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Research Article

Impact of Seasonal Change in Temperature and Sowing Date on Wheat Productivity in India: A Modelling Study

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ABSTRACT

Wheat is important for food security of India and temperature is one of the most important abiotic factors affecting its productivity. A simulation study was conducted to analyze the effect of seasonal temperature change from normal on wheat productivity in different regions of India and secondly to determine the optimum sowing period for adapting the wheat to changed growing season temperature conditions. The CERES-Wheat simulation model available in DSSAT v4.5.0.0 was used to simulate wheat productivity at seven locations spread across wheat growing area of India. The results showed that the seasonal increase (normal + 3.0°C) in temperature may result in reduction in productivity of wheat sown at any time, except in case of late sown wheat at Palampur (northern hill zone) and Ludhiana (north western plain zone). The decrease in temperature may result in a reduction in productivity of early, timely and late sown wheat at Palampur and at Kanpur. While at Ludhiana productivity of timely and late sown wheat and at Udaipur that of late sown wheat was reduced. At rest of the location the decrease in temperature had favourable affect on wheat productivity. The productivity of early sown wheat at Ranchi and Raipur and that of late sown wheat at rest of the locations was less affected by seasonal increase in temperature as compared to other times of sowing. The wheat productivity at Raipur (Central zone) was most susceptible to change in temperature as compared to rest of the zones.

Key words: Heat stress, Wheat, Seasonal, Temperature, DSSAT

Introduction

Wheat (*Triticum aestivum* L.) is very important for food security of India and it is the second largest wheat producer in the world and produced 94.88 million tonnes of total wheat from 29.90 million hectares of area during 2011-2012 (Anonymous, 2013).

Many abiotic and biotic factors limit the production of wheat. Amongst the abiotic factors,

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temperature stress is one of the most important factors limiting wheat production. Temperatures outside the range of those which are generally experienced in a region can have adverse effects on crops productivity. Both high and low temperatures decrease the rate of dry matter production and the extremes can cause production to cease. Continual and terminal high temperature stresses are the two major constraints to wheat production in South Asia (Chatrath *et al.*, 2007 and Joshi *et al.*, 2007).Continual heat stress affects approximately 7 million hectares of wheat in developing countries, whereas terminal heat stress is problem in 40 per cent of the temperate environment that encompasses 36 million hectares (Reynolds *et al.*, 2001). Temperature stress is a complex function of intensity (temperature in degrees), duration and rate of change in temperature. For wheat, mean air temperature of about 20–25°C has been considered optimum for growth and development (Acevedo *et al.*, 2002) and an increase of 2°C in temperature from normal reduced potential grain yield of wheat at most places in India (Aggarwal and Sinha, 1993).

High temperature stress adversely affects plant physiological processes thereby limiting its growth and productivity. Leaf photosynthesis is negatively affected as leaf temperature rises above 25°C in cool-grown wheat leaves, but leaves acclimated to warm temperature start to show a similar decline as temperatures exceed 35°C and at 45°C leaf photosynthesis may be halved (Acevedo *et al.*, 2014). Heat stress adversely affect days to appearance of first node and tiller number thereby resulting in reduction of source capacity and future sink capability of the plant. At anthesis, high temperatures may result in pollen and anther sterility and restrict embryo development thereby reducing grain number. High temperature stress after anthesis affects the rate of grain filling, leading to reductions in grain yield (Al-Khatib and Paulsen, 1984; Tashiro and Wardlaw, 1990; Weigand and Cueller, 1981; Vashisth *et al.,* 2018).The most thermosensitive stage of wheat is double ridge to anthesis, when kernel number is being determined and any stress during this stage severely affects the grain yield (Acevedo *et al.*, 2014). The number of kernels per unit area decreases at a rate of 4 per cent for each degree increase in mean temperature during the 30 days preceding anthesis (Fischer, 1985). Over the range of 12-26°C during grain filling, grain weight is reduced at a rate of 4-8 per cent/°C increase in mean temperature (Wardlaw *et al.*, 1980; Weigand and Cuellar, 1981).

Most of the cultivated plants are sensitive to low temperatures, showing negative effects on grain yield at around 12°C (Lyons, 1973). Light saturation at lower photosynthetic rates and photoinhibition are commonly observed phenomena at low temperatures (Powles *et al.*, 1983) along with increased chlorophyll 'a' fluorescence (Van Hasselt and Van Berlo, 1980; Greer *et al.*, 1986). Prolonged exposure to light at low temperatures may result in severe and irreversible photoinhibition, followed by chlorophyll destruction from photo-oxidation and finally death of the tissue (Bongi and Long, 1987). The major effect of cold damage is the decrease in rate of photosynthesis. Furthermore, the export of carbon from the leaf decreases and soluble carbohydrates accumulate in the leaf (Pollock *et al.*, 1983; Pollock, 1984).

Research on climate change predicts a marked increase in rainfall and temperature, with temperatures projected to rise by as much as 3–4°C by the end of the century in South Asia (DEFRA, 2005). In majority of the dry environments that presently suffer from severe heat stress during grain filling, it has been shown that the enzyme soluble starch synthase in wheat appears to be rate limiting at temperatures in excess of 20°C (Keeling *et al.*, 1994). Secondly, the grain filling of wheat is seriously impaired by heat stress due to reductions in rate of current leaf and ear photosynthesis at high temperatures (Blum *et al.,* 1994). To predict the effects of changes in mean annual temperature on agricultural crops investigators have used crop-climate simulation models (Rosenzweig and Iglesias, 1994; Pathak *et al.*, 2006; Hundal and Prabhjyot-Kaur, 2007) and experiments (Wheeler *et al.*, 1996a, 1996b; Rehmani *et al.*, 2014). Such efforts have advanced our understanding of the effects of climatic changes on crop production to the extent that we can now predict the implications of climatic change for wheat production with confidence.

To study the effect of temperature in the field is expensive and time consuming, but crop growth simulation models present a suitable alternative for conducting such studies. In the present study a well known CERES-wheat model available in DSSAT v4.5.0.0 (Hoogenboom *et al.*, 2003) was used to simulate the effect of seasonal temperature change on productivity of wheat in major wheat growing regions of India. CERES-Wheat model has been used worldwide by many researches (Hundal and Prabhjyot-Kaur, 1997; Iglesias *et al.*, 2000; Ouda *et al.*, 2005; Pathak *et al.*, 2006) for conducting studies related to different aspects in wheat.

The objectives of the present study were to determine the effect of seasonal temperature change from normal (long term average) on wheat productivity in different zones of India. Secondly, to determine zone wise optimum sowing period so as to mitigate the adverse effects of change in temperature.

Materials and Methods

CERES-wheat model

CERES (Crop Environment Resource Synthesis)-Wheat (Ritchie *et al.,* 1988; Godwin *et al.,* 1989; Singh *et al.,* 1991) is a process-based model which simulates crop growth, development and yield taking into account the effects of weather, genetics, soil and crop management. CERES-Wheat is available to users as part of the DSSAT (Decision Support System for Agrotechnology Transfer), which is a suite of crop models that have a common soil, water and nitrogen component enabling crop rotation simulation and is designed to estimate production, resource use and risks associated with crop production practices (Tsuji *et al.,* 1994 and Jones *et al.,* 1998).

Site description

The study was conducted by using the actual input data from seven (Palampur, Ludhiana, Kanpur, Faizabad, Udaipur, Ranchi and Raipur) wheat growing locations in India. The location, climatic and agro-ecological characteristics of the regions in which the study was conducted are given in the Table 1.

Input data used

The meteorological data required for calculation of normal (long term average) of solar radiation, rainfall, maximum and minimum temperatures were recorded at respective sites. The normal temperature at these locations is presented in figs. 1a and b. The normal temperature was calculated for the different locations by using long term weather data as mentioned in parenthesis after each station *i.e.* Palampur (42 years), Ludhiana (43 years), Kanpur (43 years), Faizabad (22 years), Ranchi (30 years), Raipur (42 years) and Udaipur (31 years). The crop data required for calibration and validation of the model were obtained from the field trials conducted at respective sites. The data related to soil profile was obtained by analyzing the soil samples at the respective sites.

The most popular wheat variety of the respective regions (Table 2) was used for simulation study. During the calibration of the model the genetic coefficients (Table 2) were derived by repeated iterations until a close match between simulated and observed phenology and yield was obtained. While simulation the rate of fertilizer application, irrigation and other management practices were used as recommended by the respective State Agricultural Universities in the regions.

The validation of model is an important step in crop modelling and the parameters/ indexes. The experimental data from the different years which was not used for calibration of the model was used for calculation of these parameters/ indexes and for validation of the model. The DSSAT v 4.5.0.0 has an inbuilt option to calculate these parameters/indexes.

After validation, the calibrated CERES-Wheat model was used to study the effect of change in temperature on wheat productivity. At all the locations a similar set of treatments, i.e., three sowing times (early, normal and late) with a

Table 1. Location and agro-ecological characteristics of the study sites

Location	State	Latitude (˚N)	Longitude (˚E)	Altitude (m)	Annual rainfall (mm)	Mean annual temp (˚C)		Sunshine hours	Agro-ecological characteristics[a]
						Max	Min		
Palampur	Himachal Pradesh	32° 7'	76° 31'	1220	2347	23.41	13.32	2484	Warm humid to per-humid transitional ESR with shallow to medium deep loamy brown forest and podzolic soils, low to medium AWC and LGP 270-300 days
Ludhiana	Punjab	30°56'	75°52'	247	765	29.81	16.61	2948	Hot semi-arid eco-sub region (ESR) with deep loamy alluvium-derived soils, medium available water capacity (AWC) and length of growing period (LGP) 90–120 days
Kanpur	Uttar Pradesh	26 º 29'	80 º 18'	125.9	876	31.48	18.61	2242	Hot moist semi-arid ESR with deep, loamy alluvium-derived soils, medium to high AWC and LGP 120–150 days
Faizabad	Uttar Pradesh	26° 47'	82° 12'	104	824	33.72	19.35	2605	Hot dry sub humid ESR with deep loamy alluvium-derived soils, medium to high AWC and LGP 150–180 days
Udaipur	Rajasthan	24º35'	73º42'	582.5	624	31.10	16.57	2945	Hot dry semi-arid ESR with deep loamy gray brown and alluvium derived soils, medium AWC and LGP 90 -120 days
Ranchi	Jharkhand	23°23'	85°23'	651	1394	28.56	16.49	2568	Chota Nagpur plateau and Garjat hills, hot dry-sub humid ESR with moderately deep to deep, loamy to clayey, red and lateritic soils, medium AWC and LGP 150-180 days
Raipur	Chhattisgarh	21º 15'	81º 41'	317	1203	32.69	19.78	2489	Moderately to gently sloping Chhattisgarh/ Mahanadi basin, hot moist/dry sub-humid transitional ESR with deep loamy to clayey red and yellow soils, medium AWC , LGP 150-180 days

[a]Mandal *et al*. (1999)

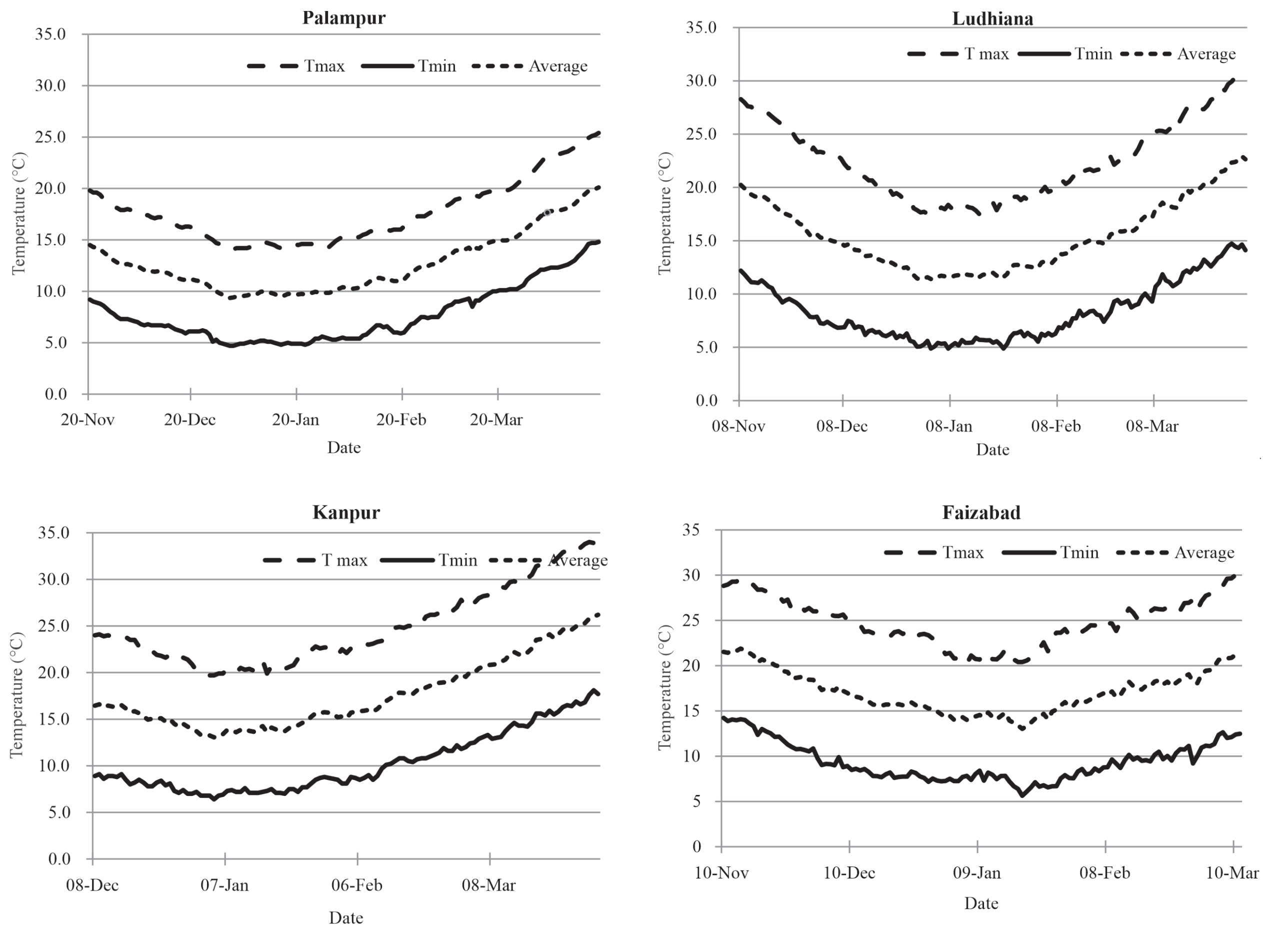

Fig. 1a. Normal temperature during growing period of timely sown wheat for different study locations

Table 2. Location wise wheat varieties used and their genetic coefficients

Location	Variety	Genetic coefficients*						
		P_1V	P_1D	P_5	PHINT	G_1	G_2	G_3
Palampur	VL 829	35	70	515	25	46	3.0	70
Ludhiana	PBW 343	30	55	515	16	38	3.2	110
Kanpur	HD 2733	20	40	500	25	38	3.2	100
Faizabad	HUW 234	24	50	512	20	38	3.2	120
Udaipur	Raj 4037	30	55	515	20	44	3.2	100
Ranchi	K9107	0	50	515	30	20	1.0	100
Raipur	Kanchan	24	50	512	30	45	3.2	100

*P1V: Days, optimum vernalizing temperature, required for vernalization
P1D: Photoperiod response (per cent reduction in rate/10 h drop in pp)
P5: Grain filling (excluding lag) phase duration (^{o}C.d)
G1: Kernel number per unit canopy weight at anthesis (#/g)
G2: Standard kernel size under optimum conditions (mg)
G3: Standard, non-stressed mature tiller weight (including grain) (g dwt)
PHINT: Interval between successive leaf tip appearances (^{o}C.d)

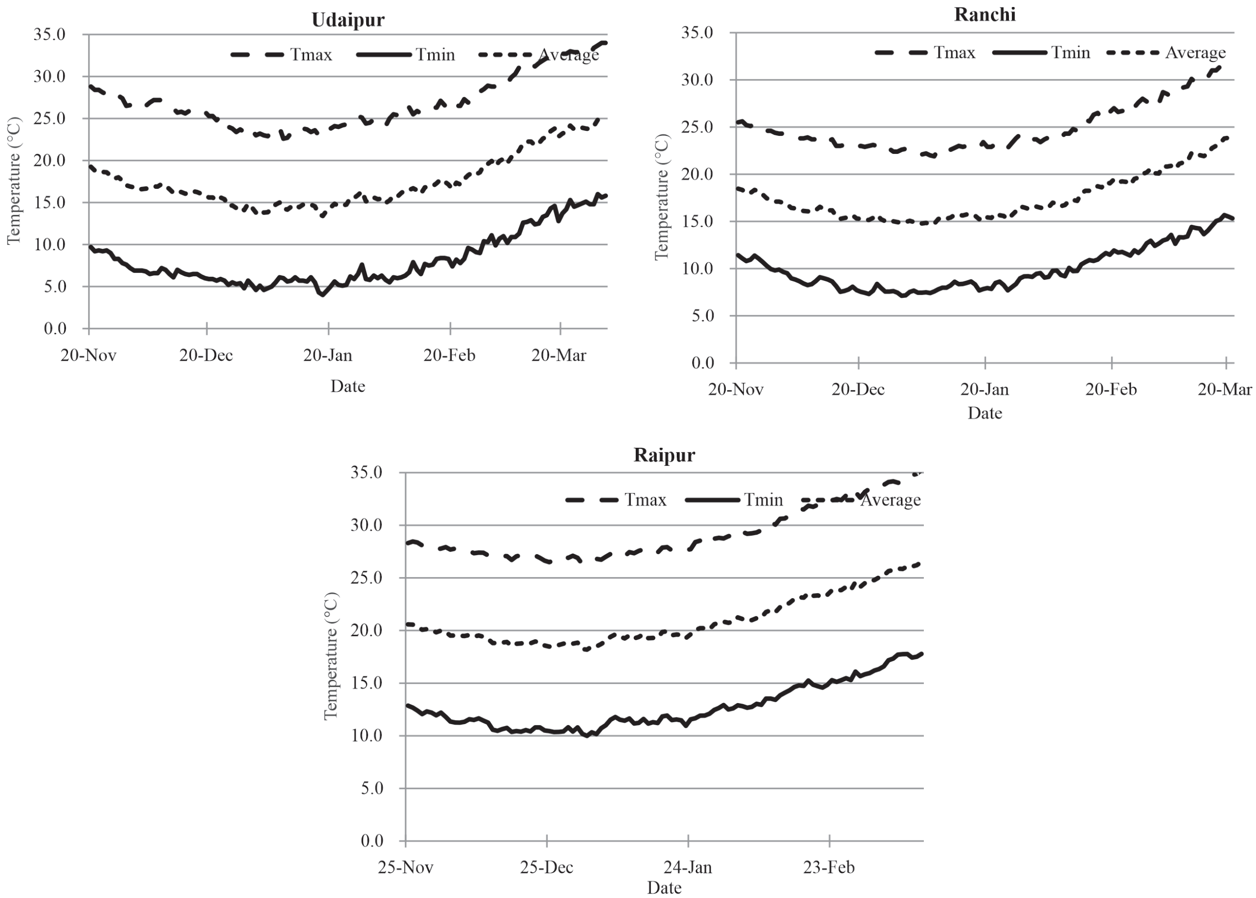

Fig. 1b. Normal temperature during growing period of timely sown wheat for different study locations

difference of 15 days amongst them were selected (Table 3). The normal date of sowing for each location was selected based on the experience of scientists working at respective locations. The three dates were selected so as to determine the least vulnerable date to change in temperature. The model was used to simulate normal productivity of wheat using normal weather data along with soil and crop data of the respective locations. Twelve temperature change scenarios (increase and decrease from normal) were created in the model while using environment modification option available in the model. The temperature was increased/ decreased by 0.5°C leading upto a normal +3.0°C temperature scenarios and the change in temperature was applied throughout the crop growing season. The model output under changed temperature scenarios in terms of wheat yield was used to calculate per cent deviation in wheat productivity from respective normal yield (simulated wheat yield while using normal weather data) for the respective time of sowing.

Table 3. Location wise dates of sowing used for simulating the change in wheat productivity due to seasonal change in temperature

Location	Dates of sowing		
	Early sown	Normal sown	Late sown
Palampur	5-Nov	20-Nov	5-Dec
Ludhiana	25-Oct	8-Nov	22-Nov
Kanpur	23.Nov	08.Dec	23.Dec
Faizabad	10-Nov	25-Nov	10-Dec
Udaipur	5-Nov	20-Nov	5-Dec
Ranchi	20-Nov	5-Dec	20-Dec
Raipur	10-Nov	25-Nov	10-Dec

Results and Discussion

Validation of CERES-Wheat model

The model was validated across seven wheat growing locations in India. The perusal of the data showed that the phenology matches quite well (Table 4). The r^2 value was also acceptable and in some case was one or near to one. The NRMSE values at all the locations for days taken for anthesis and maturity, were in excellent range (<10 per cent) as suggested by Jamieson *et al.* (1991). They reported that, the simulation is considered excellent, good, fair and poor if NRMSE is less than 10, 10-20, 20-30 and more than 30 per cent, respectively. The d-Stat in most of the cases was above 0.62 and in some cases it was even near to one.

In the present study, the grain yield was also simulated quite well and the difference between observed and simulated values was in the range of -498 to +754 kg ha^{-1}. The values of r^2 were quite acceptable except in case of Palampur where it was 0.28. However, in most of cases it was above 0.73 and was one or near one in some of the cases. The values of NRMSE for most of the locations were in the good range as proposed by Jamieson *et al.* (1991). The value of d-Stat was quite acceptable and was above 0.60 at all the locations except at Faizabad where it was 0.54.

Simulation with CERES-wheat model under different temperature regimes

The per cent deviations of early, normal and timely sown wheat productivity due to seasonal temperature change (increase / decrease) from normal temperature are presented in fig. 2.

Northern hill zone

In the early sown crop, the increase in temperature by 0.5-3.0°C from normal may reduce the productivity of wheat by 2.76 to 9.14 per cent. The productivity of early sown crop was increased with a decrease in temperature within the range of -1.0 to -2.0°C; however, further decrease in temperature negatively affected its productivity. The productivity of timely sown crop was negatively affected if the temperatures were increased as well as decreased from normal. The productivity of late sown crop was reduced if the temperature was reduced from normal. In this zone, the productivity of late sown wheat was favored by the rise in temperature.

In this zone, during the wheat season the normal maximum and minimum temperatures are within the range of 14-25 and 5-15°C, respectively. The air temperature within the range of 20-25°C are considered to be optimum for wheat growth and development (Acevedo *et al*., 2002). Hence the late sown wheat crop was favored by increase in temperature from normal. Under anticipated rise in temperature the sowing of wheat crop after 20th November may prove beneficial for wheat growers in this zone.

North Western plain zone

In this zone (Ludhiana) the productivity of early sown crop was reduced by 4.28, 8.94, 12.38, 16.60, 19.61 and 24.12 per cent with an increase in temperature of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0°C, respectively. The early sown crop was benefited with a reduction in temperature at Ludhiana. The productivity of timely sown crop at Ludhiana decreased by 2.69 to 13.96 per cent by a temperature rise of 0.5 to 3.0°C. In case of late sown wheat, the increase in temperature by 0.5 to 3.0°C from normal at Ludhiana resulted in an increase in productivity by 1.46-6.55 per cent. The reason for increase in productivity of late sown wheat in response to increase in temperature might be due to the reason that in case of late sowing average temperature on 22 November (date of late sowing) was 17.4°C and dropped further to 15.5°C on seventh day of sowing. Although, these temperatures were within the optimum limit (12 to 25°C) suggested by Evans *et al*. (1975) but were towards the lower side, he further suggested that delays in germination adversely affect crop establishment, when temperature is typically low. Therefore, any increase in temperature within this range will enhance the germination and establishment of wheat as suggested by many other studies. Timmermans *et al*. (2007) found that low

Table 4. Validation of CERES-Wheat V4.5 for various wheat growing locations*

Variable Name	Mean		Std. Dev.		r-Square	Mean Diff.	Mean Abs. Diff.	RMSE	NRMSE (%)	d-Stat.	No. of Obs.
	Observed	Simulated	Observed	Simulated							
Northern hill zone (Palampur)											
Anthesis (DAS)	130	124	14.24	11.97	0.84	-6	7	7.79	5.99	0.91	4
Yield (kg/ha)	3284	3086	586.03	421.94	0.28	-198	501	548.73	16.71	0.65	4
Maturity (DAS)	148	151	12.09	11.30	1.00	+3	3	2.96	2.00	0.98	4
North Western plain zone (Ludhiana)											
Anthesis (DAS)	113	117	4.63	4.93	0.62	+4	4	4.95	4.38	0.77	12
Yield (kg/ha)	3971	4407	457.26	724.91	0.73	+436	450	599.03	15.09	0.77	12
Maturity (DAS)	146	146	5.93	6.56	0.54	0	4	4.64	3.18	0.85	12
North Eastern plain zone (Kanpur)											
Anthesis (DAS)	85	88	1.63	4.90	1.00	+3	3	4.43	5.21	0.62	3
Yield (kg/ha)	4817	5571	658.09	479.88	0.99	+754	754	776.90	16.13	0.70	3
Maturity (DAS)	114	114	4.92	6.53	0.99	0	2	1.73	1.52	0.98	3
North Eastern plain zone (Faizabad)											
Anthesis (DAS)	78	92	13.88	4.90	1.00	+14	14	16.63	21.32	0.62	3
Yield (kg/ha)	3872	3374	216.72	387.83	0.97	-498	498	528.63	13.65	0.54	3
Maturity (DAS)	122	120	8.65	6.13	0.99	-3	3	3.74	3.07	0.94	3
North Eastern plain zone (Ranchi)											
Anthesis (DAS)	85	88	4.80	3.54	0.61	+3	4	4.16	4.89	0.78	9
Yield (kg/ha)	4058	4196	549.51	477.06	0.54	+137	324	404.71	9.97	0.84	9
Maturity (DAS)	122	117	6.27	5.37	0.75	-5	5	5.81	4.76	0.80	9
Central zone (Raipur)											
Anthesis (DAS)	81	83	2.16	0.94	0.11	+2	2	2.65	3.27	0.49	3
Yield (kg/ha)	3520	3800	198.83	420.06	1.00	+279	279	356.43	10.13	0.72	3
Maturity (DAS)	109	108	4.03	1.70	0.98	0	2	2.38	2.18	0.83	3
Central zone (Udaipur)											
Anthesis (DAS)	78	80	4.72	4.24	0.69	+2	3	3.41	4.37	0.86	8
Yield (kg/ha)	5751	6132	1188.45	1108.69	0.79	+381	524	663.36	11.53	0.91	8
Maturity (DAS)	116	111	8.98	5.88	0.67	-6	6	7.68	6.62	0.76	8

*The zones were decided on the basis of information available at http://agropedia.iitk.ac.in/content/wheat-growing-zones-india

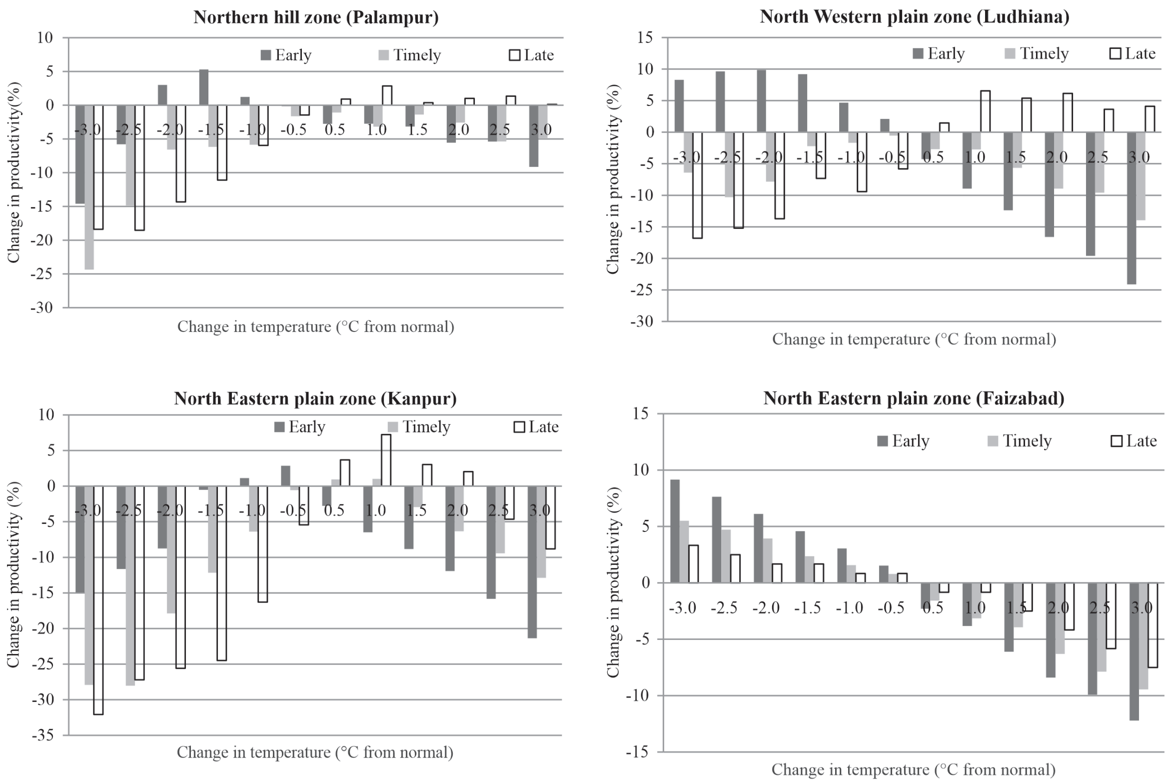

Fig. 2. Effect of seasonal temperature change on productivity of wheat sown on different dates at various locations

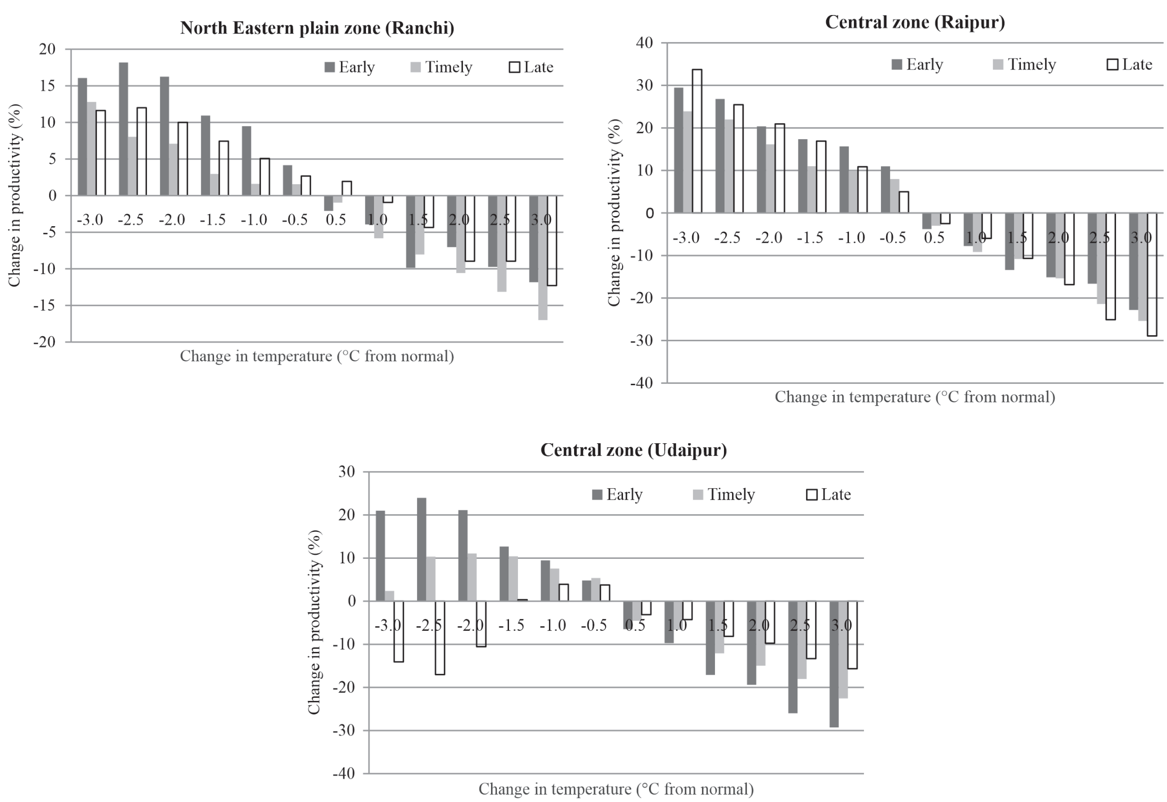

Fig. 3. Effect of seasonal temperature change on productivity of wheat sown on different dates at various locations

temperature (< 12°C) applied during germination and seedling emergence in *Solanum sisymbriifolium* and spring wheat (Hossain *et al*., 2011; Hakim *et al*., 2012; Hossain *et al*., 2012) resulted in poor and uneven emergence. Chakrabarti *et al*. (2011) and Hakim *et al*. (2012) also found that air temperature < 15°C was not suitable for the growth and development (germination, seedling stand establishment and tillering) of spring wheat. Nahar *et al*. (2010) also found that low temperature increases days by taken for germination. The results of simulation study indicated that decrease in temperature at Ludhiana reduced the productivity of late sown wheat.

Amongst the different dates of sowing in this zone, the early sown wheat was most susceptible to reduction in productivity with an increase in temperature. In this zone, under the anticipated increase in temperature predicted by various GCMs shift in sowing of wheat crop from normal sowing window to late sowing window (at Ludhiana after 3rd week of November) may prove beneficial to combat the adverse effect of rise in temperature on wheat productivity in the zone.

North Eastern plain zone

This zone included 3 locations viz. Kanpur, Faizabad and Ranchi. In this zone, at Faizabad and Ranchi, the productivity of wheat sown on any date was reduced with rise in temperature above normal. At Ranchi the normal maximum and minimum temperatures during wheat growing period are within the range of 22-32°C and 8-16°C, respectively. As these temperature ranges are towards higher limits of optimum temperature for wheat crop so an increase in temperature decreases the wheat yield for early, normal and late sown wheat crop. However, at Kanpur reduction in productivity was noticed in early sown wheat with temperature rise above normal and in case of timely sown crop beyond 1.0°C and beyond 2.0°C for late sown crop. The reduction in temperature was beneficial to crop sown on any time at Faizabad and Ranchi. However, at Kanpur in case of timely sown crop, a fall in temperature upto 1.0°C from normal was beneficial, but a further reduction in temperature upto 3.0°C negatively affected its productivity and in case of timely and late sown crop the productivity was reduced by reduction in temperature. Amongst the different dates of sowing, the early sown wheat was most susceptible to reduction in productivity with an increase in temperature at Kanpur and Faizabad, however, timely sown crop was most susceptible in case of Ranchi. Among locations the reduction in productivity of late sown wheat at Faizabad with an increase in temperature was less as compared to Kanpur and Ranchi and other times of sowing. On a whole productivity of wheat at Faizabad was less susceptible to the change in temperature as compared to other locations within this zone.

In this zone, under the anticipated increase in temperature predicted by various GCMs shift in sowing of wheat crop from normal sowing window to late sowing window (at Kanpur after 3rd week of December and at Faizabad after 1st week of December) and to early sowing (3rd week of November) at Ranchi may prove beneficial to combat the adverse effect of rise in temperature on wheat productivity in the zone.

Central plain zone

This zone contained two locations viz, Udaipur and Raipur. In this zone, the productivity of wheat sown at all the sowing times was reduced with an increase in temperature from normal and the maximum reduction was in case of early sown wheat at Udaipur and in late sown at Raipur. A reduction in temperature led to an increase in productivity of early and timely sown wheat at Udaipur, however, at Raipur all the sowing times were benefitted by reduction in temperature. At Udaipur the productivity of late sown crop was increased with a decrease in temperature upto 1.5°C from normal, but further decrease in temperature caused a reduction in productivity. In this zone, the productivity of early and late sown wheat at Udaipur and Raipur, respectively, were most susceptible to both increase and decrease in temperature. However, the late and early sown wheat at Udaipur and

Raipur respectively, were least susceptible, to increase in temperature as compared to other times of sowing. Hence, under anticipated rise in temperature the late sowing at Udaipur and early sowing at Raipur may help in reducing the harmful effects of high temperature on wheat productivity.

At Udaipur the normal maximum and minimum temperatures during wheat growing season are in the range of 22 to 34°C and 4 to 16°C respectively. These ranges are towards the higher side of the optimum temperature ranges for wheat production. At Raipur the normal maximum and minimum temperature during wheat growing season are within the range of 27-35°C and 10-18°C, respectively and these temperatures are more than the optimum range for wheat crop. Therefore, this zone is one of the most susceptible zones vulnerable to negative impacts of rise in temperature on wheat production. The study also showed that this zone is most susceptible to change in temperature as compared to rest of the zones. The magnitude of change in productivity as compared to other location is higher in this zone when compared with corresponding increase in temperature.

The results of simulation study involving seasonal temperature change revealed that the similar change in temperature did not affect the wheat productivity in the similar manner in all the zones under study and the effects also vary within the zones. Secondly, the effect of temperature change also varied with the different sowing periods. The increase in temperature by 3.0°C from normal at all locations reduced the productivity of wheat sown on any time, except for late sown crop at Palampur (Northern hill zone) and Ludhiana (North western plains zone). In the present study, late sown wheat at all locations was having lower productivity as compared to timely and early sown wheat. The increases in productivity of late sown wheat with increase in temperature depicts the per cent change in productivity of late sown wheat under elevated temperature compared to that under normal temperature conditions. It does not means that high temperature in case of late sown wheat resulted in productivity higher than timely or early sown wheat. The per cent reduction in productivity was less in the Northern hill zone as compared to the rest of the zones because the normal temperatures are lower in this region as compared to remaining areas. The increase in temperature affects the crop right from sowing, seedling mortality and crop establishment, are major problems when soil temperatures are high. Plant emergence and population establishment are the starting points of crop growth and good yield. Acevedo *et al*. (1991) showed the average number of plants established in a nursery of bread wheat genotypes planted at increasing soil temperatures in the field decreased with increasing temperature. The cardinal temperature for germination of wheat seed are minimum (3-4.5°C), optimum (25°C) and maximum (30-32°C) as reported by Bierhuizen, (1973). The increased temperature scenarios may have reduced the plant stand which may have contributed to reduced productivity. Similar to our results Asseng *et al.* (2011) found that a variations in average growing-season temperatures of ±2°C in the main wheat growing regions of Australia can cause reductions in grain production up to 50 per cent and most of this can be attributed to increased leaf senescence as a result of temperatures >34°C. These conditions are quite similar to the temperature conditions experienced by wheat in northern India and reported by Lobell *et al.* (2012). They used nine years of satellite measurements of wheat growth in northern India to monitor the rates of wheat senescence following exposure to temperatures greater than 34°C and found a statistically significant acceleration of senescence from extreme heat. In the present study, at some places the increased temperature scenario was also near or above 34°C. Secondly, the optimum temperature for growth and yield of wheat is about 18-24°C, even short periods (4-6 days) of very high temperature (35-40°C) significantly decreases grain yield (Stone and Nicolas, 1994, 1995). In many parts of wheat growing areas of India, wheat crop experiences 35°C during grain development and thus results in low productivity. Lobell *et al.* (2008) had also estimated yield losses of 3–17 per cent for each degree rise in temperature in northwest India and

Pakistan. Prasad and Djanaguiraman, (2013) reported that mean daily high temperatures >30°C for short periods (5 days), when imposed from start of heading, caused a linear decrease in grain number and when the stress was imposed after seed-set, it caused a quadratic decrease in grain weight. High nighttime temperatures >20°C during the reproductive phase decreased grain filling duration and grain weight.

A decrease in temperature by 3.0°C from normal resulted in a maximum reduction in wheat productivity at Kanpur (all dates of sowing) followed by at Palampur (all dates of sowing), Ludhiana (late sown) and Udaipur (late sown). However, it had a positive effect at Ludhiana (early sown) and Udaipur (early and timely sown) and for all dates at Faizabad, Ranchi and Raipur. The reduction in productivity with reduction in temperature may be due to light saturation at lower photosynthetic rates and photoinhibition which are commonly observed phenomena at low temperatures (Powles *et al*., 1983). This might be the reason for low productivity in response to decreased temperature at location having low temperature like Palampur and Ludhiana. Secondly, during the vegetative period, cold stress usually disturbs the balance between the energy source and the metabolic sink thereby reducing the photosynthesis rate and reduced green leaf area (Allen and Ort, 2001; Paul and Foyer, 2001). The reduction in photosynthesis rate and green leaf area will lead to reduced biomass accumulation and as a result grain yield also get reduced (Subedi *et al*., 1998). Leonardos *et al*. (2003) also found that cold stress at the seedling stage of wheat reduced the photosynthetic rate. This might have resulted in reduced dry matter accumulation and hence grain yield. The response to change in temperature at Ranchi and Raipur were similar but the magnitudes of effects were much higher at Raipur. Among the three times of sowing at all the locations except at Raipur, the late sown crop was benefited or remained less affected in terms of per cent deviation in productivity in response to increase in temperature. At Raipur, the early sown crop was less affected as compared to timely and late sown crops.

Conclusions

The simulation study on seasonal temperature change from normal indicated that the change in temperature had different effects on wheat productivity in different zones and the effects also varied with the time of sowing of the crop. The seasonal increase in temperature resulted in a reduction in productivity of wheat at all location except for late sown wheat at Palampur and Ludhiana. The productivity of late sown wheat at these locations increased with an increase in temperature. The decrease in temperature resulted in a reduction in productivity of wheat sown on all the times of sowing under study at Palampur and Kanpur and at Ludhiana the reduction in productivity was in case of timely and late sown wheat and at Udaipur for late sown wheat. At rest of locations and dates of sowing the productivity increased in response to decrease in temperature. The productivity of early sown wheat at Ranchi and Raipur and that of late sown wheat at rest of the locations was less affected by seasonal increase in temperature as compared to other times of sowing. The wheat productivity at Raipur (Central zone) was most susceptible to change in temperature as compared to rest of the zones. The results of the simulation study also revealed that a shift in sowing period of wheat may have to be undertaken to combat the adverse affects of anticipated rise in temperature. At all the locations, except at Raipur the wheat crop sown 15 days late than the present sowing time will perform better under enhanced temperature conditions. Whereas, at Raipur sowing has to done 15 days early so as to reduce the impact of high temperature on wheat productivity.

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