	(0.0019)	(0.0019)	(0.0009)	(0.0014)	(0.0024)
Ln Road length	-0.0088*	0.0381*	0.0163*	0.0138***	-0.0004	0.0023	0.0012	-0.0288***
	(0.0046)	(0.0225)	(0.0091)	(0.0051)	(0.0074)	(0.0028)	(0.0043)	(0.0068)
Ln Ruliteracy	-0.0002	-0.0031	0.0057	0.0105**	-0.0085	-0.0038	-0.0056	-0.0110*
	(0.0043)	(0.0164)	(0.0089)	(0.0050)	(0.0058)	(0.0026)	(0.0040)	(0.0066)
Ln Tractors	0.0005	0.0035	0.0032	0.0042***	-0.0063***	-0.0020**	-0.0003	-0.0027
	(0.0015)	(0.0070)	(0.0029)	(0.0016)	(*0.0023)	(0.0009)	(0.0014)	(0.0022)
Ln Pumpset	0.0041	-0.0350***	-0.0172***	-0.0232***	0.0063*	-0.0046***	0.0006	0.0325***
	(0.0025)	(0.0113)	(0.0049)	(0.0028)	(0.0038)	(0.0016)	(0.0023)	(0.0036)
Time	0.0009	0.0262***	0.0100***	0.0092***	0.0109***	0.0081***	0.0086***	0.0118***
	(0.0006)	(0.0013)	(0.0006)	(0.0004)	(0.0007)	(0.0003)	(0.0004)	(0.0006)
Constant	-4.7919***	-55.5669***	-24.7914***	-18.9866***	-18.3299***	-15.0779***	-17.3109***	-23.9606***
	(1.1515)	(2.6579)	(1.2111)	(0.7280)	(1.2587)	(0.4855)	(0.7924)	(1.1037)
District fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	785	785	785	785	785	785	785	785
Wald chi^2(27)	11687.60***	1310.65***	1957.58***	5076.39***	1423.68***	7078.89***	632.52***	6646.04***
F(1, 17)[1]	2777.66***	617.983***	120.679***	6045.422***	2701.825	1.622	8.036**	6876.937***
chi^2 (19)[2]	0.80	1.66	1.39	4.57	2.83	0.45	3.91	1.31

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2]Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

The assessment of climate impact in Trans-Gangetic Plains region showed that higher amount of rainfall leads to higher yield of rice, cotton, pearl millet, maize, barley, and rapeseed & mustard (Table 11). In case of pearl millet, both minimum and maximum temperature had a positive impact, indicating high tolerance and resiliency of the crop to changing climatic conditions. Higher irrigation appears to benefit crop yields like rice, cotton, maize, barley, and rapeseed & mustard. The sign of temperatures and rainfall in case of sugarcane yield is negative, suggesting its high sensitivity to the climatic variations. Moreover, the coefficient for fertilizer consumption had a negative sign for cotton, maize, and pearl millet yields, implying that higher dose of fertilizer lessen productivity of these crops in the region.

4.1.7 Eastern Plateau and Hills Region

Comprising states of Chhattisgarh, Jharkhand and parts of Madhya Pradesh, Odisha, Maharashtra and West Bengal, Eastern Plateau and Hills is the second largest agro-climatic zone in India in terms of geographical coverage. The climate is generally moist sub-humid to dry-sub-humid and the zone receives an average annual rainfall of 1324mm. Temperature in the region ranges from 19.95°C to 31.42°C. Rice, maize, linseed, and millets are the principal crops cultivated in the region.

As shown in Table 12, a rise in minimum temperature lowers all the crops yields in the region but the magnitude of such an effect is stronger for linseed. The higher maximum temperature, on the other hand, adversely impacts only rice yield. Rainfall appears to benefit productivity of rice and linseed while negatively affects wheat and maize yields. Irrigation variable is highly significant and increases yield of all the crops except for wheat.

4.1.8 Central Plateau and Hills Region

Central Plateau and Hills covers 10.18% of the country's area and spans over the parts of Madhya Pradesh, Rajasthan, and Uttar Pradesh states. The zone receives an average annual rainfall of 917 mm and has semi-arid to dry-sub-humid climate. The mean minimum temperature in the region is about 19.13°C, while the mean maximum is 32°C. Wheat, groundnut, jowar, rice, maize, rapeseed and bajra are some of the major crops grown in the region.

The estimated regression results presented in Table 13, indicate that sorghum, maize, groundnut, and rapeseed & mustard yields are positively impacted by rainfall while it negatively impacts wheat yield.

Table 12. Regression estimates of climate and non-climatic factors on crop yields: Eastern Plateau and Hills Region

Variables	Rice	Maize	Wheat	Linseed
Ln Rainfall	0.0461*** (0.0066)	-0.0048 (0.0120)	-0.0061*** (0.0013)	0.0109*** (0.0040)
Ln Min Temp	-0.0667 (0.1042)	-0.1775 (0.1434)	-0.0433 (0.0469)	-0.7519*** (0.1464)
Ln Max Temp	-0.1508 (0.1055)	0.3688*** (0.1244)	0.0322 (0.0603)	0.3390* (0.1895)
Ln Irrigation	0.5551*** (0.0305)	0.3295*** (0.0289)	-0.0481*** (0.0103)	0.2897*** (0.0408)
Ln Fertilizer	0.0028* (0.0015)	-0.0102*** (0.0016)	-0.0001 (0.0008)	-0.0143*** (0.0025)
Ln Road length	-0.0021** (0.0011)	-0.0061*** (0.0016)	0.0007 (0.0006)	-0.0039** (0.0019)
Ln Ruliteracy	-0.0029 (0.0058)	0.0226*** (0.0073)	0.0016 (0.0033)	0.0111 (0.0104)
Ln Tractors	0.0001 (0.0041)	-0.0272*** (0.0040)	-0.0030 (0.0021)	-0.0093 (0.0063)
Ln Pumpset	-0.0085** (0.0038)	-0.0009 (0.0038)	-0.0048** (0.0019)	0.0034 (0.0060)
Time	0.0052*** (0.0005)	0.0097*** (0.0003)	0.0076*** (0.0002)	0.0044*** (0.0005)
Constant	-12.6816*** (0.9779)	-20.7909*** (0.7631)	-14.2300*** (0.3563)	-8.3974*** (1.0989)
District fixed effects	Yes	Yes	Yes	Yes
Observations	1115	1115	1115	1115
Wald chi^2(34)	9129.79***	5816.67***	9160.47***	181.24***
F(1, 24)[1]	194.478***	6727.63***	25.435***	3.035*
chi^2 (25)[2]	40.45	2.44	4.02	3.46

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2] Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

Table 13. Regression estimates of climate and non-climatic factors on crop yields: Central Plateau and Hills Region

Variables	Sorghum	Maize	Groundnut	Wheat	Rapeseed & mustard
Ln Rainfall	0.0555*** (0.0064)	0.0109 (0.0067)	0.0474*** (0.0059)	-0.0037*** (0.0006)	0.0039* (0.0022)
Ln Min Temp	-0.4282*** (0.1426)	-0.2816*** (0.0620)	0.1792*** (0.0612)	-0.0782*** (0.0205)	0.5396*** (0.0555)
Ln Max Temp	0.0131 (0.1234)	-0.0315 (0.0382)	-0.0385 (0.0379)	0.0030 (0.0217)	0.1221* (0.0641)
Ln Irrigation	0.4574*** (0.1187)	0.3648*** (0.0229)	0.4258*** (0.0192)	-0.0744*** (0.0104)	0.0493*** (0.0152)
Ln Fertilizer	0.0076** (0.0035)	-0.0069*** (0.0011)	-0.0013 (0.0011)	0.0014** (0.0006)	0.0106*** (0.0016)
Ln Road length	0.0024 (0.0029)	-0.0017 (0.0011)	-0.0008 (0.0011)	-0.0012*** (0.0005)	0.0012 (0.0016)
Ln Ruliteracy	-0.0150 (0.0097)	-0.0113*** (0.0032)	-0.0007 (0.0030)	-0.0019 (0.0017)	0.0162*** (0.0045)
Ln Tractors	-0.0230*** (0.0046)	0.0042*** (0.0015)	0.0039*** (0.0014)	0.0002 (0.0008)	0.0025 (0.0021)
Ln Pumpset	-0.0374*** (0.0096)	-0.0263*** (0.0033)	-0.0039 (0.0030)	-0.0032 (0.0018)	0.0425*** (0.0045)
Time	0.0061*** (0.0007)	0.0093*** (0.0003)	0.0036*** (0.0002)	0.0080*** (0.0002)	0.0104*** (0.0004)
Constant	-11.1709*** (1.1990)	-18.1701*** (0.4701)	-8.9257*** (0.3845)	-14.7856*** (0.3099)	-23.2314*** (0.7984)
District fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	1729	1729	1729	1729	1729
Wald chi^2(50)	228.37***	10923.51***	3557.93***	15695.24***	10832.09***
F(1, 40)[1]	1429.077***	8638.566***	1523.778***	7.87***	5339.083***
chi^2 (41)[2]	11.16	6.87	3.44	2.26	2.46

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2]Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown

A rise in minimum temperature significantly lowers the yield of sorghum, maize, and wheat while higher maximum temperature adversely impacts maize and groundnut yield. Fertilizer consumption increases the yield of sorghum, wheat, and rapeseed & mustard. Higher irrigation appears to significantly benefit all the crop yields in the zone, except for wheat.

4.1.9 Western Plateau and Hills Region

Western Plateau and Hills includes 25 districts of Maharashtra and 14 from Madhya Pradesh and occupies an area of 332, 979 sq. km. The climate in the region is characterized as semi-arid, with an annual average rainfall of about 930 mm. The mean temperature varies from 19.95°C to 32.91°C. Wheat, cotton, sorghum, jowar and sugarcane are some of the major crops grown in this region.

The estimated regression as shown in Table 14, indicate that rise in minimum temperature had a strong negative effect on sorghum and cotton yields. A higher rainfall benefits all the crop yields, except for wheat. Cotton, sugarcane, wheat, and rapeseed & mustard yields are adversely impacted by a higher maximum temperature. Input variables such as irrigation and fertilizer increase the yield of sorghum, cotton, and rapeseed & mustard, whereas decreases that of sugarcane.

4.1.10 Southern Plateau and Hill Region

Southern Plateau and Hills with 12.38% covers the largest geographical area in the country and includes parts of southern states of Andhra Pradesh, Karnataka, and Tamil Nadu. The zone receives an average annual rainfall of 843 mm, with mean annual temperature varying from 21.41°C to 32.23°C. The climate in the region is generally semi-arid in nature. The major crops of the zone are rice, groundnut, millets, cotton, and sugarcane.

As shown in Table 15, both higher rainfall and temperature lowers the yield of rice, with a stronger effect of maximum temperature. Groundnut, wheat, and linseed yields are negatively impacted by a higher maximum temperature. Rice, groundnut, and linseed are positively and significantly impacted by irrigation. On the other hand, the input variable like fertilizer benefits rice and wheat yields only.

Table 14. Regression estimates of climate and non-climatic factors on crop yields: Western Plateau and Hills Region

Variables	Sorghum	Cotton	Sugarcane	Wheat	Rapeseed & mustard
Ln Rainfall	0.0669*** (0.0076)	0.0214* (0.0124)	0.0070 (0.0051)	-0.0020** (0.0008)	0.0187*** (0.0031)
Ln Min Temp	-0.2867** (0.1413)	-0.6749** (0.3060)	0.0026 (0.0336)	0.0034 (0.0085)	0.4826*** (0.0974)
Ln Max Temp	1.1945*** (0.3889)	-1.2066*** (0.4701)	-0.1796 (0.1397)	-0.1308*** (0.0491)	-1.7212*** (0.2308)
Ln Irrigation	0.6910*** (0.1389)	0.4579*** (0.0799)	-0.0466* (0.0266)	-0.0640*** (0.0141)	0.0548*** (0.0180)
Ln Fertilizer	0.0319*** (0.0028)	0.0293*** (0.0048)	-0.0066*** (0.0016)	0.0028*** (0.0006)	-0.0111*** (0.0017)
Ln Road length	0.0041 (0.0028)	-0.0008 (0.0022)	-0.0011 (0.0009)	-0.0001 (0.0005)	-0.0028 (0.0018)
Ln Ruliteracy	-0.0475 (0.0316)	-0.3287*** (0.0815)	-0.0595*** (0.0219)	-0.0162** (0.0074)	0.0027 (0.0182)
Ln Tractors	-0.0381*** (0.0067)	-0.0283** (0.0133)	-0.0004 (0.0041)	-0.0014 (0.0015)	0.0042 (0.0039)
Ln Pumpset	0.0072 (0.0065)	0.0140 (0.0102)	-0.0120*** (0.0035)	0.0024 (0.0015)	-0.0182*** (0.0038)
Time	0.0073*** (0.0016)	0.0449*** (0.0039)	0.0121*** (0.0011)	0.0086*** (0.0004)	0.0134*** (0.0010)
Constant	-18.5905*** (3.1000)	-92.5630*** (7.3605)	-21.1204*** (2.1160)	-16.4440*** (0.8069)	-22.4462 (1.9298)
District fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	1255	1255	1255	1253	1228
Wald chi^2(39)	439.87***	1393.01***	1512.43***	10134.02 ***	6572.16 ***
F(1, 29)[1]	3483.519***	4015.193***	17146.177 ***	11.343***	6918.301 ***
chi^2 (30)[2]	13.79	1.00	6.51	1.55	4.3

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2] Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

Table 15. Regression estimates of climate and non-climatic factors on crop yields: Southern Plateau and Hills Region

Variables	Rice	Groundnut	Wheat	Linseed
Ln Rainfall	-0.0292***	0.0495***	-0.0077***	0.0098*
	(0.0046)	(0.0068)	(0.0016)	(0.0050)
Ln Min Temp	-0.0694	-0.5207***	-0.0532	-0.1999
	(0.1041)	(0.1504)	(0.0711)	(0.2180)
Ln Max Temp	-0.1602	0.1408	-0.1208	-1.1369***
	(0.1060)	(0.1628)	(0.1133)	(0.3481)
Ln Irrigation	0.8885***	0.4835***	-0.0591***	0.2374***
	(0.0282)	(0.0252)	(0.0137)	(0.0356)
Ln Fertilizer	0.0024	-0.0133***	0.0064***	-0.0280***
	(0.0031)	(0.0040)	(0.0021)	(0.0062)
Ln Road length	-0.0046***	-0.0032**	0.0000	0.0091***
	(0.0011)	(0.0016)	(0.0007)	(0.0021)
Ln Ruliteracy	-0.0004	0.0113*	-0.0072**	-0.0009
	(0.0049)	(0.0061)	(0.0033)	(0.0102)
Ln Tractors	0.0121***	-0.0035	-0.0111***	-0.0501***
	(0.0027)	(0.0031)	(0.0019)	(0.0054)
Ln Pumpset	0.0081***	-0.0046	-0.0110***	-0.0371***
	(0.0029)	(0.0037)	(0.0021)	(0.0060)
Time	-0.0012***	0.0045***	0.0088***	0.0101***
	(0.0005)	(0.0004)	(0.0002)	(0.0007)
Constant	-1.9309**	-9.1495***	-15.8455***	-15.8353***
	(0.8512)	(0.8288)	(0.4787)	(1.4634)
District fixed Effects	Yes	Yes	Yes	Yes
Observations	1347	1347	1347	1347
Wald chi^2(39)	26103.87***	2685.03	12498.97***	388.83***
F(1, 29)[1]	6469.315***	323.057***	51.145***	53.662***
chi^2 (30)[2]	0.98	3.96	1.81	6.91

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2] Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

4.1.11 East Coast Plains and Hills Region

East Coast Plains and Hills spans over the districts of Andhra Pradesh, Odisha, and Tamil Nadu states and the Union Territory of Puducherry. The zone covers an area of 199,900 sq. km and is characterized by semi-arid to dry sub-humid climatic conditions. The mean minimum temperature remains at 22.38°C while the mean maximum temperature is 31.34°C in the region. The average annual rainfall is about 1100 mm. Rice, bajra, groundnut, sugarcane, mustard, and sorghum are some of the major crops grown in this zone.

An examination of climate impact on crop yields in East Coast Plains and Hills reveals that a higher minimum temperature lowers yield of rice, groundnut, sugarcane, and wheat, while it benefits rapeseed & mustard (Table 16). On the other spectrum, a rise in maximum temperature increase yield of all the crops, except for groundnut. A higher rainfall significantly increases yield of groundnut and sugarcane but reduces that of rice. Irrigation had a positive and significant impact on rice, groundnut, and rapeseed & mustard. An increase in fertilizer consumption insignificantly reduces rice and groundnut yields.

4.1.12 West Coast Plains and Ghats Region

West Coast Plains and Ghats encompass states of Goa, Kerala and parts of Karnataka, Maharashtra, and Tamil Nadu. It occupies 3.61% of the India's geographical area. The climate in this zone is typically dry sub-humid to per-humid with the mean annual temperature ranging from 20.60°C to 30.36°C. The West coast plains and Ghats receive about of 2418 mm rainfall, the second highest among the agro-climatic zones. The important crops grown in this region are rice, sugarcane, millets and groundnut.

The estimated regression as shown in Table 17, reveals that higher temperatures and rainfall positively impact rapeseed & mustard yield, suggesting its capacity to withstand increasing climatic variation in the region. Barring finger millet, all other crops yield appears to have benefitted from higher rainfall. A rise in maximum temperature lowers the yield of rice, groundnut, finger millet, and wheat while an increase in the minimum temperature negatively impacts groundnut only. Irrigation variable is highly significant and positively impacts rice, groundnut, rapeseed & mustard yields. On the other hand, higher fertilizer consumption lowers yield of rice, groundnut, and wheat.

Table 16. Regression estimates of climate and non-climatic factors on crop yields: East Coast Plains and Hills Region

Variables	Rice	Groundnut	Sugarcane	Wheat	Rapeseed & mustard
Ln Rainfall	-0.0151*** (0.0058)	0.0326*** (0.0085)	0.0212*** (0.0070)	-0.0013 (0.0022)	0.0043 (0.0069)
Ln Min Temp	-0.1056 (0.0907)	-0.0965 (0.1144)	-0.3602*** (0.1159)	-0.1562*** (0.0547)	0.9319*** (0.1444)
Ln Max Temp	0.0126 (0.0478)	-0.0577 (0.0540)	0.0495 (0.0800)	0.0232 (0.0244)	0.0132 (0.0623)
Ln Irrigation	0.8637*** (0.0370)	0.4584*** (0.0316)	-0.0443 (0.0336)	-0.0884*** (0.0153)	0.0766*** (0.0225)
Ln Fertilizer	-0.0006 (0.0028)	-0.0058 (0.0036)	0.0112*** (0.0038)	0.0022 (0.0018)	0.0192*** (0.0048)
Ln Road length	-0.0017 (0.0011)	-0.0017 (0.0016)	0.0002 (0.0012)	-0.0007 (0.0007)	0.0048** (0.0023)
Ln Ruliteracy	-0.0050 (0.0121)	0.0318** (0.0131)	-0.0249 (0.0221)	-0.0118* (0.0068)	-0.0193 (0.0172)
Ln Tractors	0.0081** (0.0036)	-0.0069* (0.0040)	0.0262*** (0.0061)	-0.0014 (0.0021)	0.0298*** (0.0053)
Ln Pumpset	0.0043 (0.0034)	0.0000 (0.0040)	-0.0021 (0.0047)	-0.0056*** (0.0020)	0.0277*** (0.0054)
Time	0.0003 (0.0007)	0.0031*** (0.0006)	0.0081*** (0.0011)	0.0087*** (0.0003)	0.0096*** (0.0009)
Constant	-3.6637*** (1.2968)	-7.1290*** (1.0547)	-13.2903*** (1.9954)	-15.7731*** (0.6303)	-22.6853*** (1.6372)
District fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	721	721	721	721	721
Wald chi^2(26)	11088.04***	1393.72***	1187.62***	7717.82***	5874.56***
F(1, 16)^1	993.58***	422.492***	1373.45***	2.759	3856.206***
chi^2 (17)^2	0.08	1.36	0.69	3.34	1.01

Note: ^{1}Woolridge test for autocorrelation in panel data (H$_0$: no first order auto correlation) and ^{2}Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

Table 17. Regression estimates of climate and non-climatic factors on crop yields: West Coast Plains and Ghats Region

Variables	Rice	Groundnut	Finger millet	Wheat	Rapeseed & mustard
Ln Rainfall	0.0073 (0.0064)	0.0554*** (0.0088	-0.0268 (0.0326)	0.0029 (0.0025)	0.0171** (0.0079)
Ln Min Temp	0.0407 (0.1211)	-0.3926** (0.1533)	0.2810 (0.5434)	0.0366 (0.0694)	0.6356*** (0.2083)
Ln Max Temp	-0.0513 (0.0495)	-0.0422 (0.0514)	-0.0389 (0.2144)	-0.0065 (0.0402)	0.0679 (0.1116)
Ln Irrigation	0.8773*** (0.0372)	0.4606*** (0.0295)	-0.9399*** (0.0709)	-0.0721*** (0.0177)	0.0721*** (0.0257)
Ln Fertilizer	-0.0034** (0.0014)	-0.0031* (0.0016)	0.0024 (0.0061)	-0.0005 (0.0009)	0.0118*** (0.0027)
Ln Road length	-0.0008 (0.0009)	-0.0018* (0.0010)	-0.0027 (0.0039)	0.0001 (0.0006)	0.0019 (0.0017)
Ln Ruliteracy	0.0070 (0.0092)	0.0077 (0.0092)	0.0770** (0.0386)	-0.0057 (0.0060)	0.0121 (0.0155)
Ln Tractors	-0.0016 (0.0027)	-0.0031 (0.0028)	-0.0046 (0.0115)	0.0005 (0.0017)	0.0054 (0.0047)
Ln Pumpset	-0.0029 (0.0030)	-0.0060* (0.0034)	0.0102 (0.0132)	0.0004 (0.0020)	0.0162*** (0.0057)
Time	0.0003 (0.0006)	0.0042*** (0.0003)	0.0063*** (0.0015)	0.0080*** (0.0003)	0.0106*** (0.0008)
Constant	-4.2440*** (1.1306)	-8.5686*** (0.6880)	-13.0269*** (3.2325)	-14.9332*** (0.5228)	-24.0096*** (1.4053)
District fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	720	720	720	720	720
Wald chi^2(27)	10140.20***	1676.33***	4700.76***	5560.14***	3635.13***
F(1,17)[1]	1018.909***	590.165***	2939.778***	7.664**	1989.035***
chi^2 (18)[2]	0.86	1.29	2.80	2.20	2.40

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2] Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

4.1.13 Gujarat Plains and Hills Region

The agro-climatic zone of Gujarat Plains and Hills covers the entire state of Gujarat and the Union Territories of Dadra & Nagar Haveli and Daman & Diu with 5.99% of the total geographical area in the country. The ACZ has arid to dry sub-humid climate with average annual rainfall of 862 mm. The mean minimum temperature in the region is about 19.95°C while the mean maximum remains around 32.17°C. Rice, groundnut, cotton, jowar, bajra and wheat are some of the major crops grown in the region.

As depicted in Table 18, a rise in minimum temperature significantly lowers the yield of pearl millet, cotton, groundnut, and barley. Rainfall has a positive effect on most of the crop yields, except for rapeseed & mustard. Input variable like irrigation and fertilizer benefits cotton, rapeseed & mustard, and barley yields. The maximum temperature seemed to increase yield of crops like pearl millet, cotton, groundnut, and barley.

Table 18. Regression estimates of climate and non-climatic factors on crop yields: Gujarat Plains and Hills Region

Variables	Pearl Millet	Cotton	Groundnut	Wheat	Rapeseed & mustard	Barley
Ln Rainfall	0.1319*** (0.0074)	0.0294*** (0.0096)	0.0600*** (0.0046)	0.0018** (0.0007)	-0.0042* (0.0025)	0.0071*** (0.0010)
Ln Min Temp	-3.4354*** (0.8609)	-3.2665*** (1.0673)	-2.6499*** (0.5850)	0.6114*** (0.1668)	1.1058*** (0.4120)	-0.0642 (0.2190)
Ln Max Temp	4.1505*** (1.2418)	4.8617*** (1.5184)	3.3409*** (0.8468)	-1.0785*** (0.3039)	-2.0511*** (0.7735)	0.0156 (0.3890)
Ln Irrigation	-0.0968*** (0.0203)	0.5623*** (0.1016)	0.5711*** (0.0273)	-0.0975*** (0.0172)	0.0741*** (0.0202)	0.2609*** (0.0115)
Ln Fertilizer	0.0073 (0.0072)	0.0090 (0.0140)	-0.0062 (0.0046)	0.0022 (0.0025)	0.0369*** (0.0064)	0.0057 (0.0036)
Ln Road length	0.0033 (0.0037)	0.0050 (0.0051)	0.0039 (0.0024)	0.0053*** (0.0011)	-0.0174*** (0.0038)	0.0042*** (0.0016)
Ln Ruliteracy	-0.0195 (0.0142)	0.0255 (0.0498)	-0.0002 (0.0087)	-0.0029 (0.0050)	0.0296** (0.0123)	0.0004 (0.0079)
Ln Tractors	-0.0171*** (0.0033)	-0.0252** (0.0117)	-0.0082*** (0.0020)	-0.0032** (0.0013)	0.0275*** (0.0029)	-0.0033* (0.0019)
Ln Pumpset	-0.0274*** (0.0065)	-0.1048*** (0.0195)	-0.0041 (0.0039)	-0.0155*** (0.0023)	0.0545*** (0.0056)	-0.0071* (0.0036)
Time	0.0113*** (0.0007)	0.0252*** (0.0024)	0.0039*** (0.0005)	0.0082*** (0.0003)	0.0079*** (0.0008)	0.0085*** (0.0005)
Constant	-27.5430*** (2.1528)	-60.4945*** (5.0254)	-12.9049*** (1.4264)	-13.2394*** (0.7688)	-12.8150*** (2.1876)	-17.3012*** (1.1082)
District fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	763	763	763	763	763	763
Wald chi^2(27)	3212.02***	1161.65***	2041.15***	8869.86***	7125.43***	899.88***
F(1,17)[1]	337.639***	343.295***	139.147***	0.478	697.886***	75.393***
chi^2 (18)[2]	16.37	11.44	5.07	0.57	1.25	2.48

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2]Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

4.1.14 Western Dry Region

Western Dry Region covers 12 districts of Rajasthan state. The zone occupies an area of 182,157 sq. km and has arid to extremely arid climatic conditions. The region receives the least amount of rainfall of about 428mm among the agro-climatic zones.

Table 19. Regression estimates of climate and non-climatic factors on crop yields: Western Dry Region

Variables	Pearl millet	Maize	Wheat	Rapeseed & mustard
Ln Rainfall	0.1305*** (0.0094)	0.0194*** (0.0062)	-0.0026** (0.0012)	-0.0085** (0.0034)
Ln Min Temp	-0.4224** (0.1837)	-0.2279** (0.0942)	-0.2221*** (0.0371)	0.6012*** (0.1005)
Ln Max Temp	0.0768 (0.0871)	-0.0126 (0.0414)	-0.0084 (0.0250)	-0.0226 (0.0686)
Ln Irrigation	-0.0313 (0.0306)	0.1997*** (0.0382)	-0.0179 (0.0227)	0.0384 (0.0259)
Ln Fertilizer	-0.0005 (0.0106)	-0.0144** (0.0059)	0.0034 (0.0030)	0.0265*** (0.0083)
Ln Road length	-0.0191*** (0.0042)	-0.0090*** (0.0028)	-0.0043*** (0.0012)	0.0266*** (0.0041)
Ln Ruliteracy	0.0237 (0.0226)	0.0839*** (0.0123)	0.0053 (0.0082)	-0.1009*** (0.0177)
Ln Tractors	0.0084*** (0.0031)	-0.0032* (0.0017)	-0.0012 (0.0010)	-0.0047* (0.0024)
Ln Pumpset	-0.0279** (0.0120)	-0.0912*** (0.0068)	-0.0191*** (0.0050)	0.0556*** (0.0099)
Time	0.0104*** (0.0009)	0.0076*** (0.0005)	0.0072*** (0.0005)	0.0143*** (0.0008)
Constant	-21.0042*** (1.6776)	-15.1575*** (0.9164)	-12.7844*** (0.9310)	-30.4655*** (1.4895)
District fixed Effects	Yes	Yes	Yes	Yes
Observations	490	490	490	490
Wald chi^2(20)	1779.25***	4422.63***	5966.44***	4917.32***
F(1, 10)[1]	46.734***	3435.961***	3.741*	1761.59***
chi^2 (11)[2]	4.11	3.57	0.88	2.41

Note: [1]Woolridge test for autocorrelation in panel data (H_0: no first order auto correlation) and [2]Modified Wald tests for group-wise heteroscedasticity in cross-sectional time-series FGLS regression model.
Significance level: * p <0.10, ** p <0.05, *** p< 0.01
Figures within the parentheses are standard errors.
Dependent variables i.e. crop yield is in logarithmic form.
District dummies were incorporated but the estimated coefficients are not shown.

The mean minimum temperature remains around 18.77°C while the mean maximum temperature at 33.08°C. Pearl millet, rapeseed & mustard, wheat and maize are some of the major crops grown in the region. The estimated regression in Table 19, showed that the minimum temperature has a much stronger effect on crop yields than rainfall and maximum temperature in the zone. A rise in rainfall and maximum temperature positively impacts pearl millet yield while the minimum temperature had a negative impact. A higher maximum temperature had a negative and insignificant impact on maize, wheat, and rapeseed & mustard yield. Crop yields such as maize and rapeseed & mustard appear to have benefitted from higher irrigation. Moreover, fertilizer consumption increases the yield of wheat and rapeseed & mustard in the region.

4.2 Marginal effects of climate change and projected change in crop yields

The section presents the estimates of combined marginal effects of climate change on crop yields during the period 1966-2011 and projects the likely yield changes in response to high temperatures (RCPs, 4.5 and 8.5) for different time periods. Overall, it was observed that most of the crop yields (*kharif* and *rabi*) were adversely impacted by climate change; however, the magnitude of such effects vary across ACZs. In assessing the combined marginal effects of climate change, it was observed that rainfall had a positive impact on most of the crop yields but was not sufficient enough to counterbalance the combined impact of maximum and minimum temperature. Further, the estimated coefficients and projected impacts were moderately lower, probably due to inclusion of non-climatic factors.

4.2.1 Marginal impact and projected change for *kharif* crop yields

Marginal effects: During the period 1966-2011, a decline in rice yield was observed in nearly all the ACZs, with the highest reduction of 2.62% found in eastern Himalayan Region (covering north-eastern states and parts of West Bengal). This was followed by Western Himalayan Region, Lower Gangetic Plains and Southern Plateau & Hills where rice yield reduced by 2.34%, 1.17% and 0.72%, respectively. As shown in Table 20, maize yield declined in Central Plateau & Hills (1.33%), Western Dry Region (1.03%), Trans-Gangetic Plains (0.65%), and Upper Gangetic Plains (0.03%). Regional variations are reflected from the fact that while maize was negatively impacted by climatic variations in the above regions, it was benefitted in Himalayan Regions, Lower and Middle Gangetic Plains. The maximum reduction in groundnut occurred in Southern Plateau &

Table 20. Marginal impacts (1966-2011) and projected change for *kharif* crop yields by 2030s, 2040s, 2050s and 2080s (%)

Agro-climatic zone	Crops	Marginal effects	With RCP 4.5 temperature projections				With RCP 8.5 temperature projections			
			2030s	2040s	2050s	2080s	2030s	2040s	2050s	2080s
			Δ MinT = 1.36	Δ MinT = 1.75	Δ MinT = 2.14	Δ MinT = 2.63	Δ MinT = 1.50	Δ MinT = 2.05	Δ MinT = 2.60	Δ MinT = 4.43
			Δ MaxT = 1.26	Δ MaxT = 1.50	Δ MaxT = 1.81	Δ MaxT = 2.29	Δ MaxT = 1.36	Δ MaxT = 1.83	Δ MaxT = 2.30	Δ MaxT = 3.94
			Δ R= (+/-) 5%	Δ R= (+/-) 7%	Δ R= (+/-) 10%	Δ R= (+/-) 12%	Δ R= (+/-) 5%	Δ R= (+/-) 7%	Δ R= (+/-) 10%	Δ R= (+/-) 12%
Western Himalayan Region	Rice	-2.34	-2.94	-3.66	-4.41	-5.49	-4.02	-4.39	-5.52	-9.59
	Maize	3.29	4.17	4.94	5.97	7.57	4.49	6.03	7.59	12.95
Eastern Himalayan Region	Rice	-2.62	-3.56	-4.49	-5.49	-6.79	-3.89	-5.30	-6.72	-11.39
	Maize	1.33	1.83	2.42	2.97	3.61	2.04	2.81	3.56	6.10
Lower Gangetic Plains Region	Rice	-1.17	-1.60	-1.91	-2.34	-2.96	-1.71	-2.30	-2.92	-4.87
	Maize	2.83	3.99	5.11	6.29	7.74	4.37	5.97	7.60	12.78
Middle Gangetic Plains Region	Rice	-0.17	-0.26	-0.33	-0.41	-0.51	-0.28	-0.38	-0.49	-0.80
	Maize	0.19	0.45	0.60	0.79	0.96	0.48	0.66	0.87	1.30
	Sugarcane	-8.02	-11.15	-14.19	-17.43	-21.50	-12.21	-16.65	-21.17	-35.70
Upper Gangetic Plains Region	Rice	-0.07	-0.16	-0.20	-0.27	-0.33	-0.17	-0.23	-0.30	-0.45
	Sugarcane	-0.13	-0.77	-1.15	-1.57	-1.85	-0.82	-1.16	-1.60	-2.18
	Maize	-0.03	0.12	0.18	0.27	0.32	0.12	0.17	0.25	0.27
	Sorghum	-0.68	-0.88	-1.12	-1.36	-1.67	-0.97	-1.33	-1.67	-2.91
Trans-Gangetic Plains Region	Rice	-0.37	-0.40	-0.46	-0.54	-0.69	-0.44	-0.59	-0.72	-1.30
	Cotton	-0.59	-0.86	-1.22	-1.50	-1.78	-0.98	-1.36	-1.74	-2.99
	Pearl Millet	2.09	8.43	11.35	15.58	18.90	8.63	11.95	16.49	22.03
	Maize	-0.65	-0.90	-1.25	-1.53	-1.83	-1.03	-1.43	-1.81	-3.14

Eastern Plateau and Hills Region	Rice	-0.67	-1.08	-1.36	-1.71	-2.12	-1.16	-1.57	-2.03	-3.27
	Maize	0.28	0.30	0.26	0.30	0.43	0.29	0.37	0.46	0.78
Central Plateau and Hills Region	Sorghum	-4.54	-5.71	-7.29	-8.76	-10.80	-6.35	-8.67	-10.87	-19.08
	Maize	-1.33	-1.75	-2.24	-2.72	-3.35	-1.93	-2.64	-3.33	-5.73
	Groundnut	0.55	0.95	1.26	1.59	1.94	1.03	1.42	1.84	2.95
Western Plateau and Hills Region	Sorghum	4.68	6.15	7.00	8.56	11.01	6.47	8.64	10.93	18.13
	Cotton	-1.74	-2.24	-2.77	-3.36	-4.19	-2.45	-3.32	-4.19	-7.18
	Sugarcane	-3.66	-4.39	-5.17	-6.17	-7.84	-4.75	-6.38	-7.97	-13.87
Southern Plateau and Hills Region	Rice	-0.72	-1.06	-1.32	-1.65	-2.05	-1.14	-1.55	-1.99	-3.27
	Groundnut	-1.56	-1.96	-2.54	-3.06	-3.75	-2.19	-3.00	-3.77	-6.62
East Coast Plains and Hills Region	Rice	-0.37	-0.57	-0.74	-0.93	-1.13	-0.62	-0.85	-1.09	-1.79
	Groundnut	-0.49	-0.52	-0.64	-0.74	-0.93	-0.58	-0.79	-0.97	-1.79
	Sugarcane	-9.91	-12.94	-16.70	-20.26	-24.87	-14.37	-19.65	-24.79	-42.87
West Coast Plains and Ghats Region	Rice	0.01	0.07	0.10	0.14	0.16	0.07	0.10	0.14	0.21
	Groundnut	-1.51	-1.82	-2.30	-2.75	-3.39	-2.02	-2.76	-3.44	-6.10
	Finger millet	1.10	1.38	1.78	2.14	2.63	1.54	2.10	2.64	4.63
Gujarat Plains and Hills Region	Pearl millet	-1.23	-2.00	-3.36	-4.17	-4.70	-2.45	-3.53	-4.54	-7.95
	Cotton	0.02	-0.30	-0.81	-1.06	-1.08	-0.44	-0.70	-0.95	-1.58
	Groundnut	-1.26	-2.31	-3.96	-4.97	-5.58	-2.82	-4.09	-5.31	-9.11
Western Dry Region	Pearl Millet	-0.84	-0.82	-1.04	-1.17	-1.45	-0.95	-1.29	-1.56	-3.01
	Maize	-1.03	-1.32	-1.68	-2.03	-2.50	-1.46	-2.00	-2.51	-4.37

Source: Authors' estimation

Note: Direction of rainfall for the future projections was premised on trend analysis for the period, 2001-2011.

Hills (covering parts of Andhra Pradesh, Karnataka, and Tamil Nadu) and West Coast Plains & Ghats, whereas in Central Plateau & Hills, it showed an increase of 0.55%. A wide variation was observed in sorghum yield which showed a decline of 4.54% in Central Plateau & Hills (covering parts of Madhya Pradesh, Rajasthan and Uttar Pradesh) and an increase of 4.68% in Western Plateau & Hills (covering parts of Madhya Pradesh and Maharashtra). Sugarcane was impacted the most by the changing climatic conditions in all the growing regions. The yield loss for sugarcane was to the extent of 9.91%, 8.02%, and 3.66% in East Coast Plains & Hills, Middle Gangetic Plains, and Western Plateau & Hills, respectively. While pearl millet yield showed an increase of 2.09% in Trans-Gangetic Plains, it registered a decline of 1.23% and 0.84% in Gujarat Plains & Hills and Western Dry Region, respectively. Finger millet yield increased by 1.10% in West Coast Plains & Ghats. Further, the effect of climatic variations was found to be negative for cotton in Western Plateau & Hills and Trans-Gangetic Plains, where yield reduced by 1.74% and 0.59%, respectively.

Projected impact under RCP 4.5: The projected impact of climate change on crop yields showed that rice yield will decline by 5.49% and 6.79% in Eastern Himalayan Region by 2050s and 2080s, respectively. In the near-term, it is likely to reduce by 2.94% and 3.56% in Western and Eastern Himalayan Regions, respectively. By 2040s, rice yield is projected to decline by around 2% in Lower Gangetic Plains (parts of West Bengal). In case of both Eastern and Southern Plateau & Hills, rice yield will decline by around 1.3% and 1.7% by 2040s and 2050s, respectively. On the other hand, rice yield in West Coast Plains & Ghats will benefit from future climate variations. The maximum decline is projected for maize in Central Plateau & Hills and Western Dry Region where the crop yield is projected to decline by 2.24% and 1.68% by 2040s, respectively. By 2080s, maize is likely to increase by around 7% to 8% in Western Himalayan Region and Lower Gangetic Plains. Yield loss for groundnut in Gujarat Plains & Hills is expected to be around 4% and 5% by 2040s and 2050s, respectively. In the near-term, groundnut yield will reduce by 1.96% and 1.82% in Southern Plateau & Hills and West Coast Plains & Ghats, whereas it will increase by 0.95% in Central Plateau & Hills. In the mid and long-term period, sorghum is likely to increase by around 8% and 11% in Western Plateau & Hills and decrease by the same magnitude in Central Plateau & Hills. The productivity of cotton will decline the most in Western Plateau & Hills followed by Trans-Gangetic Plains. For sugarcane, the yield is projected to decline by 11% and 13% in Middle Gangetic Plains (covering Bihar and parts of Uttar Pradesh) and East Coast Plains & Hills by 2030s. Pearl millet is likely to increase by 15.58% by mid-term period in Trans-Gangetic Plains. On the other hand, for the similar period, pearl millet yield will reduce by 4.17% and 1.17% in Gujarat Plains & Hills and Western Dry Region.

Projected impact under RCP 8.5: As shown in Table 20, by the end of the century, maize yield is projected to increase by 12% in Western Himalayan Region and Lower Gangetic Plains, respectively. Under the mid-term period, maize yield will reduce by 3.33% and 2.51% in Central Plateau & Hills and Western Dry Region, respectively. In Western and Eastern Himalayan Region, rice yield is likely to reduce by 5.52% and 6.72% by 2050s, respectively. By 2080s rice yield in Lower Gangetic Plains (covering parts of West Bengal) is projected to decline by 4.87%. Pearl millet is likely to benefit from climate change in Trans-Gangetic Plains, where its yield will increase by 11.95% by 2040s. The yield loss in case of pearl millet is expected to be around 7% and 3% in Gujarat Plains & Hills and Western Dry Region by 2080s, respectively. The maximum decline in cotton yield was observed in Western Plateau & Hills (covering parts of Maharashtra and Madhya Pradesh), where yield is expected to decline by 4.19% and 7.18% under mid- and long-term period. By 2050s, finger millet yield will increase by 2.64% in West Coast Plains & Ghats. By the end of the century, sorghum is projected to decline up to 19% in Central Plateau & Hills while on the other hand, for the similar period, it will increase by about 18% in Western Plateau & Hills. In Middle Gangetic Plains and East Coast Plains & Hills, sugarcane yield is expected to decline by 21.17% and 24.79% under mid-term period, respectively. Moreover, in Western Plateau & Hills, sugarcane yield will reduce by 6.38% by 2040s. The productivity of groundnut is projected to decline by 9.91% and 6.62% in Gujarat Plains & Hills and Southern Plateau & Hills by 2080s, respectively.

4.2.2 Marginal impact and projected change for *rabi* crop yields

Marginal Effects: The results reveal that over the period, wheat yield was negatively impacted by climatic variations in all the growing regions, except for West Coast Plains & Ghats and Gujarat Plains & Hills (Table 21). The maximum yield reduction occurred in Western Dry Region (2.73%), followed by Eastern Himalayan Region (2.03%). Moreover, the entire Gangetic Plains also showed a decline in wheat yield with the highest reduction of 1.02% in Trans-Gangetic Plains, followed by Lower Gangetic Plains (0.96%). Barley, on the other hand, showed a decline of 0.76% and 0.26% in Western Himalayan Region and Trans-Gangetic Plains, whereas

Table 21. Marginal impacts (1966-2011) and projected change for *rabi* crop yields by 2030s, 2040s, 2050s and 2080s (%)

Agro-climatic zone	Crops	Marginal effects	With RCP 4.5 temperature projections				With RCP 8.5 temperature projections			
			2030s	2040s	2050s	2080s	2030s	2040s	2050s	2080s
			Δ MinT = 1.36	Δ MinT = 1.75	Δ MinT = 2.14	Δ MinT = 2.63	Δ MinT = 1.50	Δ MinT = 2.05	Δ MinT = 2.60	Δ MinT = 4.43
			Δ MaxT = 1.26	Δ MaxT = 1.50	Δ MaxT = 1.81	Δ MaxT = 2.29	Δ MaxT = 1.36	Δ MaxT = 1.83	Δ MaxT = 2.30	Δ MaxT = 3.94
			Δ R= (+/-) 5%	Δ R= (+/-) 7%	Δ R= (+/-) 10%	Δ R= (+/-) 12%	Δ R= (+/-) 5%	Δ R= (+/-) 7%	Δ R= (+/-) 10%	Δ R= (+/-) 12%
Western Himalayan Region	Wheat	-0.47	-0.66	-0.85	-1.05	-1.29	-0.73	-1.00	-1.27	-2.14
	Barley	-0.76	-0.91	-1.04	-1.25	-1.60	-0.98	-1.30	-1.63	-2.81
Eastern Himalayan Region	Wheat	-2.03	-2.61	-3.28	-3.98	-4.93	-2.87	-3.91	-4.93	-8.49
	Rapeseed & mustard	-1.08	-1.44	-1.77	-2.16	-2.70	-1.56	-2.11	-2.68	-4.53
Lower Gangetic Plains Region	Wheat	-0.96	-1.04	-1.24	-1.45	-1.83	-1.14	-1.54	-1.90	-3.43
	Rapeseed & mustard	-1.21	-1.67	-2.01	-2.46	-3.10	-1.79	-2.41	-3.06	-5.12
Middle Gangetic Plains Region	Wheat	-0.28	-0.37	-0.46	-0.56	-0.69	-0.40	-0.55	-0.69	-1.18
	Rapeseed & mustard	1.04	1.26	1.58	1.90	2.36	1.39	1.89	2.38	4.15
	Barley	0.04	0.05	0.09	0.10	0.12	0.06	0.09	0.12	0.22
Upper Gangetic Plains Region	Wheat	-0.09	-0.11	-0.14	-0.17	-0.21	-0.12	-0.17	-0.21	-0.37
	Barley	0.01	0.03	0.04	0.06	0.08	0.03	0.04	0.06	0.08
	Rapeseed & mustard	0.20	0.29	0.37	0.46	0.57	0.32	0.43	0.56	0.91
Trans-Gangetic Plains Region	Wheat	-1.02	-1.53	-2.07	-2.57	-3.11	-1.70	-2.34	-3.01	-5.02
	Barley	-0.26	-0.30	-0.34	-0.40	-0.52	-0.32	-0.43	-0.54	-0.95
	Rapeseed & mustard	1.59	2.32	3.14	3.89	4.70	2.59	3.58	4.58	7.71

Eastern Plateau and Hills Region	Wheat	-0.26	-0.30	-0.41	-0.48	-0.58	-0.34	-0.47	-0.59	-1.07
	Linseed	-0.87	-1.23	-1.62	-2.00	-2.43	-1.36	-1.87	-2.39	-4.04
Central Plateau and Hills Region	Wheat	-0.94	-1.31	-1.69	-2.07	-2.54	-1.44	-1.96	-2.50	-4.22
	Rapeseed & mustard	2.73	3.69	4.72	5.76	7.10	4.06	5.54	7.03	11.97
Western Plateau and Hills Region	Wheat	-0.88	-1.12	-1.34	-1.62	-2.05	-1.21	-1.63	-2.05	-3.49
	Rapeseed & mustard	-1.86	-2.05	-2.10	-2.45	-3.29	-2.13	-2.79	-3.44	-6.01
Southern Plateau and Hills Region	Wheat	-1.27	-1.73	-2.14	-2.62	-3.27	-1.88	-2.55	-3.23	-5.44
	Linseed	-1.35	-1.72	-2.08	-2.51	-3.16	-1.86	-2.51	-3.16	-4.88
East Coast Plains and Hills Region	Wheat	-1.46	-2.01	-2.61	-3.19	-3.92	-2.22	-3.04	-3.86	-6.56
	Rapeseed & mustard	3.45	4.71	6.05	7.41	9.10	5.19	7.09	8.99	15.31
West Coast Plains and Ghats Region	Wheat	0.33	0.48	0.62	0.77	0.95	0.54	0.72	0.92	1.54
	Rapeseed & mustard	2.45	3.37	4.33	6.34	6.53	3.71	5.07	7.47	10.91
Gujarat Plains and Hills Region	Wheat	0.44	1.29	2.48	3.20	3.49	1.62	2.41	3.20	5.29
	Rapeseed & mustard	0.31	0.86	1.66	2.13	2.32	1.09	1.61	2.14	3.56
Western Dry Region	Wheat	-2.73	-3.71	-4.77	-5.84	-7.17	-4.09	-5.58	-7.03	-12.05
	Rapeseed & mustard	2.57	3.50	4.50	5.50	6.75	3.86	5.28	6.69	11.42

Source: Authors' estimation
Note: Direction of rainfall for the future projections was premised on trend analysis for the period 2001-2011.

in Middle and Upper Gangetic Plains, it registered a marginal increase of 0.04% and 0.01%, respectively. In nearly all the growing regions, rapeseed & mustard was positively impacted, reflecting its high tolerance and resilience to the changing climatic conditions. In East Coast Plains & Hills, Central Plateau & Hills and Western Dry Region, rapeseed & mustard showed the maximum increase of 3.45%, 2.73% and 2.57%, respectively. On the other spectrum, the yield reduced by 1.86% and 1.21% in Western Plateau & Hills (parts of Madhya Pradesh and Maharashtra states) and Lower Gangetic Plains (parts of West Bengal). During the period, linseed yield declined by 1.35% and 0.87% in the Eastern and Southern Plateau & Hills, respectively.

Projected impact under RCP 4.5: Climate projections for *rabi* crops indicate that wheat yield will reduce by 5.84% and 7.17% by 2050s and 2080s, respectively in Western Dry Region. For the similar periods, it will reduce by 3.98% and 4.93% in Eastern Himalayan Region and 2.57% and 3.11% in Trans-Gangetic Plains. In Gujarat Plains & Hills, wheat yield is likely to increase by 3.20% by 2050s. Rapeseed & mustard yield is projected to increase up to 9.10%, 7.10% and 6.75% by 2080s in East Coast Plains & Hills, Central Plateau & Hills, and Western Dry Region, respectively. On the other hand, by 2040s, rapeseed & mustard yield is likely to reduce by around 2% in Lower Gangetic Plains and Western Plateau & Hills. By 2050s, barley yield will reduce by 1.25% and 0.4% in Western Himalayan Region and Trans-Gangetic Plains, respectively.

Projected impact under RCP 8.5: The projected impact of climate change for *rabi* crop yields revealed that by 2080s, wheat yield is projected to decline by 12.05%, 8.49% and 6.56% in Western Dry Region, Eastern Himalayan Region and East Coast Plains and Hills, respectively. In Trans-Gangetic Plains, wheat yield will decline by 3.01% under the mid-term period (Table 21). On the other hand, by 2050s wheat yield is projected to increase by about 3% in Gujarat plains and hills. The projections indicate that barley yield will not be impacted much due to climate change, as yield loss are projected to be 0.54% and 1.63% by 2050s in Trans-Gangetic Plains and Western Himalayan Region, respectively. Rapeseed & mustard yield showed high resilience and tolerance to climate change in most of the growing regions. In the long-term period, the rapeseed & mustard yield is expected to increase by around 11-12% in Central Plateau & Hills, West Coast Plains & Ghats, and Western Dry Region. On the other hand, by 2040s, rapeseed & mustard yield will decline by about 2-3% in Western Plateau & Hills and Himalayan Regions. In Eastern and Southern Plateau & Hills, linseed yield is expected to decline by 2.39% and 3.16% by 2050s.

Limitations of the study

We analysed the impact of climate change on crop yield using panel data approach; however, the study has a few limitations. First, despite adherence to the diagnostics tests, we observed that many of the control variables did not have the expected signs. But we preferred to retain the variables, against the non-significance of many of those factors and considering the role of socio-economic factors and adaptations in softening the vulnerability of crops to climatic changes. Second, due to unavailability of future climate estimates at agro-climatic zone level, our projections assume uniform changes in rainfall and temperature (maximum and minimum) across the zones and thus used all India estimates. However, climate variations differ across regions, and thus may influence the nature of climate change projections on crop yields.

5

Conclusion and Way Forward

Climate change is one of the most significant factors that directly affect the functioning of agro-ecosystems and have the potential to jeopardize the socio-economic stability of farm communities. Understanding the vulnerability of agriculture production and farmers to climate-induced perturbations requires detailed assessment of climate impact across the regional scales. This study examined the large-scale heterogeneity across the Indian landscape by capturing the idiosyncrasy of ACZs and understanding the sensitivity of major *kharif* and *rabi* crop yields to climate change at a disaggregated level. An examination of spatio-temporal variability in temperature revealed a rise in both the mean maximum and minimum temperature, with relatively more pronounced changes observed in annual mean minimum temperature across the zones. During the period 1966-2011, rainfall recorded an annual decline in Himalayan regions and Gangetic Plains Region, while an increase in Coastal regions, Plateau and Hills, and Western Dry Region.

The empirical results indicate progressive reduction in most of the crop yields under RCPs 4.5 and 8.5 temperature projections, with wide variations in the magnitude of impacts and projections by ACZs. As evident from the foregoing analysis, inclusion of socio-economic, infrastructural and technological factors may have moderated the degree of potential climate impact on crop yield. However, it is likely that the increasing incidence of extreme fluctuations in climate in the form of droughts, dry spell, floods and heat waves could result into discernible effect on agriculture production and productivity. Further, the long-term impact will be influenced by the future farm level developments, technological advancements and policy interventions by the government. Overall, Himalayan regions, Lower Gangetic Plains, Western Plateau, and Coastal regions calls for special attention where climate change results in lower yields and high farm vulnerability.

As discerned from above, changing course is critical, hence it is pertinent to shift from *'business as usual'* interventions to deal with this complex environmental phenomenon. Unaddressed climate change associated with unsustainable agricultural practices, is likely to result in inefficient utilization of natural resources thereby exacerbating poverty and inequalities within and between regions. This carries negative implications for both food availability and food access. Thus, there is an immense need to formulate sustainable adaptation measures and practices suitable to the location-specific needs for enhancing climate resiliency and building capacity of agricultural system to withstand climatic shocks. Improved awareness and communication of climate change is crucial for taking prior informed decision as responses at the farm level are still guided by the traditional experiential knowledge, which could be sub-optimal. The effectiveness of institutions can be enhanced through capacity building and reorientation of extension services especially, Krishi Vigyan Kendras (KVKs), Panchayati Raj Institutions (PRIs) and other grass-root organisations about micro-level sensitivity to climatic variations and risk-coping measures. Further, concerted efforts are needed in development and dissemination of resource saving and climate friendly technologies and in promotion of integrated watershed management which includes up-scaling techniques such as solar pumps, drip irrigation and sprinklers for greater water use efficiency. In addition, climate exposure can be further moderated with diversification to non-farm activities and enhancing the reach and accessibility of insurance covers across regions.

From policy perspective, mainstreaming climate change and adaptation in the developmental paradigm is imperative to improve the envisaged outputs and outcomes. In fact, the long-term essentiality for regional planning arises from the need for a framework that would act as a stabilizer, addressing the regional imbalances and ensuring intergenerational equity in resource use. Hence, there is a dire need to formulate region-specific interventions and plans and prioritization of adaptation strategies to deal with current and future climate change for evolving farmers-centric climate adaptation and mitigation policy.

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Appendices

Table A1: Crop sowing, germination and harvesting season

Crop	Sowing	Germination	Harvesting
Rice	May-June	July-August	September-October
Wheat	October-November	December-February	March-April
Sugarcane	January-February	March-July	August-November
Pearl Millet	June-July	August-September	October
Maize	March-April	May-August	September-December
Linseed	October-November	December-February	March-April
Groundnut	June-July	August-September	October-November
Rapeseed & Mustard	October-November	December-January	February-March
Soybean	June-July	August	September-October
Sorghum	September-October	November-February	March-April
Finger Millet	May-June	July-August	September-December
Barley	November	December-March	April-May
Cotton	April-May	May-August	September-October

Source: Crop calendar, National Food Security Mission

Table A2: Trend in Rainfall across ACZs, 2001-2011

Agro-climatic Zone	Annual rainfall (mm)	*kharif* rainfall (mm)	*rabi* rainfall (mm)
Western Himalayan Region	23.6104*** (5.3463)	28.1792*** (5.8612)	-3.0510*** (2.5754)
Eastern Himalayan Region	-13.0756* (6.9890)	3.5140 (6.0887)	14.2235*** (2.0420)
Lower Gangetic Plains Region	-38.2389*** (4.8811)	-13.0444** (4.2163)	-21.4896*** (2.4215)
Middle Gangetic Plains Region	-15.8999*** (3.5577)	-7.4484*** (2.4537)	-8.7212*** (1.3547)
Upper Gangetic Plains Region	9.7684** (3.6158)	10.3264*** (3.5890)	-1.4170*** (0.4167)
Trans Gangetic Plains Region	25.8672*** (2.7548)	26.8694*** (2.1338)	-0.2725 (0.9608)
Eastern Plateau & Hills Region	-15.5184*** (3.6219)	-8.2845** (3.4963)	-8.8908*** (0.6498)
Central Plateau & Hills Region	2.9381 (3.0556)	5.1822* (2.8493)	-1.0922 (0.6653)
Western Plateau & Hills Region	9.6105*** (3.0275)	9.5226*** (2.6216)	0.8960 (0.9714)
Southern Plateau & Hills Region	27.2405*** (5.0924)	19.5464 *** (2.3274)	5.4139** (2.5963)
East Coast Plains & Hills Region	43.4628*** (13.1086)	25.6458 *** (4.8829)	13.9322 (8.3648)
West Coast Plains & Ghats Region	76.6645*** (9.0369)	64.7328*** (8.8257)	19.0884 *** (2.8595)
Gujarat Plains & Hills Region	25.7331** (10.2673)	23.7341** (10.3381)	2.4238*** (0.6422)
Western Dry Region	20.9350*** (1.9878)	21.6397 *** (2.1813)	0.5962* (0.3061)

Note: Trend has been estimated incorporating district-fixed effects
Figures in the parenthesis is robust standard errors
Significance level: * p <0.10, ** p <0.05, *** p< 0.01

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