

Wheat Yield Responses to Rising Temperature: Insights from North Indian Plains of India

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1 **Title Page**

2 **Wheat Yield Responses to Rising Temperature: Insights from North Indian Plains of India**

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1 **Abstract**

2

3 Climate change and consequent variations in temperature pose a significant challenge for sustaining wheat
4 production systems globally. In this study, the potential impact of rising temperature on wheat yield in the north
5 Indian plains, India's major wheat growing region, was analyzed using panel data from the year 1981 to 2009.
6 This study deviates from the majority of the previous studies by including non-climatic factors in estimating the
7 impact of climate change. Two temperature measures were used for fitting the function, viz., Growing Season
8 Temperature (GST) and Terminal Stage Temperature (TST), to find out the differential impact of increased
9 temperature at various growth stages. Analysis revealed that there was a significant rise in both GST as well as
10 TST during the study period. The magnitude of the annual increment in TST was twice that of GST. Wheat
11 yield growth in the region was driven primarily by increased input resources such as fertilizer application and
12 technological development like improved varieties and management practices. Most importantly, the study
13 found that the extent of yield reduction was more significant for an increase in temperature at terminal crop
14 growth stages. The yield reduction due to unit increase in TST was estimated to be 2.26 % while rise in GST by
15 1°C resulted in yield reduction of 2.03%.

16 **Key words:** Climate change impact, wheat, panel data, agricultural policy Indo-Gangetic plains,

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1. Introduction

Worldwide, climate change is manifested in the form of rising surface temperatures, increase in frequency and intensity of heatwaves, prolonged drought spells, variation in precipitation etc. (Schiermeir 2018; Im et al. 2017; Schubert et al. 2016; Fant et al. 2016; Burt 2016; IPCC 2007, 2014). Global agriculture production has been significantly affected by climate change (Ochieng et al. 2016; Howden et al. 2007; Kato et al. 2011; Vermueleun et al. 2012). Due to high dependence on various weather parameters, agriculture is highly vulnerable to changing climate (Yu et al. 2014; Ahmed et al. 2018). Rainfall and temperature are the most important weather parameters affecting agriculture. Any variation in these parameters will increase the variability in production and also lead to yield reduction (Richardson et al. 2018; Nelson et al. 2014; Wheeler and von Braun 2013; Houser et al. 2015). Crop production systems in developing countries are impacted the most by this climate change, and they are less equipped to afford its consequences (Vermuelen et al. 2012; Gornall et al. 2010; Parker et al. 2019).

India being a developing nation is highly vulnerable to changing climate. The main reasons for this high vulnerability are greater dependence of its population on agriculture, relatively smaller landholdings, and the lack of adequate financial resources, technology, and institutions to cope with the adverse effects of such shocks (Rao et al. 2011). Climate change has enhanced the food insecurity issues of already vulnerable people in India. Although since 1990, the country has witnessed a rapid growth of economy (Narayanan, 2015), yet, it is home to more than 300 million poor people and 194.6 million undernourished individuals (Bhuyan et al 2020). Climate change directly affects agricultural production, while it indirectly affects economic growth and income distribution (Amjath-Babu et al. 2016; Hossain et al. 2019). As per the predictions, India's population is expected to reach 1.8 billion by 2050 and to feed this huge population, more food grains are needed to be produced from declining per capita arable land and irrigation water resources and expanding climatic variability (Swaminathan, 2013). Currently, India produces about 291 million tonnes of cereals to feed 1.15 billion populations and it has to be doubled by 2050 in order to meet the needs of the expected population (Government of India, 2020). Hence, it is essential to increase food supplies while combating climate variability in order to meet the food requirements of fast-growing populations in India.

Among cereals, wheat plays a critical role in India's food security. India produces 102.19 million tonnes of wheat from a total area of about 29.14 million hectares (GoI, 2019). Indian population consumes approximately 65 million tonnes of wheat annually, ranking it as the second-largest consumer of wheat in the world (Tripathi and Mishra 2017). Globally, India stands second in wheat production and it accounts for about 13.18 percent of world's wheat production as of 2019-20 (MoA&FW 2019). India exports 0.23 million tonnes of wheat annually (GoI 2019). In India, wheat is cultivated mainly in Indo-Gangetic Plains (IGP) (Tripathi & Mishra, 2017; Rao et al. 2015) and it is grown as rabi¹ crop. It is sown during the months of October - November and harvested during February - April (Dhamija et al. 2020). The ideal average daily temperature for wheat crop ranges from 20 to 25°C (Tripathi & Mishra, 2017). Wheat crop is highly susceptible to temperature variations during various growth stages, especially at the anthesis and grain filling stages (Asseng et al. 2011; Asseng et al. 2015; Lobell

¹ In India cropping is done in three seasons namely Kharif (monsoon season crop), Rabi (winter season crop) and Zaid (summer season crop).

1 et al. 2011; Tack et al. 2015). Deryng et al. (2014) reported that temperature between 25 to 35°C cause heat
2 stress for wheat plant growth, especially during the grain formation stage. Daily average temperature above 35
3 °C is detrimental for wheat plant.

4
5 In recent years, temperature extremes caused a considerable wheat yield reduction (Aggarwal, 2008; Aggarwal
6 et al. 2010; Subash and Mohan, 2012). In India, the wheat yield loss for every 1 °C rise in temperature was
7 estimated to be 4 to 5 million tonnes (Aggarwal 2008). In IGP region, delay in the harvest of rice crop resulted
8 in the late sowing of wheat and this led to wheat yield loss due to the high temperature at grain filling stage
9 (Dwivedi et al. 2017). The current temperature rise has reduced the wheat yields up to 5 percent (Gupta et al.
10 2017). The future weather predictions of the IGP region show that wheat farming may not be suitable in this
11 region due to heat stress (Mahmood et al. 2019). It is estimated that increase in global mean temperature by one
12 degree-Celsius would reduce global wheat yield of by 6 percent (Zhao et al. 2017). By 2050, the annual mean
13 temperature of India will rise by 1.5 - 3°C and this could have a damaging effect on the future wheat cultivation
14 (Mani et al. 2018). The negative impact of rising average temperature on wheat production remains as the main
15 concern for future food security.

16
17 The potential impact of global warming on wheat yields has been investigated extensively using crop simulation
18 models (Lal et al. 1998; Attri and Rathore 2003; Kumar et al. 2014; Zacharias et al. 2014). However, simulation
19 models subject to uncertainties in parameter values that further enhance uncertainties in the projected impact of
20 climate change (Lobell and Burke 2010). Additionally, these models are excessively reliant on field calibration
21 of data and lack flexibility in their application for analyzing impacts at larger scales. Statistical models have
22 been used as alternatives to data-intensive simulation models due to greater transparency regarding model
23 uncertainties and lower reliance on field calibration of data (Lobell and Burke 2010). In India, only a few
24 studies have used historical data to estimate statistical models for analyzing the impact of climate change
25 (BIRTHAL et al. 2014; Jha and Tripathi 2017). However, these studies failed to account for a complete range of
26 inputs used or technological changes, which often disallows the possibility of segregating climate change from
27 other factors like input intensification and improved crop management, which have a sizable influence on crop
28 yield (Zhai et al. 2017, You et al. 2009). Whereas in few studies conducted in India, the researchers considered a
29 more comprehensive range of inputs for obtaining more accurate representation of climate response functions
30 (You et al. 2009; Holst et al. 2013, Pattanayak and Kumar 2014). In the Indian context, specifically for wheat
31 crop existing literature using statistical models have failed to segregate the effect of climatic and non-climatic
32 factors on crop yields. Therefore, this study aims to estimate the impact of rising temperature on wheat yields
33 after segregating the effect of non-climatic factors. More specifically we use a crop specific state level panel
34 data to estimate response functions of wheat yield to rising temperature after controlling for input use and
35 technological change.

36 **2. Data and methods**

37 38 **2.1 Study Area**

39 *(Insert Fig 1 here)*

1 In this study, we have selected the major wheat cultivating states in India viz; Punjab, Haryana, Uttar Pradesh,
2 Bihar and Rajasthan (Figure 1). Except Rajasthan, all other states spread across IGP. IGP is known as ‘the food
3 bowl of India’ and this region consists of states such as Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal.
4 The IGP consists of two drainage basins, western part drains to Indus and eastern part comprises the Ganges–
5 Brahmaputra drainage systems and hence, it is one of the world’s most intensively cultivated area (Sehgal et al,
6 2013) . Rice and wheat are the two major crops cultivated in this area. The four states in the IGP selected for the
7 study hold 60.81 percent of total area under wheat cultivation and contribute 68.21 percent of total wheat
8 production in the country, while Rajasthan holds a share of over 10 percent in both area and production in the
9 year 2018-19 (GoI,2019). Though West Bengal belongs to IPG region, wheat cultivation is very less in this state
10 and hence it was not considered for the present study.

11

12 **2.2. Data description**

13 The state-level data of five major wheat-growing states in the IGP viz., Punjab, Haryana, Rajasthan, Uttar
14 Pradesh, and Bihar for the period 1981 to 2009 was used for this study. Yield data was obtained from the
15 Department of Economics and Statistics' annual publications, Government of India (GOI). Data regarding input
16 usage for wheat cultivation were compiled from various issues of the Comprehensive Scheme of Cost of
17 Cultivation published by the Directorate of Economics and Statistics, GOI. Wheat yield was measured in
18 kilogram per hectare (kg/ha), and all crop inputs except chemical fertilizer were measured as expenses per
19 hectare at 2004-05 prices (Rupees per hectare), whereas application of fertilizers was measured in kg/ha.
20 Further, missing values were imputed using a spline function for the respective states.

21 The data on climate variables were extracted from 1 x 1 degree daily gridded data obtained from the Indian
22 Meteorological Department, Pune. The daily data on maximum and minimum temperatures were transformed
23 into average season temperature for the crop growing period. Wheat is cultivated in India mostly during *Rabi*
24 (winter) season, with a growing period spanning between October-December and March-April. However, there
25 are slight variations in crop growing periods across regions depending upon weather and cropping pattern. The
26 variation in growing season across the country was accounted for in calculating average Growing Season
27 Temperature (GST) for different states. Among various climatic variables, rainfall was excluded as most of the
28 wheat-growing areas in IGP were irrigated. The share of the irrigated area to the total cultivated wheat area
29 increased rapidly in IGP over a period of time (Zaveri and Lobell 2019). The proportion of wheat grown area
30 under irrigation varied between 95.7 percent in Bihar to 99.7 percent in Rajasthan during 2015-16 (GoI 2019).
31 Wheat yield is adversely affected by terminal heat stress, especially under delayed sowing conditions
32 (Nagarajan 2005; Spiertz 2006; Singh et al. 2011). The flowering and grain filling stages are thus highly
33 susceptible to heat stress. Hence, to determine the extent of variation in crop yield due to change in temperature
34 at terminal stages of crop growth, separate measure referred to as Terminal Stage Temperature (TST) was
35 computed by taking average temperature during March to April.

36 **2.3. Methods**

37 **2.3.1. Trend Estimation**

1 Mann- Kendall statistic and Sen's slope estimator were used for examining the trends in average GST and
 2 average TST. Non-parametric tests are preferred to conventional parametric methods because the former is more
 3 powerful when probability distribution is skewed (Onoz and Bayazit 2003). Mann-Kendall statistic is a non-
 4 parametric way of identifying trends in time series data wherein the significance of trend is tested based on
 5 normalized test statistic (Z-values). This test is commonly used to determine the direction of the trend and
 6 whether it is increasing or decreasing based on signs of the Z values. A positive Z value indicates an increasing
 7 trend, while a negative Z- value denotes a decreasing trend. The Mann-Kendall test statistic is given by equation
 8 1.

$$9 \quad \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(T_j - T_i) \dots \dots \dots (1)$$

10 Where T_j and T_i are climate variables in year 'j' and 'i' respectively given $j > i$.

$$11 \quad \text{sign}(T_j - T_i) = \begin{cases} -1 & \text{if } T_j < T_i \\ 0 & \text{if } T_j = T_i \dots \dots \dots (2) \\ 1 & \text{if } T_j > T_i \end{cases}$$

12 If the number of observations is greater than 10, Mann-Kendall statistic assumed to follow a normal distribution
 13 with variance equal to

$$14 \quad \sigma^2 = \frac{n(n-1)(2n+5)}{18} \dots \dots \dots (3)$$

15 We can use Z test to test the significance of the trend. The standard Z statistic, Z_s is

$$16 \quad Z_s = \begin{cases} \frac{S-1}{\sigma} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \dots \dots \dots (4) \\ \frac{S+1}{\sigma} & \text{if } S < 0 \end{cases}$$

17 If $Z_s > Z_{\text{table value}}$, we reject the null hypothesis that no significant trend is present in the variable under
 18 consideration.

19 The magnitude of underlying trend is quantified using Sen's slope estimator, wherein the slope is computed as
 20 the change in measurement per unit change in time.

$$21 \quad Q = \frac{X_j - X_k}{j - k}, k \neq j \dots \dots \dots (5)$$

22 For a time series X within observations, there are possible $N = n(n-1)/2$ values of Q that can be calculated.
 23 According to Sen's method, the overall estimator of slope is the median of Q's N values. The overall slope
 24 estimator, Q^* is thus:

$$25 \quad Q^* = \begin{cases} Q_{\frac{N+1}{2}}, & N \text{ is odd} \\ \frac{Q_{(\frac{N}{2})} + Q_{[\frac{N+2}{2}]}}{2}, & N \text{ is even} \end{cases} \dots \dots \dots (6)$$

1 The Q^* sign indicates the trend in data, while its value indicates the steepness of the trend.

2

3 2.3.2. Methods for estimating climate change impact on crop production

4 Several methods have been employed in literature to estimate the economic impact of climate change on
5 agriculture, which can be broadly classified into following approaches viz., production function approach,
6 Ricardian analysis, and panel data approach. The production function approach is often based on experimental
7 data and provides an excellent structural form. But it fails to incorporate farmers' adaptation to minimize
8 harmful effects due to climate change, thereby results in biased estimates of climatic parameters. In Ricardian
9 analysis, farmland productivity is measured in terms of land rents (Lippert 2009) or land value (Feres et al.
10 2008) or net farm revenues (Mendelsohn and Dinar 2003; Mendelsohn 2009). Farmland productivity is
11 regressed against long-run climate normals and a set of exogenous variables to estimate the potential economic
12 impact. As Ricardian analysis holds basic assumptions of perfect competition and profit maximizing farmers, it
13 accounts for both direct impacts on crop yields as well as indirect impact in terms of substitution of inputs, the
14 introduction of different activities, and other potential adaptations to reduce the ill-effects due to climate change
15 (Mendelsohn et al. 1994). However, the hedonic approach may confound the impact of climate variables with
16 other unmeasured characteristics like soil quality that may have a bearing on land values or net revenues
17 resulting in biased estimates of climate variables (Deschenes and Greenstone 2007). Panel data regression
18 models control for omitted variable bias by using spatial and time fixed effects (Blanc and Schelkner 2017) and
19 it gives estimates which are robust and consistent over time (Choudhary and Sirohi 2020). Hence, we use this
20 method to estimate the impact of temperature on wheat yield. The empirical specification has been provided in
21 the next section.

22 2.3.3. Model specification

23 We assumed wheat yield as a function of climate factors, inputs, production technology and land quality.
24 Principal inputs such as human labor, irrigation, seed and fertilizers were included in the model, wherein the
25 first three inputs were considered in real monetary terms (Rupees per hectare), while fertilizer was included in
26 quantity terms (kg per hectare). Wheat cultivation in IGP witnessed progressive mechanization over the years by
27 replacing draft power and human labor. The relative share of bullock labor in total power expenses has declined
28 drastically over the years, with a proportionate increase in machine labor share. Taking this substitution into
29 account, the expenditure on machine labor and bullock labor were clubbed together under the head, 'power
30 expenses'. Expenses on other minor inputs like expenditure on insecticides and pesticides, expenditure on
31 manure, and other miscellaneous expenditures were clubbed together because they accounted for a small
32 proportion of total costs but varied substantially over the years. Regional dummies were used to account for
33 time persistent region-specific variations in natural endowments and socio-economic factors. The impact of
34 technological change and increase in yield potential of varieties was captured using a time trend variable. The
35 proportion of wheat in the total cultivated area (referred to as regional specialization hereon) is used as a proxy
36 to capture the effect of variables like land quality, government support programs, etc., which facilitate wheat
37 cultivation in the region but tend to vary over time.

1 The wheat yield function is specified as follows,

$$2 \quad \ln Yield_{it} = (\alpha_0 + \alpha_1 t) + \sum_{j=1}^6 \beta_j \ln X_{jit} + \gamma \ln R_{it} + w C_{it} + \sum_{r=2}^5 \delta_r D_r + u_{it} \dots \dots \dots (7)$$

3 where $Yield_{it}$ represents wheat yield for state ‘i’ at time ‘t’ (where time period t vary from 1980 to 2009), X_{jit}
 4 represents the vector of inputs like human labor, power, seed, irrigation and other inputs, R_{it} alludes to regional
 5 specialization, C_{it} is vector of climate variables, D_r is the vector of regional dummies. Here, $\alpha, \beta, \gamma, w, \delta$ are
 6 parameters to be estimated and u_{it} is the error term. Two models, Model 1 and Model 2 were estimated
 7 separately to quantify the impact of crop growing season temperature (GST) and terminal stage temperature
 8 (TST) on wheat yield, respectively. By estimating two models, we tried to discern the marginal impact of GST
 9 and TST on the productivity of wheat. Yield and input variables were transformed into logarithmic form to
 10 reduce excess variations in values, whereas the regional specialization temperature variables were retained as
 11 such. Previous studies reported a non-linear relationship between temperature and crop yields (Schelkner and
 12 Roberts 2009; Guiteras 2007); hence, both average temperature and its squared term were included in both
 13 models. The coefficients of climate variables may be interpreted as the relative change in yield due to a unit
 14 change in climatic variables, while the coefficient of input vectors may be construed as elasticity.

15

16 The marginal effects of a unit increase in temperature on wheat yields at the mean yield level were computed
 17 using Equation 8.

$$18 \quad \frac{\partial Y_{it}}{\partial T_{it}} = \beta_1 + 2 * \beta_2 * T \dots \dots \dots (8)$$

19 where β_1 and β_2 are the coefficients of temperature and squared temperature terms, and T is the mean value of
 20 temperature.

21

22 3. Results and Discussion

23 **Table 1:** Trend in growing season temperature and terminal stage temperature

State	Growing Season Temperature (GST)			Terminal Stage Temperature (TST)		
	MK Statistic	Z-Statistic	Sen’s Slope Estimator	MK Statistic	Z-Statistic	Sen’s Slope Estimator
Bihar	92	1.80*	0.021	124	2.43***	0.048
Haryana	186	3.65***	0.051	164	3.22***	0.087
Punjab	190	3.73***	0.048	174	3.42***	0.084
Rajasthan	196	3.85***	0.053	162	3.18***	0.076
UP	148	2.90***	0.036	160	3.14***	0.069

24 ***, **, * indicates significance at 1%, 5% and 10% levels of significance

1 Before discussing the impact of various factors on wheat yield, it is appropriate to understand the trend and
 2 magnitude of increase in both GST and TST. Mann-Kendall (MK) test was used to test the significance of trends
 3 in GST and TST. The magnitude of trend was computed using Sen's slope estimator. The results are presented
 4 in Table 1. As evident from the table, GST has increased significantly in all states. The annual rate of increment
 5 in GST was found to be highest for Rajasthan (0.053⁰C) followed by Haryana (0.051⁰C) and Punjab (0.048⁰C),
 6 indicating that the North-Western regions of IGP are likely to be more vulnerable to heat stress. A significant
 7 increasing trend was observed in TST in all selected states, while an annual increment in TST was found nearly
 8 twice as that of GST.

9 **Table 2:** Descriptive statistics

Variable	Description	Unit	Mean	SD	CV
Yield	Yield of the crop	kg/ha	2818	904	32.08
Human Labour	Expenditure for human labour	Rs/ha	3469	785	22.63
Power	Expenditure for both machine labour and bullock labour	Rs/ha	2885	718	24.89
Seed	Seed expenses	Rs/ha	1125	231	20.53
Irrigation	Irrigation expenses	Rs/ha	1333	590	44.26
Other Inputs	Expenditure for other inputs such as pesticides, manure and other purposes	Rs/ha	2317	875	37.76
Fertilizer	Quantity of fertilizer used per ha	kg/ha	136	55	40.44
Regional Specialization	Area under wheat in a state in proportion to total wheat cultivated area in India	%	46.3	23	49.68
Growing Season Temperature	Mean temperature during crop growing season	⁰ C	18.2	1.7	9.34
Terminal stage Temperature	Mean temperature during terminal stage of crop (March to April)	⁰ C	20.0	2.1	10.50

10 SD-Standard deviation, CV-Coefficient of variation

11 Table 2 provides descriptive statistics of variables included in the estimation of the yield response function. It
 12 can be observed that both yield and input usage display a considerable degree of variation. The stationarity of
 13 dependent and independent variables was checked using Im-Pesaran-Shin test (Im et al. 2003). The null
 14 hypothesis of all panels being unit roots was rejected at a 1 percent level of significance, indicating that the
 15 variables in the models were stationary (Table A.1 in Appendix). The ordinary least squares (OLS) technique
 16 was used to estimate coefficients, and the residuals of the model were subjected to a series of diagnostic tests.
 17 The Modified- Wald test for heteroskedasticity (Greene 2000) indicated that the residuals obtained from models
 18 estimated by OLS procedure violated the assumption of constant variance. Wooldridge test of autocorrelation in

1 panel data (Wooldridge 2002; Drukker 2003) revealed that OLS estimation procedure had autocorrelation
 2 problems. The coefficients obtained from the fixed effects model in cross-sectional dependence are consistent.
 3 However, they are not efficient and have biased standard errors. The presence of cross-sectional dependence
 4 was checked using Pesaran’s test (Pesaran 2004), which confirmed cross-sectional dependence in data. Results
 5 of auto-correlation, heteroskedasticity, and cross-sectional dependence tests are provided in Table A.2 in
 6 Appendix.

7 **Table 3:** Impact of Growing Season Temperature (GST) on wheat yield

Variables	Fixed effects (within)			FGLS [§]		
	Coefficients	Standard Error	p-value	Coefficients	Standard Error	p-value
Ln_Human Labor	0.13	0.04	0.01	0.14	0.03	0.01
Ln_Power	-0.14	0.04	0.01	-0.12	0.03	0.01
Ln_Seed	-0.08	0.04	0.03	-0.07	0.03	0.02
Ln_Irrigation	0.01	0.02	0.61	0.00	0.02	0.54
Ln_Fertilizer	0.24	0.05	0.01	0.18	0.05	0.01
Ln_Other Inputs	-0.09	0.05	0.09	-0.03	0.04	0.54
GST	0.35	0.12	0.01	0.25	0.10	0.02
Squared GST	-0.01	0.00	0.01	-0.01	0.00	0.01
Regional Specialization	-0.38	0.09	0.01	-0.23	0.09	0.01
Time	0.01	0.00	0.01	0.01	0.00	0.01
Haryana	0.75	0.06	0.01	0.67	0.07	0.01
Punjab	0.96	0.09	0.01	0.82	0.10	0.01
Rajasthan	0.06	0.08	0.49	0.06	0.08	0.45
Uttar Pradesh	0.39	0.05	0.01	0.32	0.05	0.01
Intercept	5.82	1.21	0.01	5.80	1.01	0.01
Within variation	0.83			Wald Chi-Square Statistic		3058.3
Between variation	0.29			No. of observations		140
No. of observations	140					

8 [§]Feasible generalized least squares

9 The presence of autocorrelation, heteroskedasticity, and cross-sectional dependence in the data indicated that the
 10 estimated coefficients might not be efficient and were likely to have inflated standard errors. Feasible
 11 Generalized Least Square (FGLS) estimation procedure was used in the past to generate standard errors that are
 12 asymptotically consistent and efficient (Kmenta 1986) in place of OLS estimators that are inefficient. Another

1 potential problem is omitted variable bias as factors like diseases and pests (influenced by temperature) that
2 might affect wheat yield have not been included in the model. The Ramsey regression specification error test
3 (Ramsey, 1969) was used to test the specification bias, and the assumption was satisfied by two models
4 ($P > 10.13\%$ and $P > 17.30\%$ for model 1 and model 2, respectively). The estimated coefficients of Model 1 are
5 presented in Table 3.

6 All independent variables except irrigation were found to be statistically significant in the OLS estimates for
7 Model 1. The FGLS estimates differ slightly from the OLS estimates with slight improvements. The use of
8 fertilizer contributed positively to yield growth, as expected. Human labour also was found to be positively
9 correlated with wheat yield. Similar findings were reported in some previous studies also, and the reason is that
10 progressive mechanization increased the productivity of human labour in Indo-Gangetic plains (Sekhar and Pal,
11 2012). Marginal returns to seeds were negative, pointing towards its over application. As shown in figure 4,
12 lowess plot between seed expenditure and yield per hectare also indicate a negative relationship in three states
13 out of five states considered for the study. Previously, it has been reported that supra-optimal density of
14 planting in wheat and paddy results in increased crop competition due to nutrient stress (Jha et al. 2018). Even
15 though the optimal seed rate is determined by various factors such as soil fertility, irrigation, climate, etc., the
16 recommended seed rate for wheat in India is 100 kg/ha under ideal planting conditions (GoI 2010). But average
17 seed rate in the five selected states was 128.32 kg/ha in 2010 as calculated using data from the Directorate of
18 Economics and Statistics, Government of India indicating an increase of nearly 28 percent over the optimal
19 plant population. This could be the plausible reason for negative marginal returns.

20 The irrigation variable's coefficient was positive but not statistically significant, which is not in line with the
21 findings of previous studies. Zaveri and Lobell (2019), reported that wheat yield in India during 2000s was 13
22 percent higher than it would have been without irrigation, and it is to be noted that irrigation development in
23 wheat cultivation has contributed significantly to reduce impact of heat sensitivity on yield, albeit the fact that
24 this effect is reducing in recent years. In our study, the data used for the analysis is of more recent years. In
25 major wheat-growing areas of IGP, the wheat crop is almost fully irrigated for most of the years considered,
26 which could render the variable statistically insignificant. The data used for representing irrigation in the paper
27 is the actual expenditure incurred for irrigation, used in real terms. Given the high level of subsidy for
28 groundwater-based irrigation development and the flat rate of surface irrigation charges, the irrigation
29 expenditure also has not shown much variation over the years. Additionally, we have used 'fertilizer' in our
30 analysis, unlike Zaveri and Lobell (2019), which assumes full potential only with irrigation. In the presence of
31 lack of variability in irrigation expenditure over the years in all the states considered and significant variations in
32 the fertilizer application, the fertilizer coefficient turned statistically significant.

33 The time trend was positive and significant, indicating that technological change positively contributed to yield
34 growth during the study period. Contrary to our expectation, regional specialization was found to be negatively
35 correlated with wheat yield. This may be attributed to the conventional practice of a rice-wheat cropping system
36 in the IGP that deteriorates soil fertility and land quality. This adversely affects productivity and sustainability
37 (Ladha et al. 2007; Singh and Singh 2012). The marginal returns to mechanization were found to be negative.
38 Singh et al. 2007 highlighted the need to optimize mechanization in wheat production. The study indicates that
39 operations in major wheat-producing states like Punjab and Haryana tend to be over-mechanized. Besides, the

1 coefficient of other inputs was also negative possibly because the major share of these inputs comprised the
 2 expenditure on pesticides. Increased pesticide application is associated with a corresponding increase in disease
 3 infestation or pest attacks. Yields are typically lower in years with higher pest or disease incidence, potentially
 4 explaining negative correlation between yields and pesticide application. Finally, coefficients of both normal
 5 and squared terms of GST were found to be significant. The coefficient of average GST was positive while that
 6 of the squared term was negative, justifying our hypothesis of a non-linear relationship (quadratic) between
 7 wheat yield and GST. The expected marginal effect of a unit increase in average growing season temperature
 8 was worked out, and it indicates that a 1°C rise in GST reduces the yield by 2.03 percent.

9 **Table 4:** Impact of Terminal Stage Temperature (TST) on wheat yield

Variables	Fixed effects (within)			FGLS		
	Coefficients	Standard Error	p-value	Coefficients	Standard Error	p-value
Ln_Human Labour	0.12	0.04	0.01	0.13	0.03	0.01
Ln_Power	-0.13	0.04	0.01	-0.12	0.03	0.01
Ln_Seed	-0.08	0.04	0.04	-0.07	0.03	0.02
Ln_Other Inputs	-0.09	0.05	0.08	-0.04	0.04	0.41
Ln_Irrigation	0.01	0.02	0.58	0.01	0.02	0.80
Ln_Fertilizer	0.23	0.05	0.01	0.18	0.05	0.01
TST	0.16	0.06	0.01	0.09	0.05	0.09
Squared TST	-0.01	0.01	0.01	-0.01	0.01	0.04
Regional Specialization	-0.37	0.09	0.01	-0.23	0.09	0.01
Time	0.02	0.00	0.01	0.02	0.00	0.01
Haryana	0.98	0.05	0.01	0.67	0.06	0.01
Punjab	0.94	0.06	0.01	0.79	0.09	0.01
Rajasthan	0.18	0.15	0.01	0.07	0.08	0.39
Uttar Pradesh	0.54	0.09	0.01	0.33	0.05	0.01
Intercept	8.32	0.82	0.01	7.16	0.69	0.01
Within variation	0.83			Wald Chi-Square Statistic		2805.6
Between Variation	0.26			No. of Observations		140
No. of observations	140					

1 The result of the estimation of Model 2 is presented in Table 4. Despite slight variations in the values of the
 2 coefficients, the signs are identical to Model 1. The marginal impact of 1⁰C increase in TST at mean yield levels
 3 resulted in a 2.26 percent reduction in yield. The results imply that heat stress during terminal stages of crop
 4 growth is more detrimental to wheat productivity in the IGP. The results align with the previously reported
 5 findings (Nagarajan 2005; Spiertz 2006; Singh et al. 2011). Since the primary focus is to discern the contribution
 6 of temperature on wheat yields, it is convenient to treat the impact of non-climate factors as residuals (You et al.
 7 2009). The climate yield function (Yield^{climate}) was estimated by subtracting the contribution of non-climate
 8 factors (You et al. 2009). The Yield^{climate} is calculated using the following equation:

$$9 \quad \ln Yield^{climate} = \ln Yield_{it} - (\alpha_0 + \alpha_1 t) - \sum_{j=1}^6 \beta_j \ln X_{jit} - \gamma \ln R_{it} - \sum_{r=2}^5 \delta_r D_r \dots \dots \dots (9)$$

10

(Insert Fig 2 here)

11

12 The values of the natural logarithm of Yield^{climate} were plotted against the GST (Figure 2) and TST (Figure 3).
 13 The downward sloping trend lines indicate the negative impact of temperature on wheat yields.

(Insert Fig 3 here)

14

15 The optimum temperatures for wheat growth are ~22⁰C for vegetative development and 21⁰C for reproductive
 16 development, while ~35.4⁰C is the maximum limit for grain filling (Porter and Gawith 1999). Wheat crop is
 17 highly susceptible to heat stress, particularly during the grain filling stage (Farooq et al. 2011). Due to proximity
 18 to the equator and popular cropping systems followed in India that involves late sowing of wheat, wheat crop
 19 faces exposure to terminal heat stress, which means average daily temperatures above 17.58⁰C during the
 20 growing period (Joshi et al. 2007). High temperature reduces the phenological duration, source-sink metabolism,
 21 grain number, grain weight, grain yield, and grain quality (Asseng et al. 2011). An increase in temperature has
 22 been correlated with the decline in wheat yield in North-western India, as the rise in temperature in the month of
 23 March is particularly detrimental to crop yield (Mukherjee et al. 2019). An increase in growing season
 24 temperature above the optimal range (17-26⁰C) by 1⁰C reduces grain yields by 4% in wheat (Acevedo and
 25 Nachit 1990). Our study results indicated that the potential impact of GST rise is likely to be lower since the
 26 study accounts for a wide range of on-farm adaptations to climate change using spatial fixed effects and
 27 variation in input use over time. This could explain the disparity in estimated impacts on wheat yield across
 28 regions over time. The findings of previous studies on impact of climate change on wheat yield in India and
 29 South Asia have been tabulated in Table 5.

30 Simulation models have been widely used to predict the potential impact of climate change on wheat yield in
 31 India. A study conducted by Kumar et al. (2014) has predicted that wheat yield would reduce by 6 percent for
 32 timely sown wheat by 2050. Surface temperatures are predicted to increase by 1.5- 3⁰C by 2050 (Mani et al.
 33 2018). Therefore the predicted impact in the form of reduction in wheat yield by 2050 using our estimates would
 34 be in a range of 3-6 percent, which concurs with simulation model results for the same period. However, some

1 studies predicted that wheat yields are likely to increase due to a surge in CO₂ concentration through the increase
 2 in temperature above 3⁰C would cancel out potential gains (Lal et al. 1998).

3 **Table 5:** Comparison with previous studies

Study	Region	Predicted Impact
Kumar et al. 2014	Indo- Gangetic Plains	Predicted yield reduction by 2050 was 6-23 % and 15-25 % by 2080
Attri and Rathore, 2003	North India	Reduction in yield by 8.2-14.3 % and 0.3-0.9 % in rainfed and irrigated conditions respectively under A1 scenario.
Lal et al.1998	North western India	The combined effect of thermal stress and increase in CO ₂ concentration amounted to 21%increase in wheat yields.
Birthal et al. 2014	India	Wheat yield was predicted to decrease by 0.5-8.5 % by 2035 and 3.5 - 15.4 % by 2065.
Lobell et al. 2012	Indo-Gangetic Plains	Reduction in yields by 20% for an increase in temperature by 2 ⁰ C.
You et al. 2009	China	Wheat yield was predicted to decrease by 3-10 % due to climate change.

4
 5 Several studies have reiterated the importance of accounting for non-climate factors while estimating the
 6 potential impact on crop yields directly (You et al. 2009; Zhai et al. 2017). However, direct estimation studies in
 7 the Indo-Gangetic plains have failed to account for a wide range of non-climate factors while estimating
 8 potential impact of climate change (Birthal et al. 2014). The estimated impact of climate change was found
 9 higher than our estimates, although the lower bound values are similar. Accounting for non-climate factors like
 10 variations in input use provides realistic forecast, especially in regions that have experienced a spurt in input
 11 usage (You et al. 2009); also it helps to control for confounding errors and provide more optimistic estimates of
 12 potential impact.

13 **4. Economic implications**

14 An attempt is made to estimate the economic impact of one-degree rise in GST and TST on wheat yield in five
 15 selected states by multiplying marginal effects of GST and TST with mean annual production during the entire
 16 study period. The results indicated that a one-unit rise in GST and TST leads to an annual loss of 1.04 million
 17 tonnes and 1.12 million tonnes of wheat, respectively, for the five states together. Some of the recent studies
 18 reported that climate change has slowed down agricultural total factor productivity (TFP) growth (Zhong et al.
 19 2019; Ortiz-Bobera et al. 2021). TFP growth is the residual of the output growth not accounted for by the input
 20 growths, determined mainly by research and development. The annual total factor productivity (TFP) growth of
 21 wheat in India for 1975-2005 is about 1.92 percent (Chand et al. 2011). At the state level, it is about 1.3 percent
 22 in Punjab, 1.7 percent in Haryana, 1.8 percent in Rajasthan, and 1.6 percent in Uttar Pradesh (Mittal and Kumar,
 23 2005). The share of TFP growth in output growth of wheat is about 58.9 percent at the national level (Chand et

1 al. 2011). We calculated the trend growth in wheat production in the five states following an exponential
2 growth model and about 2.43 percent per year. This turns out that the contribution of TFP in the output growth
3 is about 1.43 percent. This shows that the TFP growth in India's wheat production has occurred against the loss
4 caused by temperature rise, either as GST or TST. We compare the impact of temperature rise against the TFP
5 growth in wheat production in India. The annual production increment of wheat in the five states due to TFP
6 growth turns out to be to the tune of 0.98 million tonnes at mean, whereas that of a one-unit increase in GST and
7 TST could turn out to be to the tune of 1.04 and 1.12 million tonnes, respectively.

8 **5. Limitations of the study**

9 This study has not considered the positive effects of elevated CO₂ concentration on wheat yield. The estimates
10 obtained from the study may be regarded as upper-bound estimates. Besides, the study estimated the potential
11 impact on timely sown wheat. However, delayed planting exposes the wheat crop to severe heat stress that could
12 reduce wheat yield exponentially (Lobell et al. 2012; Singh et al. 2011). Several factors like the delayed
13 establishment of rice nurseries and hence delayed harvesting in the Upper Gangetic Plains of India have
14 increased incidence of delayed planting of wheat (Dwivedi et al. 2017; Kumar et al. 2019), which may further
15 adversely affect wheat yield. In the event of perceived negative impacts on wheat yield, farmers are expected to
16 adapt by using early maturing varieties or other agronomic measures. However, the present study tried to
17 provide estimates after accounting for contribution of non-climatic factors, which largely represent farmers'
18 adaptation behaviors and spatial effects.

19 **6. Conclusions**

20 This study tried to segregate the impact due to climatic and non-climatic factors on wheat yield. We also
21 analyzed two separate models, including growing season temperature (GST) and terminal stage temperature
22 (TST) to understand the extent of impact on yield due to rise in temperature at various stages of crop growth.
23 During the study period, there was a significant increase in GST and TST in major wheat-producing regions of
24 the IGP, whereas the latter's growth rate was almost twice the former. Annual increment in GST ranges from
25 0.021⁰C to 0.053⁰C while it ranges from 0.048⁰C to 0.087⁰C in case of TST. The relationship between wheat
26 yield and temperature (both GST and TST) was found to be negative and non-linear. The adverse effect of rising
27 temperature was more prominent in the terminal stages of wheat growth. As per our study, an increase in GST
28 by 1⁰C reduces wheat productivity by 2.03 percent, while a similar increase during the terminal stage reduces
29 yield by 2.26 percent. It contrasts well with the TFP growth in output growth of wheat, at 1.43 percent per year.
30 The TFP growth contributes to about an increment of 0.98 million tonnes of wheat annually in the five IGP
31 states considered. But one unit increase in GST and TST could impact a production loss to the tune of 1.04 and
32 1.12 million tonnes, respectively. Therefore, the temperature rise depresses the TFP growth and, therefore, the
33 output growth in wheat in the selected IGP states. Thus, the undesirable effects of climate change on wheat
34 yields could undermine the efforts to ensure the burgeoning population's food security. Therefore, concerted
35 efforts need to be made for developing adaptation strategies to moderate the impact of rising temperature.

36

37

Declarations

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Availability of data and material:.

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code Availability: The analysis for this study was carried out using licenced STATA/SE 15 software. We have undertaken only menu driven procedures and not used any custom codes.

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1

Appendix A

2 **Table A.1** Im-Pesaran-Shin Panel unit root test for stationarity

Variable	Z-t-slide-bar Statistic
Ln_Yield	-3.84***
Ln_Human Labour	-2.00**
Ln_Power	-1.72**
Ln_Irrigation	-2.88***
Ln_Fertilizer	-2.69***
Ln_Seed	-2.10**
Ln_Other Inputs	-3.20***
Ln_Regional Specialization	-4.73***
Growing Season Temperature	-4.30***
Terminal Stage Temperature	-4.96***

3 ***, **, * indicates significance at 1%, 5% and 10% levels of significance

4

5

6 **Table A.2** Residual Diagnostics

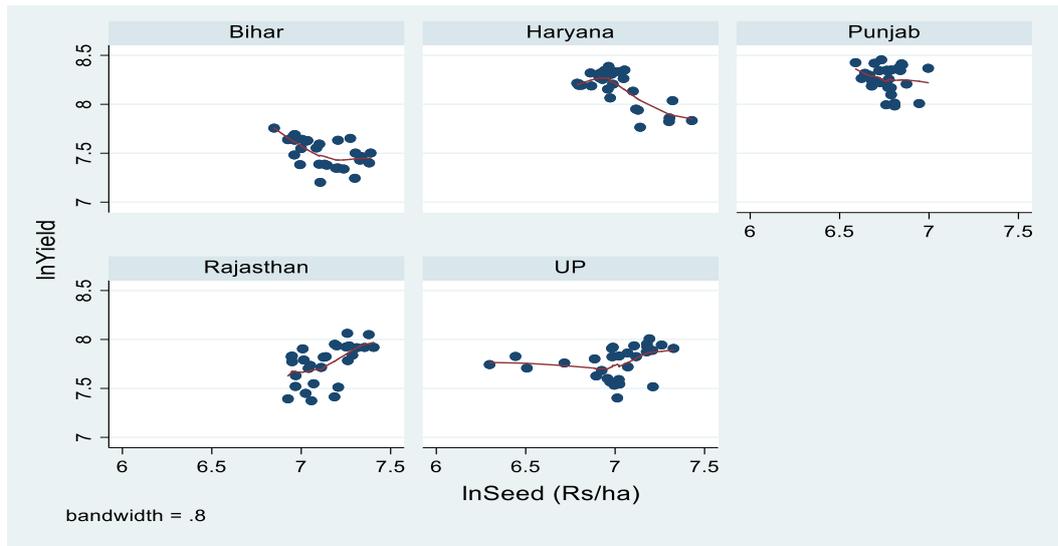
Model	Modified Wald Test		Pesaran's test		Wooldridge test	
	Statistic	p-value	Statistic	p-value	F statistic	p-value
Model 1	41.65	0.01	4.27	0.01	10.20	0.03
Model 2	36.32	0.01	3.49	0.01	11.33	0.03

7 1. Modified Wald test for group-wise heteroskedasticity, H₀: Error terms are homoskedastic

8 2. Pesaran's test for cross-sectional dependence in panel data, H₀: Error terms are not auto-correlated

9 3. Wooldridge test for autocorrelation in panel data, H₀: There is no cross-sectional dependence

10



1
2 **Fig 4** State wise lowess plot of yield and seed application

3

Figures

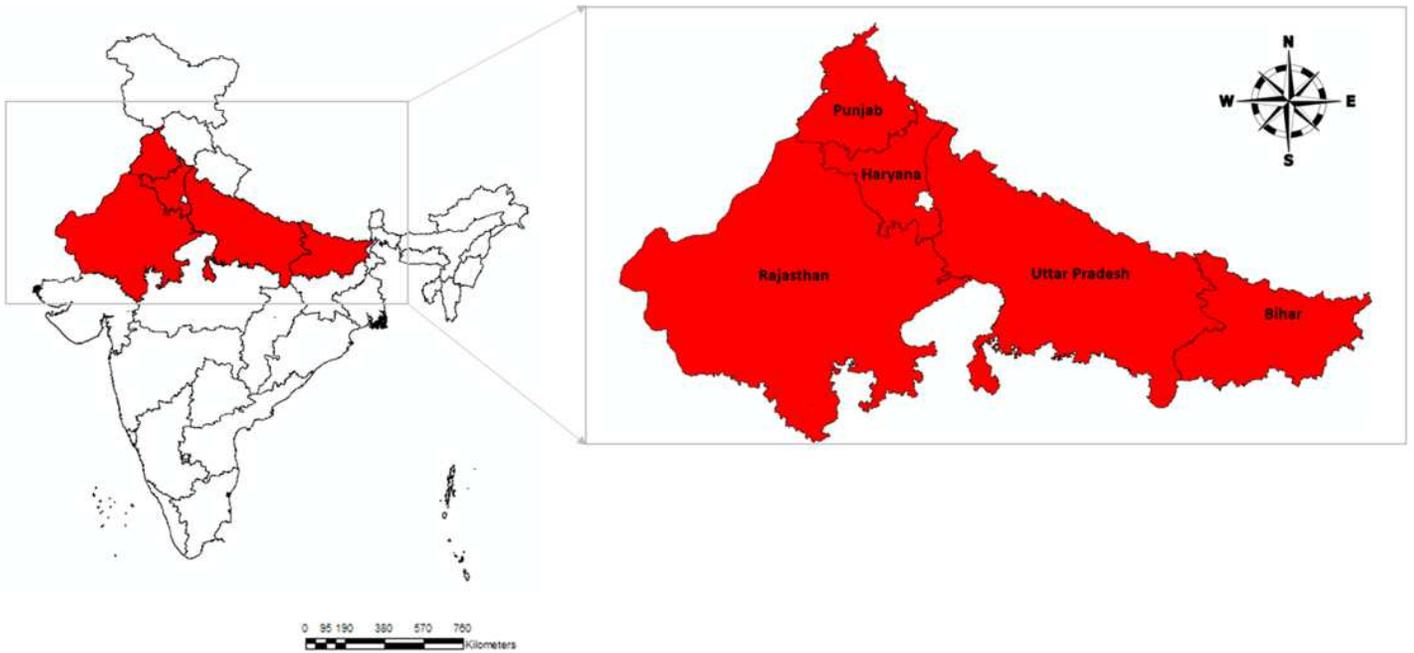


Figure 1

Map of study area

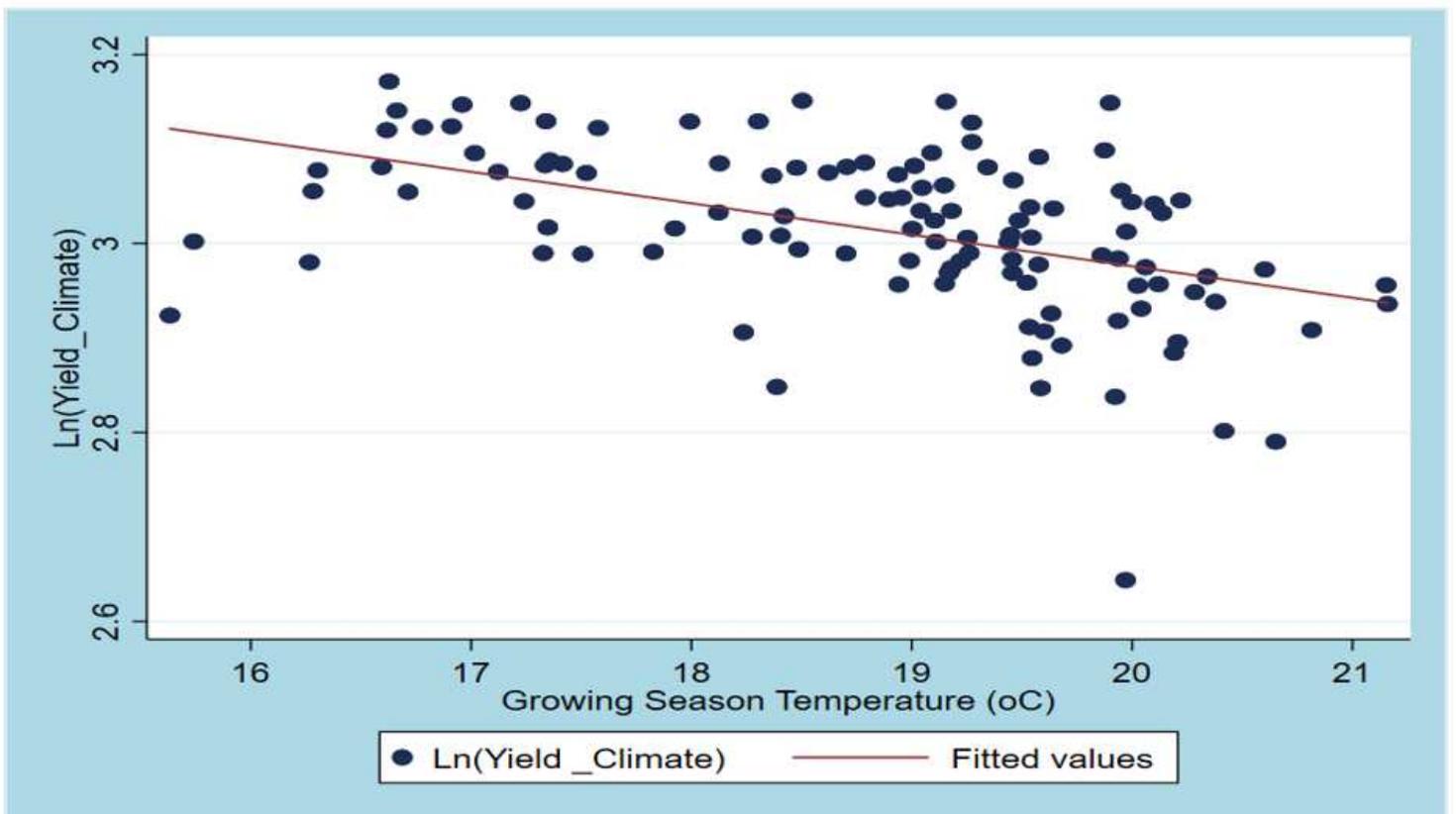


Figure 2

Correlation between GST and Yield climate

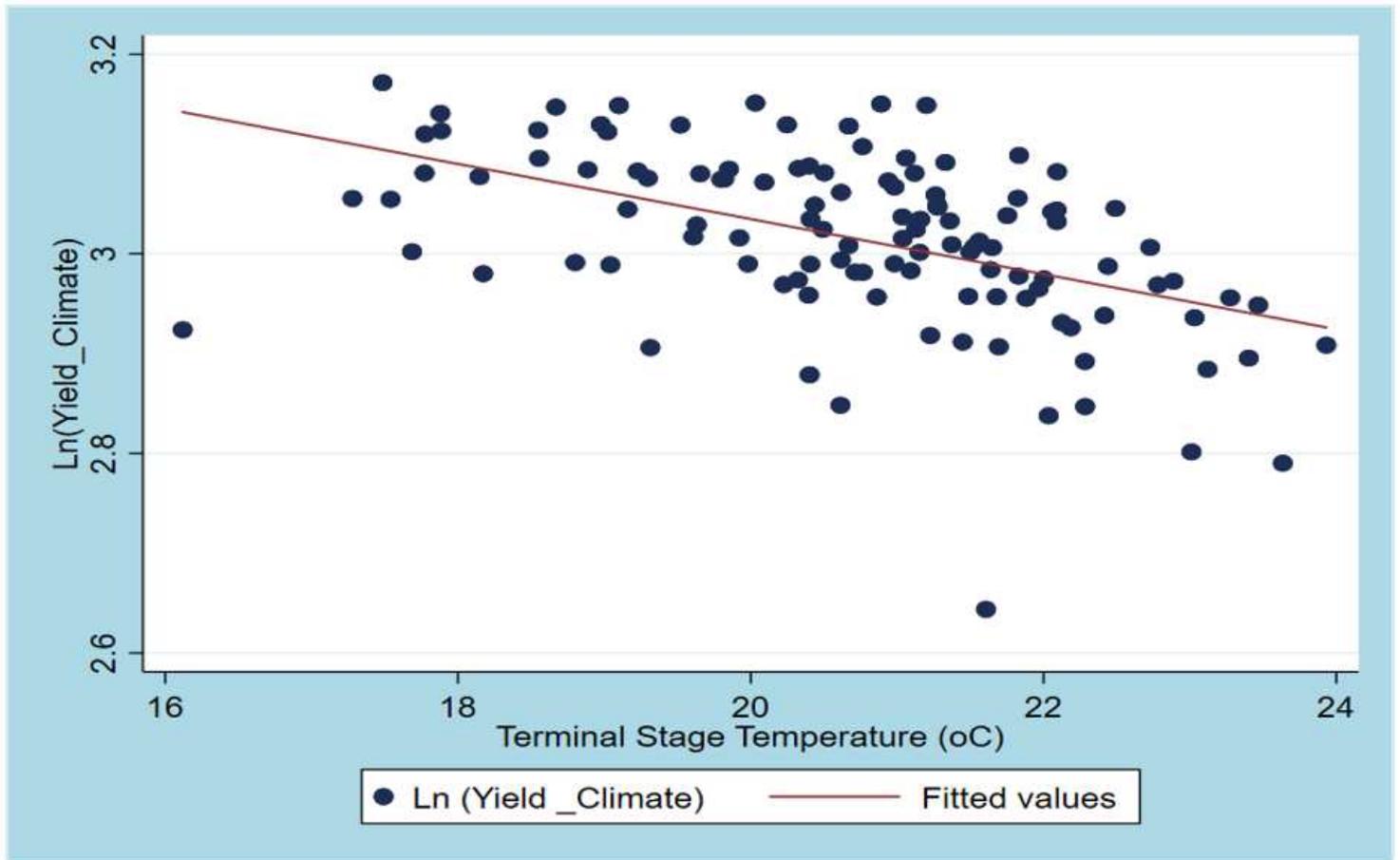


Figure 3

Correlation between TST and Yield climate

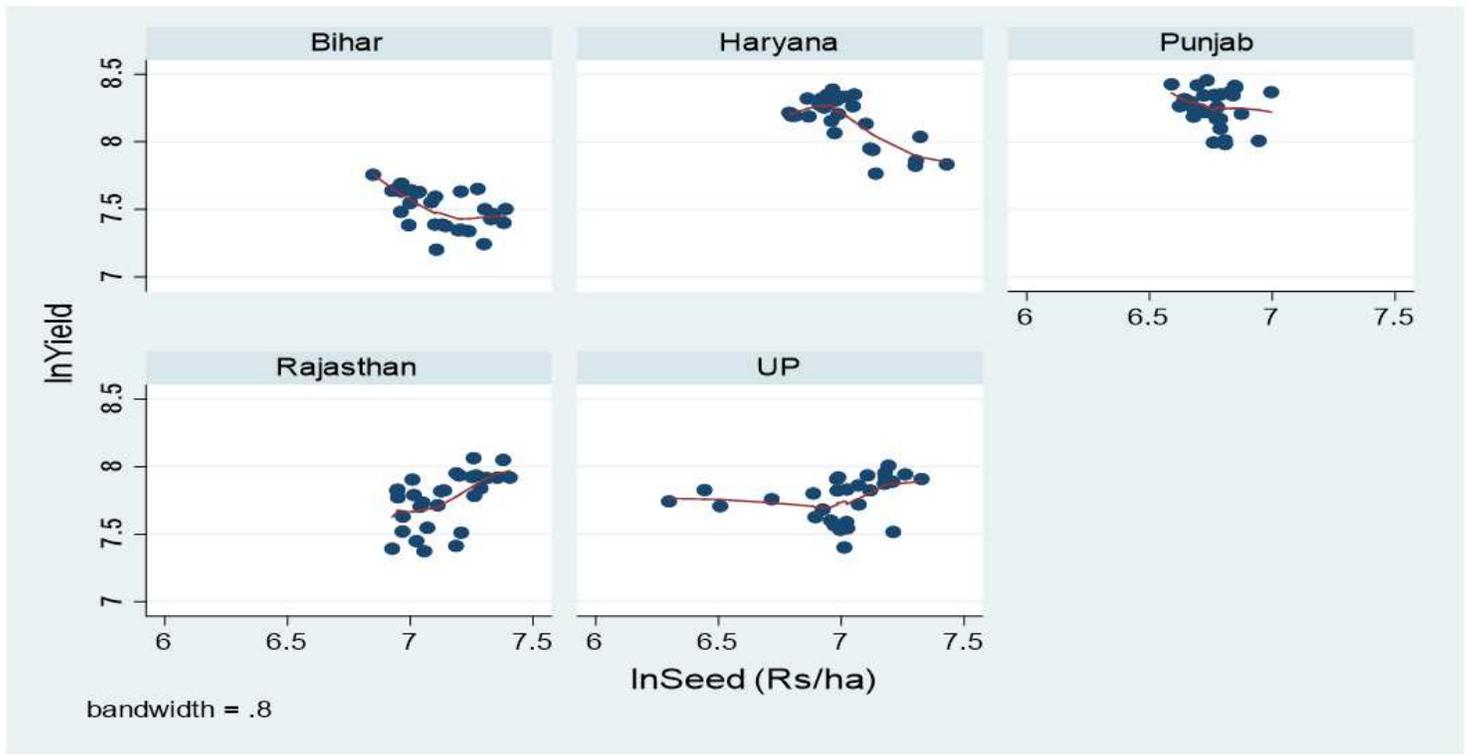


Figure 4

State wise lowess plot of yield and seed application