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Assessing the impact of climate change on crop yields in Gangetic Plains Region, India

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ABSTRACT

Against the increasing vulnerability of agriculture and farm livelihoods to climate change, the study attempted to analyse the trend in climate variables and their impact on major crop yields during the period from 1966-2011, across 4 agro-climatic zones forming Gangetic Plains Region. A rising trend was observed in annual and seasonal (*kharif* and *rabi*) mean maximum and minimum temperature across the zones. Rainfall on the other hand, showed a declining trend. Overall, climate change adversely impacted crop yield, but the magnitudes of such effects vary spatially. The results reveal that rice and wheat yield will decline in the entire Gangetic region. By 2050s, maize yield will be higher by 6 percent in Lower Gangetic Plains; pearl millet will increase by 15 percent and rapeseed & mustard by 3.8 percent in Trans-Gangetic Plains. Amongst the crops, sugarcane yield was the most impacted to climate change and is expected to reduce by 21 percent in Middle Gangetic Plains towards end of the century. Hence, there is a need to formulate sustainable adaptation measures and practices suitable to location-specific needs for enhancing climate resiliency and capacity of agricultural system to withstand climatic shocks.

***Key words**:* Climate change, trend, impact, crop yield, projections, FGLS, Gangetic Plains Region

The looming harmful effects of climate change and variations impede the transition towards sustainable agriculture. Variability in rainfall and temperatures and sudden onset of extremes (dry spells, droughts, floods, heat waves and hailstorm) adversely affects crop yields leading to low level of productivity (Mall *et al.,* 2006; Bal *et al.,* 2014; Zacharias *et al.,* 2014; Yadav *et al.,* 2016; Bal and Minhas*,* 2017; Mohanty *et al.,* 2017). Such climate induced production risks not only impacts food security but also jeopardizes the socio-economics stability of farm communities (Singh *et al.,* 2018; 2019). However, the impact of climatic variations on crops differs across the geographical landscape given the diverse agro-climatic settings in the country. Therefore, inclusion of adaptations while evaluating impacts produces wide variation in the final outcomes and projections. Thus, this paper attempts to develop estimates of link between crop yield, climate variable and other socio-economic, infrastructural and technological factors in different agro-climatic zones in Gangetic Plains. Further based on different future climate scenarios, the study also projected the likely change in major *kharif* and *rabi* crop yields in the region.

MATERIAL AND METHODS

Study area

Gangetic Plains Region covers about 15.89 percent of India's total geographical area with approximately 73 percent of its total population residing in rural areas (Census, 2011). The region is generally referred to as the food bowl, producing nearly 50 percent of the total food production in the country (Pal *et al.,* 2009). Gangetic Plains consists of four agro-climatic zones, *viz.* Trans-Gangetic Plains, Upper Gangetic Plains, Middle Gangetic Plains and Lower Gangetic Plains. The idiosyncrasy of ACZs reveals that Middle Gangetic Plains followed by Trans-Gangetic Plains occupied 4.98 and 4.47 percent of the total geographical area of the country. In terms of population, Middle Gangetic Plains (comprising Bihar and parts of Uttar Pradesh) was the most populated region, constituting 14.02 percent of the country's population. As shown in Table 1, Trans-Gangetic Plains (9.39 percent) had the highest while Lower Gangetic Plains had the lowest gross cropped area amongst the zones. Relatively Middle Gangetic Plains recorded the lowest average foodgrain yield per hectare.

Lower Gangetic Plains (covering parts of West Bengal) had the maximum average annual rainfall of about 1485mm, while Trans-Gangetic Plains received the lowest amount of rainfall of 673mm. The annual mean minimum temperature (21.21°C) was relatively higher in Lower Gangetic Plains. The annual mean maximum temperature in Gangetic Plains Region ranged between 31-33°C.

Data sources

The study uses panel data approach to examine the

Table 1: Spatial features of ACZs in Gangetic Plains Region

Variables	Trans-Gangetic Plains	Upper Gangetic Plains	Middle Gangetic Plains	Lower Gangetic Plains
Climate	Extreme arid to dry sub-humid	Dry sub-humid to semi-arid	Moist sub humid to dry sub humid	Moist sub-humid to dry sub-humid
Annual rainfall (mm) (1966-2011)	672.73	878.24	1113.14	1485.36
Annual Mint (°C) (1966-2011)	18.26	18.87	19.45	21.21
Annual Maxt (°C) (1966-2011)	31.90	32.28	32.08	31.55
States[@]	Chandigarh (1, 0.08), Delhi (9,1.01), Haryana (21, 30.07), Punjab (20, 34.25), Rajasthan (3, 34.60)	Uttar Pradesh (41, 100)	Uttar Pradesh (23, 42.51), Bihar (38, 57.49)	West Bengal (15, 100)
Area[$] ($km^2$)	147044 (4.47)	141881 (4.32)	163793 (4.98)	69730 (2.12)
Population (Persons)[w]	77045988 (6.36)	124493345 (10.28)	169736896 (14.02)	79807245 (6.59)
Gross cropped area[P] (ha) 2016-17	17865062 (9.39)	15287799 (8.04)	14580454 (7.66)	8501020 (4.47)
Food grains yield (Ton/ha) 2016-17	3.640	2.345	1.590	2.659

Source: Authors Estimation. Census of India (2011), Singh (2006), NICRA District Agricultural Contingency Plans, Indian Meteorological Department, Directorate of Economics and Statistics, Ministry of Agriculture and Farmers' Welfare.
Note: Total Geographical Area of India: 3287469 sq. km and number of districts: 640 (Census, 2011)
[$]Figures in the parentheses includes percentage share of ACZ in the total geographical area of the country
[w]Figures in the parentheses includes percentage share of ACZ in the total population of the country
[P]Figures in the parentheses includes percentage share of ACZ in the total Gross Cropped Area of the country
[@]Figure in the parenthesis represents (Number of Districts, Total percentage area of state under ACZ)

impact of climate on crop yields across different regions. A district-level panel for the period 1966-2011, covering 80 districts spread across 4 agro-climatic zones in Gangetic Plains Region was constructed. The data on area and production of crops and variables like road length, literacy, numbers of tractors and pump sets and fertilizer consumption 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 with 1966 base district boundaries. The selection of the crops for the study was based on their respective area coverage under each of the ACZs. The data on rainfall and temperature was obtained from the Indian 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.

Empirical strategy

The present study used the following model,

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

Where, y_{dt} represents crop yield, w_{dt} is a vector of climate variables (rainfall, maximum and minimum temperatures), x_{dt} denote socio-economic and other 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 respectively. 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 and Greenstone (2007), Guiteras (2009), Saravanakumar (2015), all incorporated entity fixed effects to eliminate the omitted variable bias. Further, a time trend has been incorporated in the model, as a proxy to absorb the technological effects and other

Table 2: Trend in rainfall and temperature during 1966-2011

ACZ	Annual			Kharif			Rabi		
	Rainfall (mm)	Min temp (°C)	Max temp (°C)	Rainfall (mm)	Min temp (°C)	Max temp (°C)	Rainfall (mm)	Min temp (°C)	Max temp (°C)
Lower Gangetic Plains	-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	-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	-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	-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)

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

Table 3: Projected changes in temperature under RCP 4.5 scenario

Variable	2030s	2050s	2080s
Annual minimum temperature (°C)	1.36 ± 0.18 (13.2%)	2.14 ± 0.28 (13.1%)	2.63 ± 0.38 (14.4%)
Annual maximum temperature (°C)	1.26 ± 0.20 (15.9%)	1.81 ± 0.27 (14.9%)	2.29 ± 0.36 (15.7%)

Figure in the parenthesis indicate the associated uncertainty range

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

farm level adaptations adopted by the farmers in the course of changing climatic conditions within an ACZ. To ensure robustness of the applied panel regression, we employed certain residual diagnostics. Serial correlation biases the standard errors and reduces efficiency of the parameters (Drukker, 2003); hence for necessary correction we tested for the 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 for group-wise heteroscedasticity (Greene, 2000). Based on the above verifications, we applied feasible generalized least squares (FGLS) method with necessary corrections for autocorrelation and heteroscedasticity to estimate model (1), under the assumptions that; within panels, there is AR (1) autocorrelation and that the coefficient of the AR (1) process is common to all the panels. However, it is important to note that FGLS is feasible and tend to produce efficient and consistent estimates of standard errors, provided that N < T that is panel time dimension, T, is larger than the cross-sectional dimension, N (Beck and Katz, 1995; Hoechle, 2007). In our case, this assumption was satisfied as under each ACZ, number of districts, representing the cross-sectional units (N) was less than the time period of 46 years.

The marginal effects of the weather parameters were calculated at their mean values from the regression coefficients (which measure elasticity). Thus, the combined marginal effect of climate variables, *viz*. rainfall, minimum and maximum temperature on crop yield was quantified using equation (2).

$$\frac{dy}{dc} = \left(\beta_{MT} * \left[\frac{\overline{Y}}{\overline{MT}}\right] + \beta_{MNT} * \left[\frac{\overline{Y}}{\overline{MNT}}\right] + \beta_R * \left[\frac{\overline{Y}}{\overline{R}}\right]\right) \ldots\ldots(2)$$

Where, $\frac{dy}{dc}$ is combined marginal effect of change in climate variables on the crop yield, β denote coefficients

Table 4: Estimated regression coefficients of climate impact on crop yields in Lower Gangetic Plains

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)
Year	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 chi2(17)	6542.28	2207.28***	4365.7***	5105.89***
F(1,7)[1]	366.438***	1759.775***	0.955	1133.817***
chi2 (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 variable i.e. crop yield is in logarithmic form.; District dummies were incorporated but the estimated coefficients are not shown.

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.

Projected impact of climate change

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 RCP 4.5 scenario, relative to the base 1976-2005 to project the changes in crop yields.

Further, the projected change in crop yield was calculated using equation (3),

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

Where, ΔY denote change in crop yield, ΔR in rainfall and ΔT in temperature under different scenarios $\left(\frac{Y\partial}{R\partial}\right)$ and and $\left(\frac{Y\partial}{\partial T}\right)$ are their marginal effects.

RESULTS AND DISCUSSION

Trends in rainfall and temperature

The spatial analysis of climatic variables showed a decreasing trend in annual rainfall in Gangetic Plains, with the maximum decline observed in Upper Gangetic Plains (covering parts of Uttar Pradesh). As shown in Table 2, a non-significant increasing trend in *rabi* rainfall was found in case of Lower Gangetic Plains (0.156mm/year). In *kharif* season, Upper Gangetic Plains (-3.134 mm/year) and Lower Gangetic Plains (-1.746 mm/year) showed a significant decreasing trend in rainfall. Both annual mean minimum and maximum temperature showed an increasing trend in all the agro-climatic zones. Minimum temperature in *kharif* season showed a relatively high rising trend of about 0.019 °C in Lower Gangetic Plains and Trans-Gangetic Plains. During *rabi* season, a rising trend of 0.029 °C/year in minimum

Table 5: Estimated regression coefficients of climate impact on crop yields in Middle Gangetic Plains

Variables	Rice	Maize	Sugarcane	Wheat	Rapeseed & Mustard	Barley
Ln Rainfall	0.0081	-0.0426***	0.0132**	0.0005	0.0299***	0.0058**
	(0.0056)	(0.0080)	(0.0060)	(0.0014)	(0.0044)	(0.0026)
Ln Min Temp	-0.0193	0.0424 (0.0631)	-0.1973**	-0.0107	0.2024***	0.0549
	(0.0517)		(0.0638)	(0.0269)	(0.0623)	(0.0397)
Ln Max Temp	-0.0356	0.0026 (0.0365)	-0.0840	-0.0245	0.0825	-0.0787**
	(0.0345)		(0.0653)	(0.0247)	(0.0615)	(0.0335)
Ln Irrigation	0.8584***	0.3386***	-0.0651**	-0.0601***	0.0898***	0.2680***
	(0.0324)	(0.0275)	(0.0289)	(0.0158)	(0.0194)	(0.0105)
Ln Fertilizer	-0.0012	0.0012 (0.0009)	-0.0005	-0.0013***	-0.0019	-0.0015**
	(0.0008)		(0.0010)	(0.0005)	(0.0013)	(0.0007)
Ln Road length	-0.0008	-0.0001	-0.0003	0.0000	-0.0006	-0.0005
	(0.0006)	(0.0006)	(0.0008)	(0.0004)	(0.0009)	(0.0005)
Ln Ruliteracy	-0.0023	0.0171***	-0.0269**	-0.0002	-0.0191**	-0.0024
	(0.0060)	(0.0061)	(0.0123)	(0.0040)	(0.0089)	(0.0055)
Ln Tractors	0.0127***	-0.0089***	0.0177***	-0.0016	0.0242***	0.0023
	(0.0025)	(0.0025)	(0.0047)	(0.0017)	(0.0037)	(0.0023)
Ln Pumpset	-0.0032	-0.0374***	0.0009	-0.0088***	0.0520***	-0.0008
	(0.0034)	(0.0037)	(0.0053)	(0.0024)	(0.0053)	(0.0031)
Year	-0.0001	0.0093***	0.0096***	0.0082***	0.0101***	0.0087***
	(0.0006)	(0.0004)	(0.0008)	(0.0003)	(0.0006)	(0.0004)
Constant	-3.2343***	-19.0546***	-16.1836***	-15.3907***	-21.5207***	-17.6718***
	(1.0156)	(0.7032)	(1.4902)	(0.5117)	(1.1701)	(0.7187)
District fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	966	966	966	966	966	966
Wald chi2(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
chi2 (22)[2]	0.42	4.31	2.38	0.76	1	1.9

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.

temperature and 0.022 °C/year in maximum temperature was observed in Middle Gangetic Plains.

As evident from Table 3, the mean minimum and maximum temperature under RCP 4.5 scenario surpasses 2°C by the end of the 21st century. The near-term warming in both annual maximum and minimum temperature remains around 1.3°C. In addition to the above the study assumed another near-to-mid-term period (2026-2055) as an average of the projection made for near-term (2016-2045) and mid-term (2036-2065) periods respectively. Further, a uniform variation of 5, 7, 10 and 12 percent in rainfall was assumed for the different periods. However, the direction of change in rainfall (positive or negative) under each ACZ was based on trend analysis during the period from 2001-2011.

Impact of climate change: regression estimates

Lower Gangetic Plains: As shown in Table 4, 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 while fertilizer consumption increase yield of rice and maize. Further, it was observed that rise in maximum temperature adversely impacted rice, wheat and rapeseed & mustard yield. The coefficient of trend was positive and highly significant for all the crop yields.

Middle Gangetic Plains: The estimated regression results after controlling for district fixed and inclusion of trend as shown in Table 5, reveals that higher temperatures lowers the

Table 6: Estimated regression coefficients of climate impact on crop yields in Upper Gangetic Plains

Variables	Rice	Sugarcane	Maize	Sorghum	Wheat	Barley	Rapeseed & Mustard
Ln Rainfall	-0.0140***	-0.0177***	0.0350***	0.0060	0.0004	0.0072***	0.0127***
	(0.0037)	(0.0039)	(0.0054)	(0.0074)	(0.0011)	(0.0020)	(0.0032)
Ln Min Temp	-0.0104	-0.0243**	0.0122	-0.0594**	-0.0039	-0.0025	0.0178
	(0.0184)	(0.0110)	(0.0136)	(0.0295)	(0.0046)	(0.0056)	(0.0123)
Ln Max Temp	-0.0106	0.0377	-0.0316***	0.0013	-0.0053	0.0055	0.0408***
	(0.0148)	(0.0230)	(0.0116)	(0.0363)	(0.0073)	(0.0105)	(0.0135)
Ln Irrigation	0.8030***	-0.0069	0.2628***	0.1935	0.0033	0.2902***	0.1063***
	(0.0287)	(0.0263)	(0.0218)	(0.1375)	(0.0190)	(0.0094)	(0.0148)
Ln Fertilizer	0.0108***	0.0224***	-0.0539***	-0.0600***	-0.0144***	0.0128***	0.0788***
	(0.0029)	(0.0041)	(0.0028)	(0.0098)	(0.0024)	(0.0027)	(0.0041)
Ln Road	-0.0013**	-0.0001	-0.0007	0.0028	-0.0006	-0.0006	-0.0007
length	(0.0006)	(0.0006)	(0.0006)	(0.0020)	(0.0004)	(0.0005)	(0.0010)
Ln Ruliteracy	0.0016	-0.0041	-0.0050	-0.0109	-0.0051	0.0015	0.0061
	(0.0057)	(0.0113)	(0.0049)	(0.0171)	(0.0038)	(0.0053)	(0.0074)
Ln Tractors	0.0170***	0.0081**	-0.0110***	-0.0739***	-0.0050***	0.0033*	0.0290***
	(0.0021)	(0.0036)	(0.0018)	(0.0063)	(0.0014)	(0.0020)	(0.0028)
Ln Pumpset	0.0132***	0.0053	-0.0127***	-0.0658***	-0.0028	0.0024	0.0361***
	(0.0026)	(0.0043)	(0.0022)	(0.0078)	(0.0017)	(0.0024)	(0.0034)
Year	-0.0009*	0.0058***	0.0148***	0.0139***	0.0087***	0.0080***	0.0029***
	(0.0005)	(0.0008)	(0.0004)	(0.0012)	(0.0003)	(0.0004)	(0.0006)
Constant	-1.8791**	-9.9467***	-29.5775***	-26.3545***	-16.3380***	-16.6363***	-7.5739***
	(0.8920)	(1.5606)	(0.7795)	(2.2623)	(0.5045)	(0.7171)	(1.1925)
District fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1253	1253	1253	1253	1248	1253	1225
Wald chi2(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***
chi2 (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 variable i.e. crop yield is in logarithmic form; District dummies were incorporated but the estimated coefficients are not shown.

yield of rice, sugarcane and wheat. The effect of minimum temperature was stronger for sugarcane while in case of rice and wheat the magnitude of maximum temperature dominates. Higher rainfall positively affects all crop yields except that of maize. Irrigation variable was found to be highly significant and positively impacted yield of rice, maize, rapeseed and barley in the zone.

Upper Gangetic Plains: As depicted in Table 6, higher rainfall increases yield of maize, sorghum, wheat, barley and rapeseed & mustard while it reduces that rice and sugarcane. Rise in minimum temperature had a harmful effect on crop yields except maize and rapeseed & mustard. On the other hand, higher maximum temperature adversely impacted yields of rice, maize and wheat. In Upper Gangetic Plains, fertilizer consumption was found to be highly significant for the crop yields. However, an increase fertilizer leads to higher yield in case of rice, maize barley and rapeseed & mustard only. Higher irrigation benefits the crop yields except that of maize for which the respective coefficient is also non-significant.

Trans-Gangetic Plains: The assessment of climate impact shows that rainfall significantly affects all the crop yields in Trans-Gangetic Plains. Higher amount of rainfall leads to higher yield of rice, cotton, pear millet, maize, barley and rapeseed & mustard (Table 7). In case of pearl millet, both minimum and maximum temperature had a positive impact indicating high tolerance and resiliency of crop to changing climatic conditions in the zone. Higher irrigation appears to benefit yield of crops like rice, cotton, maize, barley and

Table 7: Estimated regression coefficients of climate impact on crop yields in Trans-Gangetic Plains

Variables	Rice	Cotton	Pearl Millet	Maize	sugarcane	Wheat	Barley	Rapeseed & Mustard
Ln Rainfall	0.0138*** (0.0044)	0.0343*** (0.0122)	0.0900*** (0.0105)	0.0156** (0.0072)	-0.0101** (0.0050)	-0.0091*** (0.0017)	0.0073*** (0.0028)	0.0190*** (0.0049)
Ln Min Temp	0.0042 (0.0875)	-1.4053*** (0.2625)	0.1244 (0.1909)	-0.3388*** (0.0963)	-0.2114*** (0.0741)	-0.1517*** (0.0333)	0.0092 (0.0530)	0.6562*** (0.0867)
Ln Max Temp	-0.1421 (0.0958)	1.3000*** (0.3479)	0.9224*** (0.1998)	0.2945*** (0.1069)	-0.2135 (0.1297)	0.1125** (0.0481)	-0.1112 (0.0731)	-0.5055*** (0.1231)
Ln Irrigation	0.8285*** (0.0372)	0.5298*** (0.1080)	-0.0639** (0.0257)	0.2379*** (0.0343)	-0.1027*** (0.0309)	-0.0643*** (0.0148)	0.2701*** (0.0130)	0.0478** (0.0209)
Ln Fertilizer	0.0018 (0.0015)	-0.0134** (0.0052)	-0.0043 (0.0032)	-0.0165*** (0.0019)	0.0053*** (0.0019)	0.0001 (0.0009)	0.0044*** (0.0014)	0.0241*** (0.0024)
Ln Road length	-0.0088* (0.0046)	0.0381* (0.0225)	0.0163* (0.0091)	0.0138*** (0.0051)	-0.0004 (0.0074)	0.0023 (0.0028)	0.0012 (0.0043)	-0.0288*** (0.0068)
Ln Ruliteracy	-0.0002 (0.0043)	-0.0031 (0.0164)	0.0057 (0.0089)	0.0105** (0.0050)	-0.0085 (0.0058)	-0.0038 (0.0026)	-0.0056 (0.0040)	-0.0110* (0.0066)
Ln Tractors	0.0005 (0.0015)	0.0035 (0.0070)	0.0032 (0.0029)	0.0042*** (0.0016)	-0.0063*** (*0.0023)	-0.0020** (0.0009)	-0.0003 (0.0014)	-0.0027 (0.0022)
Ln Pumpset	0.0041 (0.0025)	-0.0350*** (0.0113)	-0.0172*** (0.0049)	-0.0232*** (0.0028)	0.0063* (0.0038)	-0.0046*** (0.0016)	0.0006 (0.0023)	0.0325*** (0.0036)
Year	0.0009 (0.0006)	0.0262*** (0.0013)	0.0100*** (0.0006)	0.0092*** (0.0004)	0.0109*** (0.0007)	0.0081*** (0.0003)	0.0086*** (0.0004)	0.0118*** (0.0006)
Constant	-4.7919*** (1.1515)	-55.5669*** (2.6579)	-24.7914*** (1.2111)	-18.9866*** (0.7280)	-18.3299*** (1.2587)	-15.0779*** (0.4855)	-17.3109*** (0.7924)	-23.9606*** (1.1037)
District fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	785	785	785	785	785	785	785	785
Wald chi2(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***
chi2 (19)[2]	0.8	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 variable i.e. crop yield is in logarithmic form; District dummies were incorporated but the estimated coefficients are not shown.

rapeseed & mustard. The sign of temperatures and rainfall in case of sugarcane yield was negative suggesting high sensitivity of crop yield to the climatic variations. The coefficient for fertilizer consumption was found to be negative for cotton, maize and pearl millet yield, reflecting that higher dose of fertilizer lowers the productivity of the crops in the region.

Marginal impacts and forecasts

The section presents the estimates of combined marginal impacts of climate variables and future projections on crop yields. Overall, it was observed that most of the crop yields were adversely impacted by climate change; however the magnitude of such effects was different across the ACZs. In some cases, maximum temperature and minimum temperature compensated each other leading to lower effects. Moreover, it was observed that the impact of rainfall was not sufficient enough to counterbalance the combined impact of maximum and minimum temperatures on crop yields. As shown Table 8, during the period from 1966-2011, a decline in rice yield was observed in all the ACZs with the maximum reduction of 1.17 percent found in Lower Gangetic Plains (parts of West Bengal). While, climate variations negatively impacted maize yield in Trans-Gangetic Plains (0.65 percent) and Upper Gangetic Plains (0.03), it appears to have benefitted the crop in

Table 8: Marginal effects of climate change (1966-2011) and projected change on *kharif* and *rabi* crop yields in various agro-climatic zones of Gangetic Plains Region

Agro-climatic Zone	Crops		Marginal Effects	2030s	2040s	2050s	2080s
				Δ MinT= 1.36	Δ MinT= 1.75	Δ MinT= 2.14	Δ MinT= 2.63
				Δ MaxT= 1.26	Δ MaxT= 1.50	Δ MaxT= 1.81	Δ MaxT= 2.29
				Δ R= (+/-) 5%	Δ R= (+/-) 7%	Δ R= (+/-) 10	Δ R= (+/-) 12%
Lower Gangetic Plains	*kharif*	Rice	-1.17	-1.60	-1.91	-2.34	-2.96
		Maize	2.83	3.99	5.11	6.29	7.74
	rabi	Wheat	-0.96	-1.04	-1.24	-1.45	-1.83
		Rapeseed & Mustard	-1.21	-1.67	-2.01	-2.46	-3.10
Middle Gangetic Plains	*kharif*	Rice	-0.17	-0.26	-0.33	-0.41	-0.51
		Maize	0.19	0.45	0.60	0.79	0.96
		Sugarcane	-8.02	-11.15	-14.19	-17.43	-21.50
	rabi	Wheat	-0.28	-0.37	-0.46	-0.56	-0.69
		Rapeseed & Mustard	1.04	1.26	1.58	1.90	2.36
		Barley	0.04	0.05	0.09	0.10	0.12
Upper Gangetic Plains	*kharif*	Rice	-0.07	-0.16	-0.20	-0.27	-0.33
		Sugarcane	-0.13	-0.77	-1.15	-1.57	-1.85
		Maize	-0.03	0.12	0.18	0.27	0.32
		Sorghum	-0.68	-0.88	-1.12	-1.36	-1.67
	rabi	Wheat	-0.09	-0.11	-0.14	-0.17	-0.21
		Barley	0.01	0.03	0.04	0.06	0.08
		Rapeseed & Mustard	0.20	0.29	0.37	0.46	0.57
Trans-Gangetic Plains	*kharif*	Rice	-0.37	-0.40	-0.46	-0.54	-0.69
		Cotton	-0.59	-0.86	-1.22	-1.50	-1.78
		Pearl Millet	2.09	8.43	11.35	15.58	18.90
		Maize	-0.65	-0.90	-1.25	-1.53	-1.83
	rabi	Wheat	-1.02	-1.53	-2.07	-2.57	-3.11
		Barley	-0.26	-0.30	-0.34	-0.40	-0.52
		Rapeseed & Mustard	1.59	2.32	3.14	3.89	4.70

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

Lower Gangetic Plains and Middle Gangetic Plains. The yield loss for sugarcane was to the extent of 8.02 percent in Middle Gangetic Plains. Further, the effect of climatic variations has been found to be negative for cotton in Trans-Gangetic Plains where yield reduced by 0.59 percent. Pearl millet yield showed an increase of 2.09 percent in Trans-Gangetic Plains. The maximum reduction in wheat occurred in Trans-Gangetic Plains and Lower Gangetic Plains (0.96 percent) where yield reduced by 1.02 and 0.96 percent. Barley on the other hand showed a decline of 0.26 percent in Trans-Gangetic Plains, whereas in Middle Gangetic Plains and Upper Gangetic Plains, it registered a marginal increase of 0.04 and 0.01 percent. Barring Lower Gangetic Plains where yield reduced by 1.12 percent, rapeseed & mustard was positively impacted by climate change in all other zones.

The projected impact of climate change on crop yields showed that rice yield will decline by 1.60 and 2.96 percent in Lower Gangetic Plains by 2030s and 2080s. Regional variations are reflected from the fact that while maize yield is likely to reduce by 1.25 percent in Trans-Gangetic Plains, it is projected to increase in other zones. In the mid-term scenario, sugarcane is likely to reduce by 17.43 and 1.57 percent in Middle Gangetic Plains and Upper Gangetic Plains respectively. By 2050s the productivity of cotton will decline by 1.50 percent in Trans-Gangetic Plains. Pearl millet is likely to increase by 15.58 percent by mid-term period in Trans-Gangetic Plains. By 2050s, sorghum is expected to decline by 1.36 percent. By 2050s and 2080s wheat yield will reduce by 2.57 and 3.11 percent in Trans-Gangetic Plains. Rapeseed & mustard is projected to reduce by around 2 percent in Lower Gangetic Plains by 2040s. In the mid-term scenario barley will reduce by 0.4 percent Trans-Gangetic Plains.

CONCLUSION

The present study examined the impact of climate change on major crop yields across various agro-climatic zones in Gangetic Plains Region. An examination of spatial and temporal variability in temperatures revealed a rise in both the annual mean maximum and minimum temperature, but change in annual mean minimum temperature was more pronounced than the annual mean maximum temperature in all the agro-climatic zones. Further during the period from 1966-2011, annual and seasonal rainfall showed a declining trend across the zones. Overall, the empirical results showed that climate change adversely impacts both the *kharif* and *rabi* crop yields across ACZs. As evident from the foregoing analysis, the near-term impact of climate change on crop yields will not be severe. 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. Concerted efforts are needed in development and dissemination of climate resilient varieties and practices, promotion of integrated watershed management for greater water efficiency and crop diversification. Moreover, 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. Mainstreaming climate change and adaptation in the rural developmental paradigm is imperative to improve the envisaged agriculture outputs and outcomes.

Limitations of the study

In analysing the impact of climate change on crop yield using panel data approach, our study had several limitations. First, despite adherence to the diagnostics tests, we observed that many of the controls variables (irrigation, fertilizers, road length, rural literacy, pumpsets and tractors) didn't have the expected signs. But we preferred to retain the variables, against the non-significance of many of those factors and also considering the role of socio-economic and other factors 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 thereby may influence the nature of future climate impacts and projections.

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