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Vulnerability of Indian wheat against rising temperature and aerosols☆

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ABSTRACT

Potential impacts of change in climate on Indian agriculture may be significantly adverse, if not disastrous. There are projections of potential loss in wheat yield due to the rise in daily minimum (Tmin) and maximum (Tmax) temperature, but only few researchers have considered the extent of such loss on a spatial scale. We therefore, systematically studied the effect of change in Tmax, Tmean (daily average temperature) and Tmin, solar radiation (Srad) and precipitation (RAIN) during wheat growing seasons (from 1986 to 2015) on wheat crop yield over five wheat growing zones across India, taking into account the effect modification by aerosol loading (in terms of aerosol optical depth, 2001–2015). We note that for the entire India, 1 °C rise in Tmean resulted a 7% decrease in wheat yield which varied disproportionately across the crop growing zones by a range of −9% (peninsular zone, PZ) to 4% (northern hills zone, NHZ). The effect of Tmean on wheat yield was identical to the marginal effect of Tmax and Tmin, while 1% increase in Srad enhance wheat yield by 4% for all India with small geographical variations (2−5%), except for the northern hill region (−4%). Rise in 1 °C Tmean exclusively during grain filling duration was noted positive for all the wheat growing regions (0–2%) except over central plain zone (−3%). When estimates of weather variables on wheat yield was combined with the estimated impact of aerosols on weather, the most significant impact was noted over the NHZ (−23%), which otherwise varied from −7% to −4%. Overall, the study brings out the conclusive evidence of negative impact of rising temperature on wheat yield across India, which we found spatially inconsistent and highly uncertain when integrated with the compounding effect of aerosols loading.

1. Introduction

In recent decades, growth of India's agricultural sector has been remarkable with almost fivefold increase in food grains production by last 50 years thereby, transforming India to a net food exporter (FAO, 2017). Having said that, India is also one of the most populous countries in the world comprising 18% of the global population and is expected to reach to 1.7 billion by 2050 (UN, 2017). These projections raise number of concerns especially in terms of regional and global food security, as feeding such huge and ever-increasing population would require raising food production without compromising the nutritional quality. Simultaneously, the agricultural system has also severely challenged by the change in climate especially by water scarcity, temperature, solar radiation and by the increased level of pollution (Lobell et al., 2012; Gupta et al., 2017). In addition to these, several factors like climate variability, extreme weather event, crop management practices and soil fertility affect the wheat crop and ultimately induce uncertainties in yield and grain prices (Lobell et al., 2011, 2013; Burney and Ramanathan, 2014). Therefore, it becomes essential to understand the processes involved in crop growth and development to ensure that the food supplies remain in pace with the growing demand.

Wheat is one of the main cereal crops of India's rice-wheat

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cropping system and with the current production of 98.4 million tonnes, India is the second largest wheat producing country of the world (FAO, 2018). The total area under the wheat crop is about 30.2 million hectares (DES, 2017) (Fig. 1). Being a sensitive crop to weather, regional vulnerability of wheat to climate change and variability are matter of concern and has been addressed under different scenarios. There is a medium confidence that the changing climate will adversely affect the productivity of the wheat crops in the different parts of the world (Lobell and Field, 2007; Challinor et al., 2014; Asseng et al., 2015, 2017; Liu et al., 2016; Zhao et al., 2016; Liu et al., 2018; Li et al., 2019; Dowla et al., 2018). Recently Liu et al. (2018) projected that under 1.5 °C–2 °C temperature rise scenarios, global wheat production will change by −2.3–7.0% and −2.4–10.5% respectively, compared to a baseline of 1980–2010. Wheat grows under wide range of environments however, it enjoys cool environment in its early stage with rising temperature to a maximum during grain filling (Kingra et al., 2018; Lobell et al., 2012). Increase in temperature may however, leads to multiple complications especially in terms of shortening of growth period, decrease in number of spikes, increase heat stress affecting water use efficiency and greater susceptibility to diseases (Talukder et al., 2014; Mahdi et al. 2013; Singh et al., 2013a,b). Heat stress also adversely impair the grain filling of wheat (Blum et al., 1994; Ortiz et al., 2008; Farooq et al., 2011; Lesjak and Calderini, 2017; Barlow et al., 2015). In India, 1 °C increase in daily maximum and minimum temperature are reported to reduce 2–4% of wheat yield (Gupta et al., 2016) while a net reduction of 19–28 Mt of wheat yield is projected for 3–5 °C rise in temperature (Mall et al., 2006; Aggarwal and Singh, 2010). Considering the projected 0.4–2.6 °C rise in global surface temperature by next 50 years (by 2046–2065; IPCC, 2014), and to a range of 2.9 °C (under RCP 4.5, Rao et al., 2016) to 5 °C (under RCP 8.5, Basha et al., 2017) for India by 2100, there has been widespread concern on possible impact of changing climate on wheat yield, productivity and its nutritional quality.

Possible impact may further be complicated due to uncertain implications of atmospheric aerosols which by means of light extinction and modifications in cloud microphysical properties, may rapidly adjust the thermal balance of lower atmosphere,

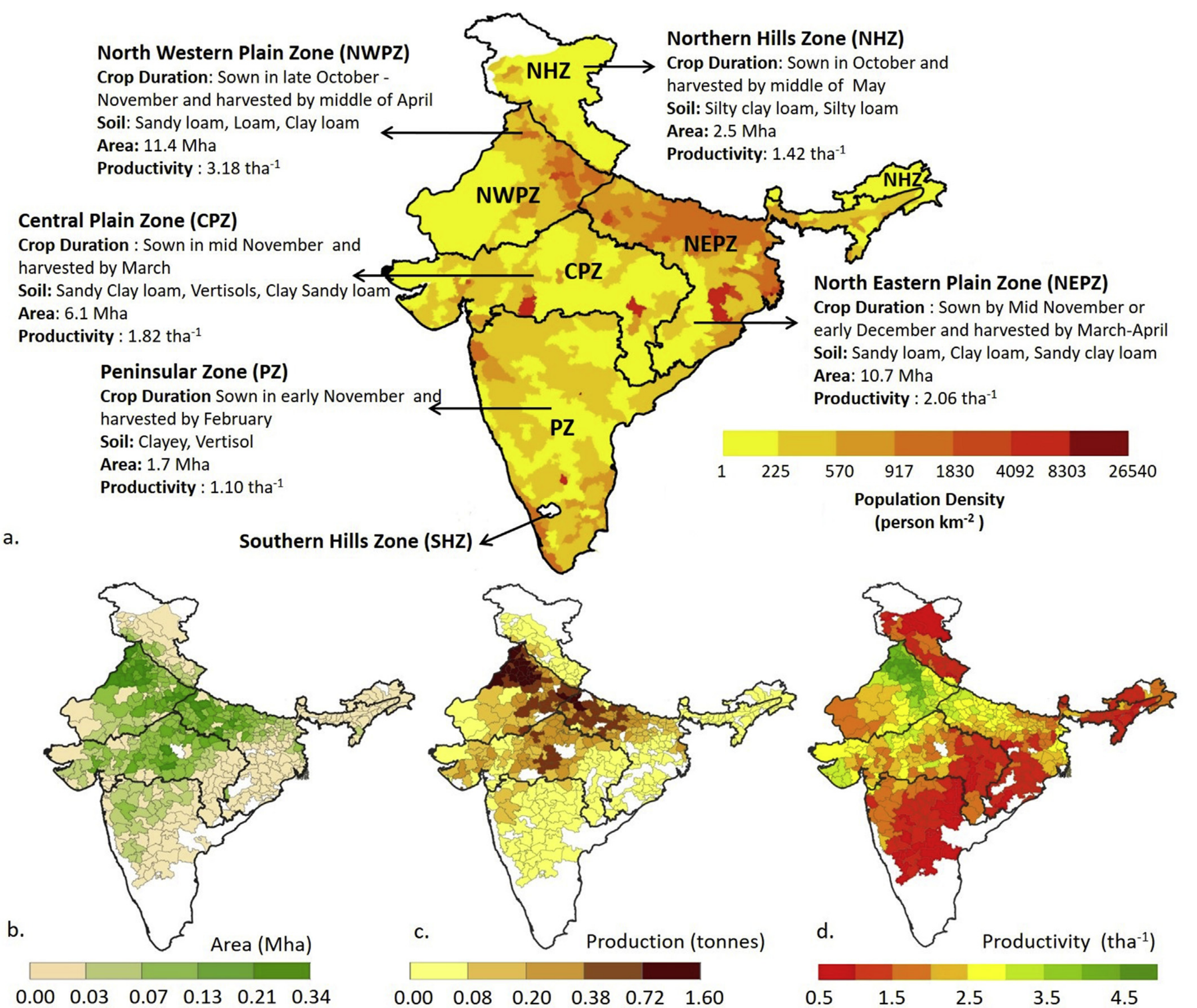

Fig. 1. Description of wheat crop growing zones across India. (a) population density of India, (b) area under production, (c) wheat production and (d) wheat yield. **Note.** All data were averaged over 1986–2015. Population data is the curtsey of Indian census (MHA, 2011). White space indicates no/limited data.

thereby influencing many physiological behaviours of wheat crop (Myhre et al., 2013; Chen et al., 2018). Beside modifying insolation, aerosols also influences boundary layer height thereby, weakening the atmospheric turbulence (Petäjä et al., 2016). There are several evidences of negative impacts of aerosols on wheat production (Chameides et al., 1999), while to precisely quantify the extent of loss necessitates multiple dimensions especially like crop type, soil health, climatic conditions and radiative properties of aerosols. Emission of airborne fine particulates has been recently reviewed by Singh et al. (2017a) over South Asia emphasizing the great extent of spatial and temporal variation both in aerosol loading and sources. There are reports of persistence of thick aerosol layer across India (Sen et al., 2017; Lobell et al., 2018; Dey and Di Girolamo, 2011; Ramachandran et al., 2012), while aerosol loading particularly over the Indo-Gangetic Plain (IGP) is often remain the centre of investigation (Kumar et al., 2018; Mhawish et al., 2018, 2019; Singh et al., 2017a,b; 2018). Undoubtedly, the IGP has the highest aerosol burden within South Asia followed by central and southern India (Kumar et al., 2018; David et al., 2018).

There are some global efforts on quantifying the effects of elevated temperature, trace gases and aerosols on wheat production, while such projections are exceedingly rare over India. Considering such uncertainties, we focused on investigating how variations in different temperature matrices and aerosol concentration is influencing wheat production over different wheat growing zones of India. Our analysis is unique by means of analysing long-term (1986–2015) spatial and temporal variation of maximum and minimum temperature, solar radiation and Aerosol Optical Depth (AOD, 2001–2015) across the wheat growing zones of India. The cumulative effect of maximum and minimum temperature and solar radiation on wheat yield was analysed by means of linear regression and thereafter, the weather variables were regressed on aerosols optical depth. The partial derivatives obtained from both the regression were used to estimate the impact of aerosols on the wheat yield. Additionally, effect of temperature variation particularly during grain filling stage was also simulated using Generalized Additive Model (GAM).

2. Data and methods

2.1. Study domain

By means of identifying the impact of climate variables on wheat yield, the novelty of this analysis present on classifying the entire geographical region to different subregions based on the variable agro-climatic and geographic conditions. Considering the classification criteria as developed by Indian Council of Agricultural Research, New Delhi (Kumar et al., 2014), wheat growing region of India has been classified into six zones e.g. Northern Hills Zone (NHZ), North Western Plain Zone (NWPZ), North-Eastern Plains Zone (NEPZ), Central Plain Zone (CPZ), Peninsular Zone (PZ) and Southern Hills Zone. However, SHZ has not been considered for this analysis due to unavailability of consistent dataset. Individual characteristics of each zone are included in Fig. 1. Briefly, the NHZ includes the Western Himalayan regions of Indian state of Jammu and Kashmir, Himachal Pradesh, Uttaranchal, Sikkim and Hills of West Bengal and North East State. Wheat grown in irrigated conditions in the NEPZ includes the state of eastern Uttar Pradesh, Bihar, Jharkhand, West Bengal, Orissa, Assam, Sikkim and plains of far eastern states. The NWPZ include Punjab, Haryana, Delhi, Rajasthan and Western Uttar Pradesh (except Jhansi division), Jammu and Kathua districts of J&K, Una district and Paonta valley of HP and Tarai region of Uttaranchal. The CPZ include Gujarat, Madhya Pradesh, Chhattisgarh, Jhansi division of UP and Kota and Udaipur division of Rajasthan. PZ include Southern states of Maharashtra, Andhra Pradesh, and Karnataka. Details of these zones in terms of agronomic practises, variety and production technologies may be found in the works of Kumar et al. (2014).

2.2. Input data

Among the individual wheat growing zones, district wise wheat yield data from 1986 to 2015 for 247 districts was obtained from Directorate of Economics and Statistics, Ministry of Agriculture (https://aps.dac.gov.in). Here, year denotes the year in which the wheat crop was harvested so the sowing is always be the previous calendar year. Missing data, if any were filled from International Crops Research Institute for the Semi-Arid Tropics- Village Dynamics in South Asia meso-database (http://vdsa.icrisat.ac.in/vdsa-database). Daily gridded (1° x 1°) weather variables e.g. maximum (Tmax) and minimum temperature (Tmin), and rainfall (RAIN) were obtained from the India Meteorological department (IMD); while daily mean temperature (Tmean) was computed averaging daily Tmax and Tmin. Due to unavailability of reliable solar radiation (Srad) data, daily surface solar radiation (1^x1^) was obtained from the NASA's Prediction of Worldwide Energy Resources (power.larc.nasa.gov) for similar time frame (1986–2015). Wheat sowing and harvest dates specified by all India Coordinated Research Projects (AICRPs- IARI) and National food security mission, Ministry of Agriculture (https://aps.dac.gov.in/APY) was considered for respective zones. For each wheat growing season, daily Tmax, Tmin and Srad were averaged while RAIN was considered as seasonal aggregate. Daily aerosol optical depth at 550 nm gridded at 1° x 1° was obtained from GIOVANNI (Goddard Earth Sciences Data and Information Services Centre) from 2001 to 2015 considering Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra satellite. Detail about MODIS AOD data processing and uncertainties may be found in the works of Mhawish et al. (2018, 2019).

2.3. Statistical methods

2.3.1. Association between climate variables

Initially, colinearity among the variables was assessed by Pearson's correlation test. Colinearity among the two variables was considered if correlation remain >0.7 and in that case only single variable was selected as a predictor for regression analysis. Autocorrelation was also checked in the residuals using Durbin-Watson statistics (D-W) and if any, was subsequently removed. The default lag time was 1-time unit. The D-T statistics varies from 0 to 4, where 2 refers no autocorrelation, <2 refers positive autocorrelation and >2 refers negative autocorrelation. All statistical analysis was made using statistical software R version 3.5.1 (R Core Team, 2018).

2.3.2. Regression analysis

To identify the impact of climate on yield, initially we made linear regression of wheat yield against all climate variables. Regression analysis (Eq. (1)) was done between the yield, daily average Tmax, Tmin, Srad and RAIN for individual wheat growing zone.

$$Y_{dt} = c_d + \beta_1 Tmax_{dt} + \beta_2 Tmin_{dt} + \beta_3 Srad_{dt} + \beta_4 RAIN_{dt} + \gamma t + u_{dt} \quad (1)$$

where, Y_{dt} is the crop yield, d and t refer to districts and years, c refers to the control of the district specific time independent factor, u is the residual error. We also took care of the linear time-trend (γ) that control the effect of new capital investments and technical progress made in wheat cropping system during the time span, whereas β captures the estimate of effect on wheat yield due to weather variables. The non-linear association between yield and temperature (Tmax, Tmin and Tmean) was also established using Generalized Additive Model (GAM, Eq. (2)).

$$Y_{dt} = c_d + \beta_1.s(Temp_{dt}, bs = \text{“cr”}, k = 3) + \beta_2.s(Srad_{dt}, bs = \text{“cr”}, k = 3) + \beta_3.s(RAIN_{dt}, bs = \text{“cr”}, k = 3) + s(time_t, bs = \text{“cr”}, k = 30) + u_{dt} \quad (2)$$

Here, $Temp_{dt}$ represents Tmax, Tmin and Tmean for three separate equations. The *s* represents the spline function, *cr* represent the cubic regression spline and *k* represents the number of knots. Long-term time trend was controlled by smoothing calendar time with thirty degrees of freedom following Gupta et al. (2017) and Harrell (2013).

2.3.3. Impact of temperature on wheat during grain filling

We also modelled the impact of temperature variations measured during wheat grain filling phase on yield for different wheat growing zones. Temperature was considered as a linear term in GAM while both Srad and RAIN were considered as smooth term (Eq. (3)).

$$Y_{dt} = c_d + \beta_1 Temp_{dt} + \beta_2.s(Srad_{dt}, bs = \text{“cr”}, k = 3) + \beta_3.s(RAIN_{dt}, bs = \text{“cr”}, k = 3) + s(time_t, bs = \text{“cr”}, k = 30) + u_{dt} \quad (3)$$

Here, $Temp_{dt}$ represents Tmax, Tmin and Tmean for three separate equations.

2.3.4. Impact of aerosol on wheat yield

Considering the spatio-temporal diversity of aerosol particles that present across the India, we avoided any estimates of the impact of aerosol on climate variables using climate model (Gupta et al., 2016). Again, possible effect of aerosols on wheat yield are not straightforward therefore, we also avoided estimating yield loss by means of single regression equation. To simulate the effect of aerosol on wheat yield we therefore integrate the estimated effect of AOD on climate variables with the estimates of effect of the climate variable on wheat yield. To quantify, we performed single predictor regression where AOD was taken as independent predictor while all climate variables as dependent. The regression equation was further adjusted for linear time trend and district fixed effects (Eq. (4)).

$$Y_{dt} = c_d + \beta AOD_{dt} + \gamma_t + u_{dt} \quad (4)$$

where, Y_{dt} represents Tmax, Tmin and Srad in three different regression equations, and β captures the estimate of effect of AOD on climate variable. Net estimates of impact of aerosols on wheat yield was predicted using following equation:

$$\frac{dY}{dAOD} = \frac{\partial Y}{\partial Tmax}\frac{\partial Tmax}{\partial AOD} + \frac{\partial Y}{\partial Srad}\frac{\partial Srad}{\partial AOD} + \frac{\partial}{\partial Tmin}\frac{Y\partial Tmin}{\partial AOD} \quad (5)$$

where, $\frac{\partial Y}{\partial Tmax}, \frac{\partial Y}{\partial Srad}, \frac{\partial Y}{\partial Tmin}$ refer partial derivatives of the yield on weather while $\frac{\partial Tmax}{\partial AOD}, \frac{\partial Srad}{\partial AOD}, \frac{\partial Tmin}{\partial AOD}$ are the partial derivatives of weather variables on aerosol (in terms of AOD).

3. Results and discussion

3.1. Variations in climatic variables and AOD over different wheat growing zones

Spatial distribution of Tmax, Tmin and Srad averaged over 30 years (1986–2015, all inclusive) and MODIS-AOD for 15 years (2001–2015, all inclusive) over different crop growing zones exclusively for the wheat growing season are plotted in Fig. 2a–d. Temporal variations for individual parameter are included in Fig. 2 while descriptive statistics for individual crop growing season are noted in Table S1 (in supplementary). The spatial coincidence map for each parameter indicates an overall increase in long-term trend with different amplitude across the cropping zones. An overall increase in Tmax varying from 0.002 to 0.029 °C $year^{-1}$ was noted, highest over the southern region (PZ: 0.029 °C $year^{-1}$) followed by northern part (NHZ: 0.023 °C $year^{-1}$). However, the rate of increase in Tmean was particularly high over northern and north-western zone (NHZ, NWPZ: 0.015–0.017 °C $year^{-1}$) compared to rest of India (<0.011 °C $year^{-1}$). An overall increase in Tmin for all the cropping zones was also noted varying from 0.016 to 0.029 °C $year^{-1}$, except for the PZ (−0.008 °C $year^{-1}$). Our result was consistent with the findings of Ross et al. (2018) with an indication of greater warming over the southern and north-western zone which was explained by the means of anthropogenic brown haze that usually absorb the short-wave solar radiation. Almost for all the cropping zones the rate of increase in Tmin was higher compared to the Tmax, and this has been more prominent over the northern India. This conclude a general observation of increase in Tmin and Tmax across India during wheat growing season which is identical to the observation reported by Rathore et al. (2013), Birthal et al. (2014) and Rao et al. (2015).

A gradual increase in Srad varying from 0.013 to 0.027 MJ m^{-2} day^{-1} over all the wheat growing zones was noted except over NHZ (−0.047 MJ m^{-2} day^{-1}) and NEPZ (−0.028 MJ m^{-2} day^{-1}) Mall and Srivastava (2002). Considering systematic rise in airborne particulate concentration, there are numerous reports of consistent decrease in Srad over many parts of the globe (Hu et al., 2017; Kaiser and Qian, 2002; Xia et al., 2007), while over India solar dimming has been linked with greater cloudiness, possibly influenced by the indirect effect of aerosols (Padma Kumari and Goswami, 2010). On a closer look to the Srad timeseries over the region that accounts an increase (i.e. CPZ, NWPZ and PZ), we note that such increase was not consistent rather Srad decreased significantly over all the regions consistently from 2006 (−0.447 to −0.090 MJ m^{-2} day^{-1}, data not shown). Such phenomenon may possibly influenced by the rise in aerosol and cloudiness, but require further investigation which were not within the scope of the manuscript. Spatial distribution of aerosols in terms of AOD averaged from 2001 to 2015 for zone specific wheat crop growing season is also included in Fig. 2. The AOD was comparatively high (>0.3) over the parts of NEPZ and NWPZ, while for the rest of India AOD remain <0.3. Presence of high aerosol loading particularly over NEPZ and NWPZ (comprising major portion of IGP) is well documented by Kumar et al. (2018) and Mhawish et al. (2017), which have reported to exceed AOD >0.8 during post-monsoon (Singh et al., 2018) and winter seasons (Kumar et al., 2015, 2018). Interestingly, the wheat growing season (November to March) effectively span through the post-monsoon (ON) and winter season (DJF), referring the possibility of added influence of aerosols on wheat production. A significant increase in columnar AOD varying from 0.005 to 0.010 yr^{-1} across all the zones and for all India was consistent with the report of Moorthy et al. (2013) and Kumar et al. (2018).

3.2. Effects of climate variables on wheat yield: results of linear model

Correlation among the climate variables varied across the cropping zones (Table S2). We did check the colinearity within the climate variables and autocorrelation within the residuals, which was subsequently removed using Durbin-Watson statistics (D-W). Seasonal means of Tmax, Tmin, Srad and RAIN (from 1986 to 2015) were analysed against the wheat yield for all India and for

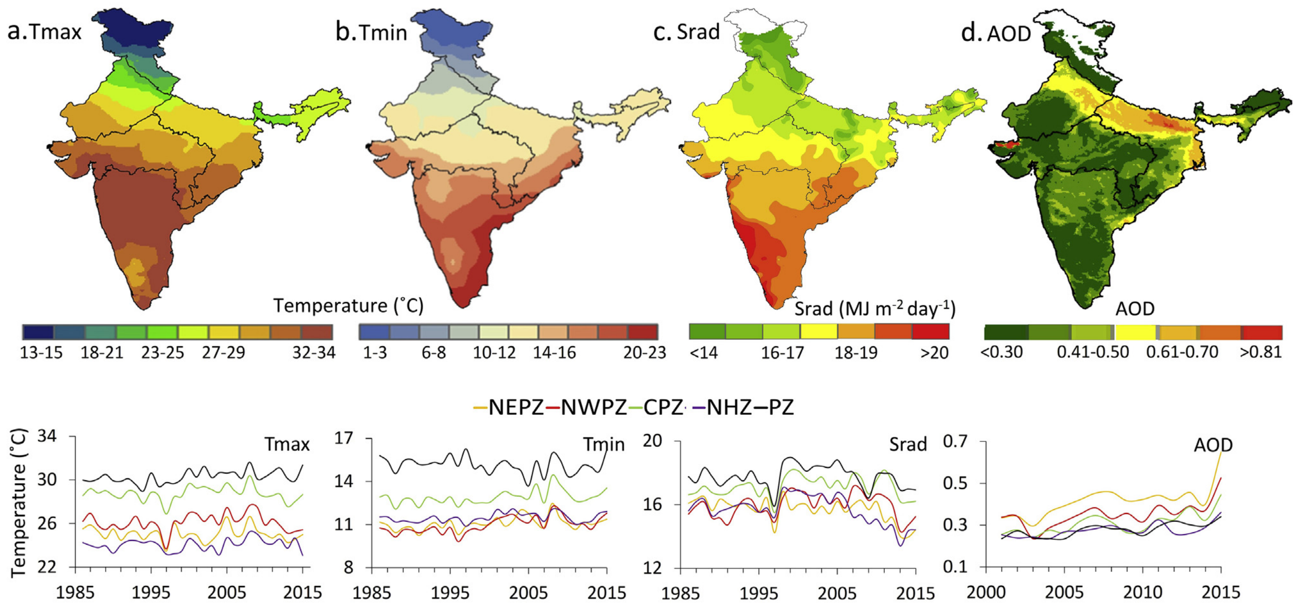

Fig. 2. Spatial distribution of (a) temperature maximum (Tmax), (b) temperature minimum (Tmin), (c) solar radiation (Srad) and (d) aerosol optical depth (AOD) in the growing season across the wheat cropping zones. **Note.** Spatial comparison of Tmax, Tmin and Srad were averaged over 30 years (1986–2015, all inclusive) and 15 years for MODIS-AOD (2001–2015, all inclusive) only for the wheat growing season as indicated in Fig. 1. White space indicates no/limited data.

individual crop growing zone, and the estimates of linear regression are tabulated in Table 1. Overall, the effect of rising temperature on wheat yield was negative almost for all the scenarios while no impact of rainfall was traced on wheat yield. The effect of change in Srad on wheat yield was however positive for India (4%) with small geographical variations (2–5%), except for NHZ where a 4% reduction in wheat yield was measured.

For each degree rise in Tmean over India wheat yield tends to reduce by 7%. Apparently, this seems to be catastrophic as recent climate projection over India expect the surface temperature to rise beyond 5 °C by 21st century (Basha et al., 2017). However, such impact will vary disproportionately across the geographical region. We note a strong spatial heterogeneity in the effects of temperature on wheat yield. The maximum loss of yield due to 1 °C rise in Tmean was particularly evident over the peninsular zone (PZ, 9%) and over the central plain zone (CPZ, 8%) compared to the northern plain region (NEPZ, NWPZ: 5%). The effect of 1 °C rise in Tmax on wheat yield was also negative for India (4%), varying from 1 to 8%, having maximum loss over PZ followed by CPZ while minimum over northern plain zone (1–4%). The effect of change in Tmin was spatially inconsistent with ranges varying from −1% to 9%. Interestingly, with 1 °C rise in Tmin we note a 9% increase in wheat yield over northern hill zone (NHZ), in contrast to the rest of the wheat growing regions which otherwise shows a loss of yield to a range of 1–5%. The effect of rain on Indian wheat yield was not evident may be due to largely being irrigated while effect of change in solar radiation was practically positive (2–5%) except over the NHZ (−4%). The Variation in wheat yield by the change in Srad may be also partially influenced by aerosol-radiation interaction, which has been further explored in subsequent section.

Almost for all the scenarios, the effect of unit rise in Tmean on yield was in identical to the aggregate marginal effect of Tmin and Tmax, but this do not hold true for Srad. This may ideally indicate that with the unit rise in Tmax and Tmin, the model would provide equivalent projection as in case of increase in Tmean. This was also evident by Gupta et al. (2016) when district specific climate data was modelled for 1981–2009 for the entire India. However, considering the projection (Rathore et al., 2013) and observation (Padma Kumari et al., 2007) on the possibility of greater increase in Tmin compared to the Tmax over India, we preferred our model to individually control the Tmax and Tmin. Our analysis essentially extends the earlier cross-country study on temperature effects on wheat by Lobell et al. (2011) and Gupta et al. (2016), especially by means of considering spatial nature of the effect. A general decrease in wheat yield across India was earlier reported within a range of 2–9% for 1 °C rise in Tmax and 4% for 1 °C rise in Tmin, which we

Table 1
Effect of climatic variables on wheat yield for all India and in different crop growing zones.

Variables	NHZ		NEPZ		NWPZ		CPZ		PZ		All INDIA	
Tmean		0.04**		−0.05***		−0.05***		−0.08***		−0.09***		−0.07***
Tmax	−0.05**		−0.01		−0.04**		−0.06***		−0.08***		−0.04**	
Tmin	0.09**		−0.05***		−0.01		−0.02		−0.03**		−0.03***	
Srad	−0.04*	−0.04*	0.02*	0.03***	0.03	0.02	0.05***	0.04***	0.04**	0.03**	0.04**	0.04**
RAIN	−0.00	−0.0001	0.00	0.00	0.00**	0.00**	−0.00***	−0.00***	−0.00***	−0.00***	0.00	0.00
Durbin-Watson Statistics	2.00		2.00		2.00		2.00		2.00		2.00	
No. of Observations	510		2550		1260		1920		1140		7380	
Linear Time Trend	Yes		Yes		Yes		Yes		Yes		Yes	

Note. Significance level: * 0.05, **0.01, *** 0.001.

found geographically varied within a range of −9 to +9% (Mall et al., 2006; Lobell et al., 2012; Gupta et al., 2016).

3.3. Effects of climate variables on wheat yield: results of non-linear model

Non-linear association between the temperature and wheat yield was also assessed using restricted cubic splines. Number of knots was applied based on Akaike information criterion to avoid data over-smoothing. The difference in wheat yield at different temperature matrices for individual wheat growing zone are included in Fig. 3. The non-linear model replicate the projection made using linear model with overall decrease in wheat yield with corresponding increase in temperature. Almost in all the cases, a clear indication of a small increase in temperature at higher and/-or lower end of temperature distribution was associated to a greater impact on wheat yield. In terms of wheat growing zones, the exposure curve varies considerably while in each case, the effect of temperature at high/-low level of distribution were more drastic with lower level of confidence intervals.

3.4. Effects of climate variables on wheat yield: implications during grain filling

Wheat crop is extremely sensitive to the elevated temperature, especially during reproductive and grain filling stage. Any temperature except the optimum can be especially deleterious, resulting injury or irreversible damages. The optimum temperature during grain filling stage (typically 70th to 90th days after sowing) is typically $21.3 \pm 1.5\,^{\circ}C$, and any change in temperature during flowering to grain maturity may result in reduction of yield (Farooq et al., 2011 and reference therein). We therefore, also constitute the impact of change in temperature during wheat grain filling duration with yield, using linear regression model only after smoothing the influence of Srad and RAIN.

Change in wheat yield due to unit rise in temperature during grain filling duration with 95% confidence intervals (CI) is included in Fig. 4. Overall, the influence of temperature variation during grain filling duration on wheat yield was mostly positive, varied within a range of −3 to 2% across the cropping zones (Table S3). The most distinct (negative) effect was simulated over CPZ (up to 3% loss) while for the rest of the region, impact was largely positive, varying from 0 to 2% with 1 °C increase in temperature. Reduction in wheat yield over CPZ possibly driven by the fact that the region is comparatively warmer compared to the rest of the zones while corresponding increase in crop yield over PZ (and over NEPZ) is rather unclear, as both regions are comparatively warmer (and colder) and have recorded a reduction in yield with increase in temperature by linear model. For rest of the wheat producing zones, the impact was minor (<0.3%). Possible reasons for such spatial variations may be many, most importantly be the Indian

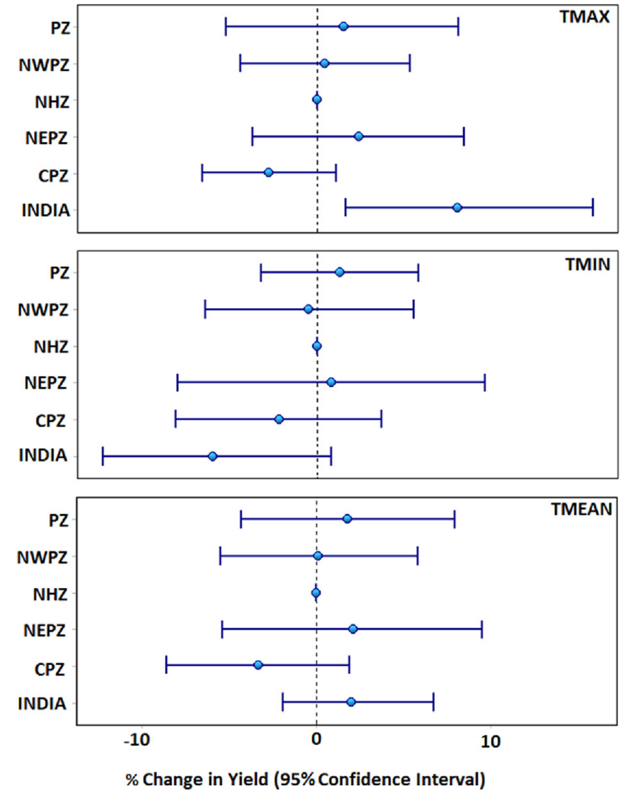

Fig. 4. Percent change in wheat yield against temperature during grain filling duration.

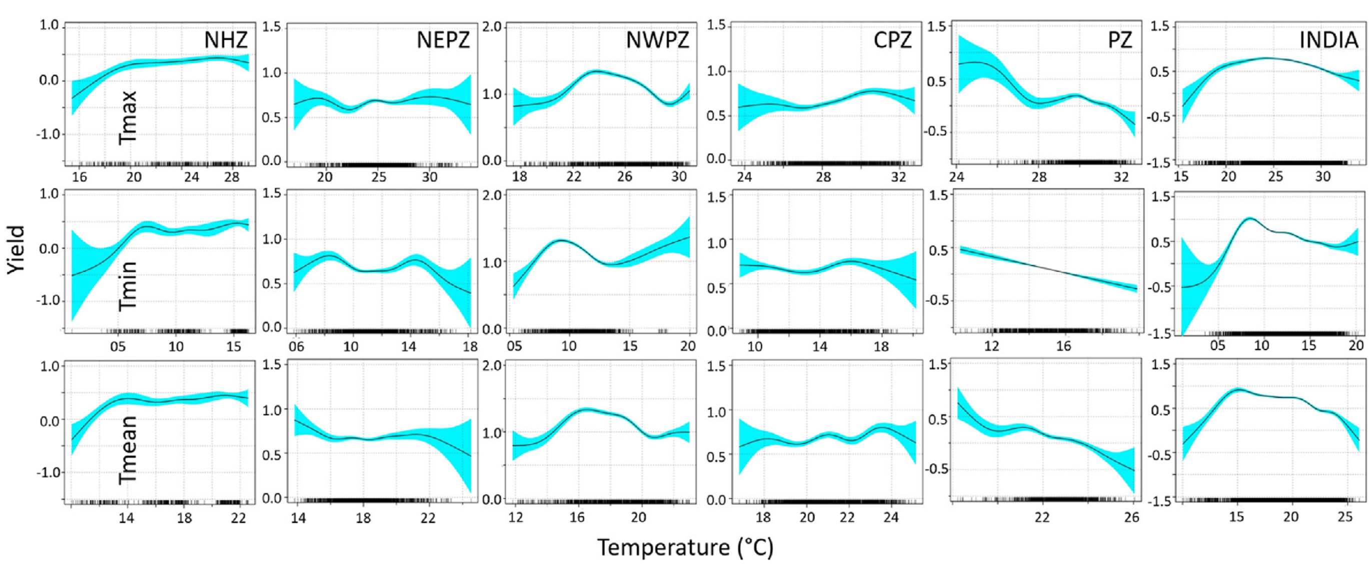

Fig. 3. Wheat yield using restricted cubic spline against different temperature matrices. **Note**. The shaded region indicates 95% confidence interval.

wheat largely being irrigated, and has been reported to reduce yield loss in case of temperature stress (Gupta et al., 2016; Challinor et al., 2014; Asseng et al., 2011; Mall et al., 2018).

3.5. Impact of aerosols on wheat yield

Aerosols have diverse impacts on crop, like reduction in aerosols will potentially increase solar irradiance (Hu et al., 2017) which should be beneficial for crop growth. In contrast, increase in solar irradiance will subsequently enhance daily temperature maximum thereby, inflicting negative impact on crop. Canopy photosynthesis tends to be light-use efficient in diffuse irradiance compared to the direct solar radiation (Roderick et al., 2001). Considering these uncertainties, impact of aerosols on wheat yield was also modelled, combining the estimates of weather impact on yield with estimated impact of AOD on weather variables. To estimate the change of wheat yield against aerosol loading, we used the regression coefficients noted in Tables 1 and 2 in equation (5), and the estimated coefficients (*dy/dAOD*) were summarized in Table 2.

Overall, the influence of aerosol loading on wheat yield was negative for all India (1%) and varied within a range of −23% (over NHZ) to −3% (over NEPZ, NWPZ). The spatial influence of aerosols varied considerably as with corresponding increase in aerosols. It's important to mention that we did not check the variation in diurnal temperature range due to aerosols. In terms of the impact of aerosols on wheat yield, this was invariably negative across India.

3.6. Aerosol-radiation-temperature and wheat yield: discussion and conclusions

We hereby, conclude with reasonable confidence that effect of rising temperature on wheat yield was negative for India, which has been spatially inconsistent and varied slightly among different temperature matrices. Overall, for India, we found 7% decrease in wheat yield with 1 °C rise in Tmean, projected almost equally for marginal impact of Tmax (4%) and Tmin (3%). However, such impact varied considerably for different crop growing zones, likewise 1 °C rise in Tmean and Tmax was most detrimental over peninsular zone and the central plain zone, while loss of wheat yield for 1 °C rise in Tmin was most prominent over north-eastern plain zone. This certainly indicate that the influence of change in temperature is not consistent and necessitates regional adaptation practises. We have also computed the effect of change in temperature especially during wheat grain filling stage, which was within a range of −3% to −2%. In an attempt to model the effect of rising aerosol concentration on wheat yield, we used satellite-retrieved aerosol loading (in terms of AOD) in a statistical analysis of historical wheat yield data for all the districts over India. An increase in AOD was found to reduce wheat yield, spatially varying from −23 to −3%, with most drastic impact on northern hill zone.

Among the wheat growing zones, we found that the increase in Tmean will be detrimental over the peninsular and central plain zones compared to the IGP (NEPZ + NWPZ). The projection remained almost similar when increase in temperature was noted only during wheat grain filling duration. The central plain zone emerged as the most susceptible region when aerosol loading was integrated with the concurrent climate variables. Although the research concludes the possibility of considerable reduction in wheat yield in lieu of changing climate across India, the 'food basket of India' Indo-Gangetic plain reveals better adapted to changing climate and exhibit comparatively minimum yield loss compared to other crop growing zones.

There are few references that relate aerosol-temperature-radiation impacts on Indian wheat yield. Initially, Lobell et al. (2011) concluded that recent (1980–2008) climate trends were large enough to reduce 5.5% of global wheat production. Further, a statistically significant acceleration of wheat senescence was noted from satellite observations over North India due to extreme heat, which was above and beyond the effect of increased mean temperatures (Lobell et al., 2012). Considering the combined effect of climate change and short-lived climate pollutants (1980–2010), Burney and Ramanathan (2014) noted a 36% reduction in wheat yield, that may extend to 50% over the wheat producing zones over IGP. Recently, Gupta et al. (2016) concluded a reduction in wheat yield by 2–4% due to 1 °C rise in daily Tmax and Tmin (1981–2009), while 4.8% yield has been reduced by one standard-deviation increase in AOD. This is compared to a 8% reduction in wheat yield due to the heavy haze and aerosol pollution over China (Tie et al., 2016) with overall 5–30% reduction in crop yield (Chameides et al., 1999). Here, we estimate a 7% decrease in wheat yield which was varying spatially within a range of −9 to 4% for each degree increase in daily mean temperature.

Our analysis is improved in the context of using larger datasets, controlling solar radiation, separate consideration of temperature maximum, minimum and average, and by virtue of understanding the spatial heterogeneity of impacts across India. However, several caveats to our analysis do exist. We did not consider the technological innovations and genetic improvements that essentially integrate with agricultural system which may partially offset our estimates. Likewise, with better wheat varieties and irrigation practises farmers may able to adapt with changing climate. Further, our study is limited to model specification/hypothesis and of a choice of baseline.

Table 2
Influence of aerosol loading on climatic variables and wheat yield for all India and in different crop growing zones.

Parameters	NHZ	NEPZ	NWPZ	CPZ	PZ	All India
Tmax	3.03	−0.07	1.65***	1.06	−0.19	0.69
Tmin	0.47	0.39**	−0.56	0.16	0.34	−0.73
Srad	3.08**	−0.56	1.18	−0.15	−1.23*	−0.10
No. of Observations	255	1275	630	960	570	2985
District fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Linear Time trend	Yes	Yes	Yes	Yes	Yes	Yes
dy/dAOD	−0.23	−0.03	−0.03	−0.07	−0.04	−0.01

Note. Level of significance: * 0.05, **0.01, *** 0.001.

Conflicts of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.07.114.

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