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Effect of intra-seasonal temperature on wheat at different locations of India: A study using CERES-Wheat model

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ABSTRACT

CERES-Wheat model (DSSAT v 4.5.0.0) was used to analyze the effects of rise in intra-seasonal temperature on productivity of wheat and to optimize sowing time for mitigating the effects of rise in intra-seasonal temperature at seven wheat growing locations representing different zones of India. The results showed that the temperature rise had differential effect on wheat yield in different zones and also with dates of sowing. Central zone(Udaipur and Raipur) was the most susceptible (yield reduced upto 10.2%) to the rise in temperature by 3.0˚C from normal. The Northern hills (Palampur) zone was least susceptible. At Palampur, wheat yield increased upto 4.07% with rise in temperature by 3.0˚C from normal during early phases of crop growth while during later phases of crop growth the yield decrease was 3.46-5.79%. The temperature during first fortnight of February was most critical to wheat productivity. However in Northern hills zone, second fortnight of March was most critical as during this period the above normal temperature caused a reduction in productivity of wheat.

Keywords : Heat stress, temperature, CERES-wheat model, simulation, zones.

Wheat (*Triticumaestivum* L.) is the second main source of world's food energy and nutrition. It supplied about 19 and 21% of the total calories and proteins, respectively, required by the world's population (Anonymous, 2011). Although, wheat can be grown in a wide range of climatic conditions but many abiotic and biotic factors limits its yield. Most of the wheat growing areas of the world experience above optimum temperatures at some point in their life cycle and have a large negative impact on productivity. Continual heat stress affects nearly 7 million hectares of wheat in developing countries, whereas terminal heat stress is a problem in 40% of the temperate world that encompasses 36 million hectares (Reynolds *et al.,* 2001). During March 2004, temperatures were higher in the Indo–Gangetic plains by 3-6ºC and as a result, the wheat crop matured earlier by 10-20 days and wheat production dropped by more than 4 million tonnes in the country (Aggarwal, 2008).

The objectives of the present study was first to investigate the effect of rise in intra-seasonal temperature on wheat productivity in different wheat growing zones of India. Secondly, to identify the most critical phases of crop growth during which the above normal temperature causes maximum damage. Thirdly, to identify the optimum sowing time as mitigation strategy against above normal temperature.

MATERIALS AND METHODS

The wheat yield and meteorological data of seven major wheat growing locations were collected from respective station (Table 1). It may be seen that there was large spatial variation in maximum and minimum temperatures across the locations (Fig. 1).

The CERES-Wheat model was calibrated using the field experimental data for the most popular wheat variety (Table 2) using the recommended crop management practices

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

Wheat Growing Zone[a]	Location and State	Lat.(N)	Long.(E)	Altitude (m)	Annual rainfall (mm)	Mean annual temp (°C) Max	Min	Agro-ecological characteristics[b]
Northern hill zone	Palampur, Himachal Pradesh	32° 7'	76°31'	1220	2347	23.4	13.3	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
North western plains zone	Ludhiana, Punjab	30°56′	75°52′	247	753	29.8	16.6	Hot semi-arid eco-sub zone (ESR) with deep loamy alluvium-derived soils, medium available water capacity (AWC) and length of growing period (LGP) 90 –120 days
North eastern plains zone	Kanpur, Uttar Pradesh	26º29'	80º18'	125.9	876	31.5	18.6	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	33.7	19.4	Hot dry sub humid ESR with deep loamy alluvium-derived soils, medium to high AWC and LGP 150–180 days
	Ranchi, Jharkhand	23°23'	85°23'	651	1394	28.6	16.5	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
Central zone	Raipur, Chattisgarh	21º15'	81º41'	317	1203	32.7	19.8	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
	Udaipur, Rajasthan	24º35'	73º42'	582.5	624	31.1	16.6	Hot dry semi-arid ESR with deep loamy gray brown and alluvium derived soils, medium AWC and LGP 90 -120 days

[a]Wheat& Barley Growing Zones, cited from http://www.dwr.in/ on 28-7-2016.

[b]Mandal *et al.,* (1999)

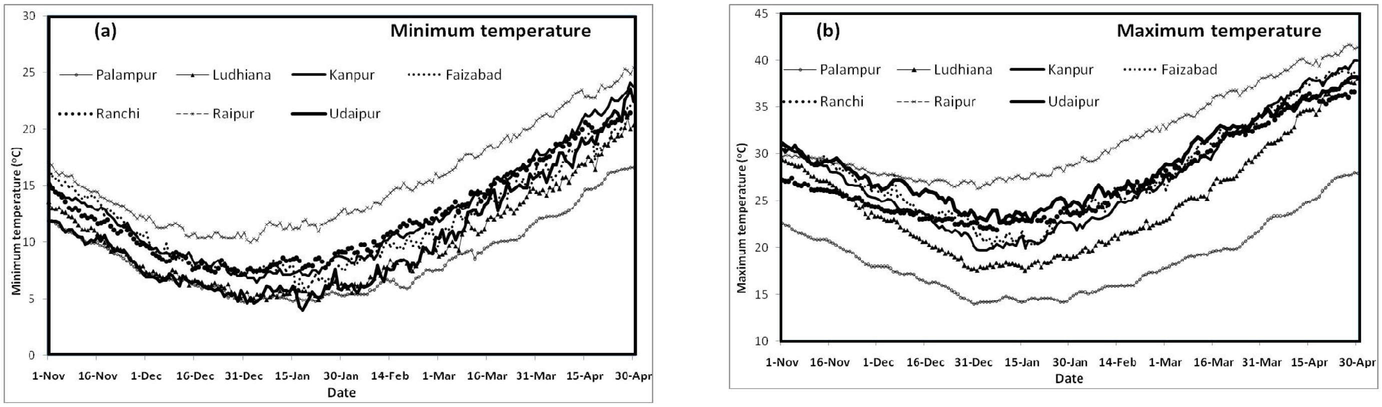

Fig. 1:Normal(a) minimum and (b) maximum temperatures during growing period of wheat at different locations

Table 2: Location wise 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 (% reduction in rate/ 10 h drop in pp); P5: Grain filling (excluding lag) phase duration (˚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 (˚C.d)

for the respective stations.The genotypic coefficients were derived by repeated iterations until a close match between simulated and observed phenology and yield was obtained. The performance of the model was validated with the experimental data from the years which were not used for calibration of the model and was used for calculation of these parameters/ indices and for validation of the model.

The statistical measures such as the root mean square error (RMSE) and normalized root mean square error (NRMSE) were calculated following Jamieson *et al.,* (1991).The d-stat or index of agreement (D-index) was estimated following Willmott *et al.,*(1981).

After validation, the CERES-Wheat model was used as a research tool to study the effect of rise in intra-seasonal temperature on wheat productivity. At all the locations a similar set of treatments, i.e., three dates of sowing (early, normal and late) with a difference of 15 days were selected. The normal date of sowing corresponds to the time when most of the farmers undertake sowing of wheat crop at the respective locations. The model was used to simulate normal yield using normal weather data along with soil and crop data of the respective locations. Above normal temperature scenarios were created by increasing both maximum and minimum temperatures from normal in the increments of 1.0˚C up to 3.0˚C. The temperature was increased for 15 days duration, keeping the normal temperature during rest of the crop growth period. The increase in temperature was imposed at fortnightly intervals between 1st December to 30th April. The model output in terms of wheat yield was used to calculate per cent deviation in wheat productivity from the respective time of sowing under different above normal temperature scenarios.

RESULTS AND DISCUSSION

Validation of the CERES-Wheat model

The results (Table 3) shows that the phenological

Table 3: Validation of CERES-Wheat V4.5 for various wheat growing locations

Variable Name	Mean		Std. Dev.		r-Square	Mean	Mean	RMSE	NRMSE	d-Stat.	No. of
	Observed	Simulated	Observed	Simulated		Diff.	Abs. Diff.		(%)		Obs.
Palampur											
Anthesis (DAS)	130	124	14.24	11.97	0.84	-6	7	7.79	5.99	0.91	4
Yield ($kgha^{-1}$)	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
Ludhiana											
Anthesis (DAS)	113	117	4.63	4.93	0.62	+4	4	4.95	4.38	0.77	12
Yield ($kgha^{-1}$)	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
Kanpur											
Anthesis (DAS)	85	88	1.63	4.90	1.00	+3	3	4.43	5.21	0.62	3
Yield ($kgha^{-1}$)	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
Faizabad											
Anthesis (DAS)	78	92	13.88	4.90	1.00	+14	14	16.63	21.32	0.62	3
Yield ($kgha^{-1}$)	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
Ranchi											
Anthesis (DAS)	85	88	4.80	3.54	0.61	+3	4	4.16	4.89	0.78	9
Yield ($kgha^{-1}$)	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
Raipur											
Anthesis (DAS)	81	83	2.16	0.94	0.11	+2	2	2.65	3.27	0.49	3
Yield ($kgha^{-1}$)	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
Udaipur											
Anthesis (DAS)	78	80	4.72	4.24	0.69	+2	3	3.41	4.37	0.86	8
Yield ($kgha^{-1}$)	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

events matched quite well. The difference between observed and simulated days taken for anthesis at various locations varied from -6 to +4 days, except at Faizabad. Similarly, the difference in observed and simulated days taken for maturity was -6 to +3 days. The r^2 and d-statvalueswere acceptable. The NRMSE values at all the locations for days taken for anthesis and maturity, were in excellent range (<10%) as proposed by Jamieson *et al.,* (1991). The grain yield for wheat crop was simulated quite satisfactorily and the differences between observed and simulated values were in the range of -498 to +754 kg ha^{-1}. The values of r^2 was above 0.73 and was nearly one for some places except Palampur (r^2=0.28). The value of d-Stat was quite acceptable and was above 0.60 at all the locations.The validation results showed that the model calibration was quite satisfactory and may be used for further applications.

Effect of temperature rise on wheat yield

The calibrated model was used to study the effect of rise in intra-seasonal temperature and the results are presented in the following sections.

Northern hills zone : At Palampur, representing northern hill zone, the rise in temperature by 1.0°C from normal was harmful during mid January to end March for early, mid February to end March for timely sown wheat and mid January to mid April for late sown wheat (Table 4). Temperature rise during January to mid February was beneficial for the timely sown wheat. In this zone the timely sown crop was benefited / less affected due to rise in temperature as compared to other sowing.

The rise in temperature by 2.0°C from normal during February and March, second fortnight of March and mid February to mid April in case of early, timely and late sown wheat, respectively, reduced its productivity (Table 5). The rise in temperature during January to mid March for the timely sown and during January to mid February for late sown wheat increased their productivity. In this zone, with a rise in temperature by 2.0°C from normal, the productivity of timely sown wheat was more benefited while that of late sown wheat was less adversely affected.

The rise in temperature by 3.0°C from normal was harmful during second fortnight of January and March in case of early sown, second fortnight of March in timely sown and mid March to mid April in case of late sown wheat (Table 6). The increase in temperature during January to mid March increased the yield of the timely and late sown wheat. The temperature rise by 3.0°C in case of late sown wheat during initial stages proved beneficial, but that towards end proved harmful for productivity of wheat, however, timely sown wheat remained less affected by the rise in temperature.

North western plain zone : At Ludhiana, representing north western plain zone, the rise in temperature by 1.0°C form normalduring January to February, mid January to mid March and from February to mid March in case of early, timely and late sown wheat, respectively, led to reduction in wheat yield (Table 4). However, temperature rise by 1.0°C during December to January was beneficial (1.8-5.2%) for late sown crop. In North Western plain zone the productivity of late sown wheat was increased/less affected due to increase in temperature by 1.0°C from normal.

The rise in temperature by 2.0°C from normal during January and February in early sown, mid January to mid March in timely sown and February to midMarch in late sown wheat, decreased the productivity by 2.93-5.68% (Table 5). However, a rise of 2.0°C during 16-31 December for timely sown and during December to January for late sown led to an increase in productivity. In this zone, the productivity of late sown wheat was less affected by a rise of 2.0°C from normal temperature.

The rise in temperature by 3.0°C from normal during December to end February, mid January to mid March and February to end March reduced the yield of early, timely and late sown wheat, respectively (Table 6). However, temperature rise of 3.0°C during December to mid January for timely sown crop and during December to end January for late sown crop was beneficial. In this zone, the late sown wheat was benefited by the rise in temperature during early phases and was adversely affected during later phases of crop growth.

North eastern plain zone : Kanpur, Faizabad and Ranchi were the three stations under this zone. At Kanpur, the temperature increase by 1.0°C from normal during mid January to end February for early, 1-15 December and mid January to end February for timely and from February to mid March for late sown wheat led to reduction in wheat productivity(Table 4). However, temperature rise during December to mid January for timely, mid December to mid January for timelyand mid December to end January for late sown crop was beneficial.At Faizabad, temperature rise by 1.0°C from normalduring January in case of early, first fortnight of December and January and whole of February in case of timely and duringsecond fortnight of December and February in case of late sown wheat led to a reduction in its productivity.At Ranchi, the rise in temperature

Table 4: Effect of temperature increase by 1.0°C from normal during different periods on grain yield of wheat at various locations

Time of sowing	Date of sowing	Dec1-15	Dec16-31	Jan1-15	Jan16-31	Feb1-14	Feb 15-28	Mar 1-15	Mar16-31
Palampur									
Early	Nov. 5	0.00	0.00	0.27	-1.41	-0.58	-0.46	-1.76	-2.91
Timely	Nov. 20	0.00	0.00	0.40	2.40	3.18	-0.32	-0.67	-2.72
Late	Dec. 5	0.00	0.00	1.29	-0.19	-1.16	-0.42	-0.57	-0.44
Ludhiana									
Early	25-Oct	-1.75	0.16	-1.93	-4.06	-2.15	-2.33	0.00	0.00
Timely	8-Nov	0.52	0.69	0.43	-1.64	-2.17	-2.58	-2.60	0.00
Late	22-Nov	2.11	5.24	1.85	2.26	-1.29	-2.34	-2.78	-0.03
Kanpur									
Early	23.Nov.	1.81	1.38	1.43	-2.45	-3.05	-2.97	0.00	0.00
Timely	08.Dec.	-2.69	3.01	5.54	-1.53	-4.03	-2.90	0.05	0.00
Late	23.Dec.	0.00	0.56	6.54	1.92	-2.43	-3.39	-4.36	0.00
Faizabad									
Early	10-Nov	1.09	0.00	-0.82	-1.46	-0.09	-0.03	0.00	0.00
Timely	25-Nov	-0.89	0.00	-1.29	0.52	-1.35	-2.29	-0.06	0.00
Late	10-Dec	0.30	-3.01	1.77	-0.06	-0.06	-1.65	-0.18	0.00
Ranchi									
Early	20-Nov	2.17	2.71	0.91	-1.54	0.09	0.00	0.00	0.00
Timely	5-Dec	-2.28	-0.63	-1.53	-0.06	-2.62	-2.77	-0.03	-0.03
Late	20-Dec	0.00	3.65	1.61	1.05	-2.70	-3.42	-3.26	0.00
Raipur									
Early	10-Nov	-3.07	-1.48	-1.60	-1.66	-1.72	-0.90	-0.03	0.00
Timely	25-Nov	0.00	-1.32	-1.24	-1.24	-0.98	-0.70	-2.79	-0.11
Late	10-Dec	0.00	-2.05	-2.02	-1.95	-0.36	-1.19	-2.28	-2.05
Udaipur									
Early	5-Nov	-1.75	-2.22	-3.68	-2.90	0.00	0.00	0.00	0.00
Timely	20-Nov	-1.00	-0.73	-1.06	-3.71	-3.08	-0.01	0.00	0.00
Late	5-Dec	2.49	0.24	-0.59	-0.09	-2.21	-2.84	-0.01	0.00

by 1.0°C from normal, during December to March for timely sown and February to mid March for late sown wheat reduced its yield. However, wheat yield was increased with rise in temperature during December to mid Januaryandmid Decemberto end January in early and late sown wheat, respectively. In this zone the late, early and early sown crop at Kanpur, Faizabad and Ranchi, respectively, will be benefited/ less affected due to rise in temperature by 1.0°C than normal.

The temperature rise by 2.0°C form normal during second fortnight of December and during mid January to end February in early sown crop and from February to mid March for timely and late sown wheat led to yield reduction (1.0-5.78%) (Table 5). However, the rise in temperature during first fortnight of January increased wheat productivity (2.10-9.15%) of wheat sown on all dates. At Faizabad, the rise in temperature by 1.0°C form normal during December to mid February in early sown wheat, from December to end February in timely sown wheat and during mid December to mid March in late sown wheat decreased its productivity. At Ranchi, the rise in temperature by 1.0°C from normal during January to mid February in early sown, first fortnight of December and mid January to end February in timely sown and mid January to mid March in late sown crops, reduced the wheat productivity. In this zone, at Kanpur and Faizabad, with a rise in temperature by 2.0°C from normal, the late sown wheat was benefited / less affected and at Ranchi the productivity of early sown crop was less affected as compared to timely and late sown wheat.

The temperature rise by 3.0°C from normal during December and mid January to end February in early sown, mid January to mid March in timely sown and mid January to end March in late sown wheat led to a reduction in its productivity. However, temperature rise during December to mid January increased the yield of timely sown wheat and that during mid December to mid January enhanced the productivity of late sown wheat.At Faizabad, the yield of early sown wheat was reduced if the temperature was increased by 3.0°C from normal during December and mid January to mid February. The yield of timely sown wheat decreased if the temperature increased during December and mid March. At Ranchi, temperature increase by 3.0°C from normal during January to mid February in early sown, during 1-15 December and January to end February in timely sown and during January to mid March in late sown wheat reduced the its productivity. However, the productivity of late sown wheat was benefited with temperature increase during second fortnight of December. In this zone, at Kanpur, Faizabad and Ranchi the yield of timely, late and early sown wheat, respectively, was benefited / less affected by increase of 3.0°C as compared to other sowings.

Central zone : Raipur and Udaipur were the two station & under this zone. At Raipur, the wheat yield decreased with temperature rise by 1.0°C from normal during December to February in early sown,mid December to mid March in timely sown and during mid December to end March in late sown wheat (Table 4). At Udaipur, the temperature rise during December and January in early sown, December to mid February in timely sown and during January and February in late sown crop led to a reduction in wheat productivity (Table 4). However, the increase in temperature during December was beneficial for the late sown crop.In this zone, with an increase in temperature by 1.0°C from normal,the timely sown wheat at Raipur and late sown wheat at Udaipur was less affected as compared to other dates of sowing.

The productivity of early sown wheat was reduced if the temperature increased by 2.0°C from normalduring December to February (Table 5). The productivity of timely sown wheat was reduced with rise in temperature during December to mid March at Raipur. The yield of late sown wheat was reduced with rise in temperature during 16-31 December, mid January to end March. At Udaipur the wheat productivity of early, timely and late sown crop was reduced by increase in temperature during December and January, January to mid February and January to end February, respectively (Table 5). However, the increase of 2.0°C from normal temperature during December benefited the timely sown crop. In this zone, the yield of early sown wheat at Raipur and that of late sown wheat at Udaipur remained less affected with a rise in temperature by 2.0°C from normal.

The temperature increase by 3.0°C from normal during December to mid January and February in case of early sown, during December to end March in case of timely sown and during December to mid January and February to mid April in case of late sown wheat reduced its productivity.At Udaipur, the temperature rise by 3.0°C from normal from December to end January, January to end February and December to mid March reduced the yield of early, timely and late sown wheat, respectively (Table 6). Temperature rise during December increased the yield of timely sown wheat. In this zone, the early and timely sown wheat at Raipur and Udaipur, respectively, remained less affected as compared other dates of sowings due to temperature increase by 3.0°C from normal.

Table 5 : Effect of temperature increase by 2.0°C from normal during different periods on grain yield of wheat at various locations

Time of sowing	Date of sowing	Dec1-15	Dec16-31	Jan1-15	Jan16-31	Feb1-14	Feb 15-28	Mar 1-15	Mar16-31
					Palampur				
Early	Nov. 5	0.00	0.00	0.56	0.35	-1.85	-0.96	-2.80	-6.13
Timely	Nov. 20	0.00	0.00	2.00	1.14	2.34	2.65	2.40	-4.46
Late	Dec. 5	0.00	0.00	2.76	1.65	1.73	-1.03	-0.36	-1.54
					Ludhiana				
Early	25-Oct	-0.44	0.27	-3.35	-5.68	-4.46	-4.59	0.00	0.00
Timely	8-Nov	-0.09	2.98	1.01	-2.93	-4.01	-4.82	-2.69	0.00
Late	22-Nov	4.50	6.12	6.35	3.60	-0.59	-5.37	-5.65	-0.05
					Kanpur				
Early	23.Nov.	0.64	-3.70	2.10	-1.98	-5.78	-2.92	0.00	0.00
Timely	08.Dec.	0.16	1.69	7.63	0.08	-1.90	-3.11	-3.22	0.00
Late	23.Dec.	0.00	0.81	9.15	0.00	-1.04	-2.58	-4.36	-0.26
					Faizabad				
Early	10-Nov	-0.36	-8.96	-5.26	-0.85	-2.43	-0.06	0.00	0.00
Timely	25-Nov	-0.77	-9.60	-4.30	-0.60	-3.04	-4.53	-0.09	0.00
Late	10-Dec	0.72	-5.44	-0.63	-1.62	-0.90	-1.53	-2.22	0.00
					Ranchi				
Early	20-Nov	1.65	1.68	-0.48	-4.79	-2.62	0.00	0.00	0.00
Timely	5-Dec	-1.73	1.18	0.98	-2.82	-1.79	-2.71	-0.03	-0.03
Late	20-Dec	0.00	0.95	1.45	-1.65	-4.71	-3.23	-3.23	0.00
					Raipur				
Early	10-Nov	-3.01	-2.02	-4.13	-1.63	-2.50	-1.66	-0.06	0.00
Timely	25-Nov	-2.93	-1.77	-1.80	-2.48	-0.82	-2.25	-5.43	-0.20
Late	10-Dec	1.55	-0.96	0.10	-3.30	-1.16	-2.58	-7.37	-5.85
					Udaipur				
Early	5-Nov	-3.09	-4.10	-6.79	-5.81	-0.01	0.00	0.00	0.00
Timely	20-Nov	2.13	1.48	-3.16	-6.37	-3.06	-0.01	0.00	0.00
Late	5-Dec	-0.09	1.26	-0.47	-0.72	-2.44	-2.72	-0.03	0.00

Table 6 : Effect of temperature increase by 3.0°C from normal during different periods on grain yield of wheat at various locations

Time of sowing	Date of sowing	Dec1-15	Dec16-31	Jan1-15	Jan16-31	Feb1-14	Feb 15-28	Mar 1-15	Mar16-31	Apr 1-15	Apr16-30
					Palampur						
Early	Nov. 5	0.00	0.00	1.06	-0.68	1.00	1.18	-3.80	-5.79	0.00	0.00
Timely	Nov. 20	0.00	0.00	1.33	1.47	1.47	1.62	1.75	-3.81	-0.15	0.00
Late	Dec. 5	0.00	0.00	4.07	2.60	0.74	2.32	2.79	-3.46	-6.84	0.00
					Ludhiana						
Early	25-Oct	-1.46	-1.86	-3.55	-7.70	-6.61	-4.73	0.00	0.00	0.00	0.00
Timely	8-Nov	1.32	3.83	1.32	-2.11	-3.76	-4.93	-5.04	0.00	0.00	0.00
Late	22-Nov	3.73	8.25	7.61	2.49	-2.34	-4.88	-5.60	-2.75	0.00	0.00
					Kanpur						
Early	23.Nov.	-0.32	-0.89	0.86	-4.27	-5.87	-5.86	0.00	0.00	0.00	0.00
Timely	08.Dec.	1.78	4.20	6.39	-2.23	-4.76	-6.53	-3.19	0.00	0.00	0.00
Late	23.Dec.	0.00	4.38	10.54	-1.88	-3.37	-7.24	-8.26	-1.62	0.00	0.00
					Faizabad						
Early	10-Nov	-0.92	-5.94	0.00	-1.90	-4.10	0.61	-0.52	0.70	0.00	0.00
Timely	25-Nov	-0.67	-4.24	-1.13	-0.15	-1.45	-3.48	-1.13	1.22	0.00	0.00
Late	10-Dec	1.22	0.70	1.34	0.61	-0.21	-1.80	-1.10	1.31	0.00	0.00
					Ranchi						
Early	20-Nov	0.97	0.54	-2.08	-6.67	-5.30	0.00	0.00	0.00	0.00	0.00
Timely	5-Dec	-2.56	0.98	-0.72	-3.26	-4.81	-7.49	-0.03	-0.03	0.00	0.00
Late	20-Dec	0.00	2.07	-0.43	-0.82	-3.72	-7.44	-3.19	0.00	0.00	0.00
					Raipur						
Early	10-Nov	-2.41	-1.48	-2.98	0.33	-4.88	-3.04	-0.12	0.00	0.00	0.00
Timely	25-Nov	-2.81	-3.07	-3.07	-2.90	-4.25	-2.67	-6.44	-8.19	-0.28	0.00
Late	10-Dec	-0.30	-1.22	-1.22	0.59	-3.77	-5.95	-3.64	-10.21	-7.40	0.00
					Udaipur						
Early	5-Nov	-4.86	-7.51	-9.58	-8.73	-0.01	0.00	0.00	0.00	0.00	0.00
Timely	20-Nov	2.26	1.59	-3.49	-6.80	-6.01	-3.09	0.00	0.00	0.00	0.00
Late	5-Dec	-0.50	-0.21	-1.00	-2.88	-5.56	-5.75	-2.91	0.00	0.00	0.00

Simulation results revealed that above normal temperature did not affect the wheat yield in the same way in all the four zones under study. The effects also varied widely within the zones and also with the sowing time. The positive / negative impacts of high temperature on wheat yield increased with itsintensity.

Amongst the zones, central zone seems to be the most vulnerable to rise in temperature (3.0˚C from normal), as wheat productivity decreased almost throughout the crop growth period for wheat sown on all the dates. Maximum reduction in yield (10.2%) was also noticed in this zone in case of late sown wheat at Raipur. On the other hand, in Northern hillszone the productivity of wheat increased upto 4.07% with temperature rise by 3.0˚C from normal during early phases of crop growth. Thereafter, the yield decreased (3.46–6.84%) with rise in temperature by3.0˚C, which was less as compared to other zones. Amongst, the seven locations the differential response of wheat yield to similar (3.0˚C) rise in temperature may be due to varietal and temperature difference (normal growing season temperature of timely sown wheat at Raipur was 21.0˚C while at Palampur was 12.7˚C).Talukder *et al.,* (2014) reported heat stress can cause wheat yield reduction upto 25% and the effect varies with the varieties. Early heading wheat genotypes with slower rate of leaf senescence after heat exposure and longer post-heading duration could be more tolerant to heat stress.

Amongst the sowing dates, the yield of late sown wheat in Northern hills and North Western plain zones increased more due to heat stress (3.0˚C above normal) during early phases of crop growth and were less reduced with heat stress in later phases of growth.The yield of timely, late and earlysown wheat at Kanpur, Faizabad and Ranchi, respectively, in North Eastern plain zone and early and late sown wheat at Raipur and Udaipur in the Central zone suffered to a lesser extent as compared to other date of sowings. Asseng *et al.,* (2011) found that a variations in average growing-season temperatures (±2 °C) in Australia can cause reductions in wheat production up to 50% and this can be due to increased leaf senescence as a result of temperatures >34°C. Lobell *et al* (2012)in northern India used nine years of satellite measurements of wheat growth to monitor rates of leaf senescence due to exposure to temperatures > 34°C and found a statistically significant acceleration of senescence from extreme heat. In our study at some places the increased temperature scenario was also near or above 34°C.

Among the times of above normal temperature by 3.0˚C,second fortnight of March in Northern hills zone, February in and North Western plain zone,February at Kanpur, mid January to February at Faizabad and mid January to mid February at Ranchi (North Eastern zone) was most critical as during this period temperature rise caused reduction in productivity of wheat sown on any date. In Central zone,February at Raipur and January at Udaipur was most critical as maximum reduction in productivity of wheat sown on any date occurred during this period.

Over the zones, except Northern hills zone first fortnight of February month was most critical as above normal temperature by3.0˚C decreased the productivity of wheat sown on any date.In North western plain zone above normal temperature by3.0˚C during early vegetative stages favoured the yield of timely and late sown wheat.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 wheat growing areas of India, wheat experiences 35°C during grain development which reduce theyield. Lobell*et al.,* (2008) had also estimated yield losses of 3–17% 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 (5days), 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.

CONCLUSIONS

The present study indicates that the temperature rise had differential effects on wheat yield in different zones and the effects also varied with the sowing time. The results showed that the positive and negative effects of above normal temperature on wheat productivity increased with the level of stress. Amongst the zones, Central zoneis the most susceptible and North hillszone being the least susceptible to temperature rise (3.0˚C from normal).Amongst the sowing dates, the productivity of late sown wheat in Northern hills and North Western plain zones; timely, late and early sown wheat at Kanpur, Faizabad and Ranchi, respectively, in North Eastern plain zone and early and timly sown wheat at Raipur and Udaipur, respectively, in the Central zone suffered to a lesser extent as compared to other date of sowings.Over the zones, barring Northern hills zone the temperature during first fortnight of Februarywas most critical to wheat productivity. In Northern hills zone, second fortnight of March was most important as during this period the above normal temperature caused a reduction in productivity of wheat irrespective of dates of sowing under study.

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REFERENCES

Acevedo, E., Silva, P. andSilva, H. (2002). Wheat growth and physiology. In: Curtis BC,Rajaram S,MacphersonHG (Eds.) Bread Wheat Improvement and Production, FAO Plant Production and Protection Series, No. 30. Food and Agriculture Organization of the United Nations, Rome, Italy.

Acevedo, E., Silva, P. and Silva, H.(2014). Wheat growth and physiology. Available at http://www.fao.org/docrep/006/y4011e/y4011e06.htm, citedon 10-4-2014.

Aggarwal, P.K.(2008) Global Climate Change and Indian Agriculture: Impacts, adaptation and mitigation. *Indian J.Agric.Sci.,* 78(10):911-919.

Anonymous (2011). Calories and Proteins value of wheat. Cited from http://www.fao.org.

Asseng, S., Foster, I. and Turner, N.C.(2011). The impact of temperature variability on wheat yields. *Global Change Bio.,*17(2):997–1012.

Farooq, M., Bramley, H., Palta, J.A. andSiddique, K.H.M.(2011).Heat stress in wheat during reproductive and grain-filling phases. *Criti. Reviews Pl.Sci.* 30:491–507.

Fischer, R.A. (1985). Physiological limitation to producing wheat in semitropical and tropical environments and possible selection criteria. In: Proc. Int. Symp. Wheat for More Tropical Environments, Mexico, DF, CIMMYT, pp. 209-230.

Jalota, S.K., Kaur, H., Ray, S.S., Tripathi, R., Vashisht, B.B.and Bal S.K. (2012).Mitigating Future Climate Change Effects by Shifting Planting Dates of Crops in Rice-Wheat Cropping System. *Zoneal Environ. Change.* 12(4): 913-922.

Jamieson. P.D., Porter, J.R. andWilson, D.R.(1991). A test of computer simulation model ARC-WHEAT1 on wheat crops grown in New Zealand. *Fld. Crops Res.,* 27:337–350.

Lobell, B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P. andNaylor, R.L.(2008).Prioritizing climate change adaptation needs for food security in 2030. *Science,* 319:607–610.

Lobell, D.B., Sibley, A.,Monasterio, J.I.O.(2012). Extreme heat effects on wheat senescence in India. *Nature Clim.Change,* 2:186–189.

Mandal, C., Mandal, D.K., Srinivas, C.V., Sehgal, J., Velayutham, M. (1999). Soil-climatic database for crop planning in India. NBSS Publ. NBSS&LUP, Nagpur.

Prasad, P.V.V. andDjanaguiraman, M.(2013).Impact of season-long and short-episodes of high temperature stress on growth and development of wheat. Proceedings of the Workshop on Modeling Wheat Response to High Temperature (Eds. Alderman PD, Quilligan, E., Asseng, S., Ewert, F. and Reynolds, M.P.) held at CIMMYT, El Batán, Mexico, on19-21 June 2013.

Reynolds, M.P., Nagarajan, S., Razzaque, M.A. andAgeeb, O.A.A.(2001). Heat tolerance. In: Reynolds, M.P., Ortiz-Monasterio, J.I., McNab, A. (Eds), Application of Physiology in Wheat Breeding, CIMMYT, Mexico, pp.124-135.

Ritchie, J.T., Singh, U., Godwin, D.C. andBowen, W.T.(1998). Cereal growth development and yield. In: Tsuji, Y.G., Hoogenboom, G. and Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, pp. 79–98.

Saini, H.S. andAspinal, D.(1982).Abnormal sporogenesis in wheat (*TriticumaestivumL.*) induced by short periods of high temperature. *Ann.Bot.*, 49:835–846.

Stone, P.J. andNicolas, M.E.(1994). Wheat cultivars vary widely in their responses of grain yield and quality to short periods of postanthesis heat stress. *Australian J.Pl.Physio.*, 21:887–900.

Stone, P.J. andNicolas, M.E.(1995).Asurvey of the effects of high-temperature during grain filling on yield and quality of 75 wheat cultivars. *Australian J.Agric.Res.,*46:475–492.

Talukder,A.S.M.H.M., Glenn,K., McDonald and Gill, G.S.(2014).Effect of short-term heat stress prior to flowering and early grain set on the grain yield of wheat. *Fld. Crops Res.,* 160:54-63.

Wardlaw, I.F., Sofield, I. andCartwright, P.M. (1980). Factors limiting the rate of dry matter accumulation in the grain of wheat grown at high temperature. *Australian J. Pl.Physio.,* 7:387-400.

Wiegand, C.L. andCuellar, J.A. (1981). Duration of grain filling and kernel weight of wheat as affected by temperature. *Crop Sci.*, 21:95-101.

Willmott, C.J.(1981).On the validation of models. *Physical Geog.,* 2:184–194.

Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddema, J.J., Klink,K.M., Legates, D.R. Odonnell, J. andRowe, C.M.(1985). Statistics for the evaluation and comparison of models.*J. Geoph. Res.*,90:8995–9005.

Wollenweber, B., Porter, J.R. andSchellberg, J.(2003). Lack of interaction betweenextreme high-temperature events at vegetative and reproductive growth stagesin wheat. *J.Agron.Crop Sci.*,189:142–150.

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