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Dynamics of Wheat Production and Productivity in North West Plain Zone of India in Relation to Thermal Regime

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ABSTRACT

Wheat is highly thermo-sensitive, particularly, when exposed to thermal stress at its reproductive stage. In India, the Northern states of Punjab, Haryana and Uttar Pradesh are the most productive regions with more or less assured irrigation but yield level fluctuates widely across the sub-regions. The average yield decreases by about 497 kg/ha with every unit increase in average temperature in a range of 17.5 ^{0}C at Ludhiana to 20.4 ^{0}C at Kanpur during the wheat season. The present analysis is aimed at quantifying the combined effect of high temperature, above the normal range, and continuous exposure duration to such temperature stress that causes significant amount of yield loss at Ludhiana, one of the most favorable environment for wheat and to extend the application of quantified relationships to other major growing areas, viz. Hisar, Karnal and Kanpur, to estimate the yield. Rising trend of maximum temperature in 'heading to anthesis' and 'milking to dough' stages is of major concern due to sensitivity of these stages to high temperature and consequent negative impact on yield. Quantified relationships for 'average daily temperature departure by 2 ^{0}C for minimum continuous 5 days duration' with annual wheat yield developed for two phenological stages at Ludhiana are extended to estimate yield at other locations through introduction of a response factor. During the reproductive stage, a 10% reduction from the average yield is expected in 11 days of stress at Ludhiana, 10 days at Hisar, 13 days at Karnal and 15 days at Kanpur if exposed to average stress temperature departure of 3.24, 4.20, 3.63 and 3.54 ^{0}C, respectively. We also find that the requirement of exposure to stress, to have a certain amount of wheat yield reduction, is more at warmer environment (eg. Kanpur) than at locations with comparatively cooler thermal regimes (eg. Ludhiana). This may be due to the fact that the yield potential at the traditionally warmer places is already in a reduced state and wheat yield is less sensitive to further increase in temperature there. The current level of thermal stress may reduce wheat yield by 10-12% of the average yield, which may increase up to 25%, with further rise in exposure duration to thermal stress. The complex interactions between agricultural systems performance, climate, soil, and management practices make it difficult to assess the impact of individual factors on yield. But the method followed by the authors demonstrates satisfactory yield estimations in relation to varying atmospheric thermal regime, in spite of uncertainties involved in actual farm production.

***Key words*:** India; Wheat; Response factor; Thermal stress; Variability

1. Introduction

India has made a steady but significant progress in production of foodgrains, which enabled it to reach self-sufficiency. It has been made possible through substantive application of scientific knowledge and technological interventions, institutional support by the government and active participation by the farmers.

Yield of major food crops in the past few decades have stagnated in several parts of Asia, including India. Among several factors increasing water stress, arising partly from increasing temperatures, increasing frequency of El Niño events and reductions in the number of rainy days are being recognized as important ones contributing to the stagnation (Wijeratne, 1996; Aggarwal *et al*., 2000; Jin *et al*., 2001; Fischer *et al*., 2002; Tao *et al*., 2003, 2004). Climatic change is likely to exacerbate the influences of biotic and abiotic stresses making the task of producing enough food for growing population challenging.

India had a total cultivable area of 115.3 million ha under foodgrain crops in 1966-67, which increased to 124.44 million ha by 2007-08. Most of the cultivable area suitable for foodgrain production has been exploited with little scope left for further expansion. At the same time, a fall in area under kharif crops has been observed since 1991-92; the gap between area under kharif and rabi has been shrinking.

Based on agro-climatic conditions, disease spectrum and soil type, India has been divided into six wheat zones (ICAR, 1997). The North West Plain Zone (NWPZ), covering the regions of Punjab, Haryana, western Uttar Pradesh and Rajasthan, is the most productive belt contributing 70-75% of total annual wheat production. In spite of enjoying assured irrigation and other management supports, a large variability in wheat yield has been observed within this region, where the average yield ranges from 4.2 t/ha in Punjab, 3.9 t/ha in Haryana to 2.7 t/ha in Uttar Pradesh. Again, the yield growth rate showed a negative trend by 1.9 and 0.9% in Punjab and Haryana, respectively, during the period 2001-06 (Sant Kumar, 2009).

Apart from the increasing negative influence of climatic variability, decline of soil fertility due to continuous rotation of rice-wheat in NWPZ, increasing problems of drainage and soil salinity, delayed sowing due to late harvesting of the preceding crop, poor crop stand, weeds and diseases are some of the factors influencing wheat yield loss by 0.10 to 0.23 t/ha in rice-wheat and cotton-wheat systems across the NWPZ (DWR, 2002; Gupta *et al*. 2003). A study on the climatic trends and variability between 1960-2003 for North Western region of India at monthly, seasonal (rainy and winter) and annual time scales revealed increasing trend in maximum temperature at annual and seasonal time scales, with a very sharp rise for years 2000 and beyond. The rate of increase of maximum temperature during rainy season, is alarmingly higher than that during winter season. The minimum temperature is also showing increasing trend at annual and seasonal time scales with high rate of increase during winter (ICAR, 2008).

As water is more or less assured, temperature may play an important role in governing yield variability in the NWP Zone. Rise in minimum temperature by an average of 1.5 ^{0}C at many places of Indo-Gangatic plains has been reported (Sinha *et al*., 1998; Pathak *et al*., 2003). At Ludhiana, in Punjab, the minimum and average temperatures are increasing significantly at the rates of 0.06 and 0.03 ^{0}C per year, respectively, and during the last 32 years, the minimum temperature had increased by 1.9 ^{0}C (Pathak and Wassmann, 2009). The yield loss of wheat in India, due to rising temperature has been projected as 4-5 million tonnes per year with every degree rise of temperature throughout the growing period even after considering the benefits of carbon fertilization (Aggarwal, 2007).

Temperature has a differential effect on vegetative and reproductive phases of wheat growth (Shpiler and Blum, 1986; O'Toole and Stockle, 1991). The reproductive stage is critical in setting the extent to which the grain yield potential is realized. While a decrease in minimum temperature increases the crop duration and yield, an increase in minimum temperature increases respiration rates contributing towards a decline in yield (Matthews *et al*. 1995).

Adaptation and performance of wheat crop is best in areas with moderate thermal regimes and sub-humid to semi-arid climatic conditions. It has a wide latitudinal distribution and in Northern hemisphere the pole-ward limit of economic wheat production corresponds with May isotherm of 10 ^{0}C. Wheat prefers optimum diurnal temperature range of 15-25 ^{0}C with longer cool growing season. The ranges of optimum mean temperature during the vegetative and reproductive phases are 15-20 and 20-25 ^{0}C, respectively. High temperatures, beyond 30 ^{0}C, synchronizing with low relative humidity at maturity were found to reduce economic yield drastically (Table 1).

Sensitivity to high temperature increases as vegetative growth develops and tillering proceeds towards the end of vegetative stage (O'Toole and Stockle, 1991). The sensitivity to high temperature during this phase is expressed as a decreased duration of vegetative stage and reduced leaf area and growth (Shpiler and Blum, 1986). A reduction in total number of leaves and spike-bearing tillers is also an effect of high temperature during this phase (Midmore *et al*., 1984). The main effect of heat stress after floral initiation is observed on number of kernels. The number of kernels per unit area decreases at a rate of 4% for each degree increase in average temperature during the 30 days preceding anthesis (Fischer, 1985).

Table 1. Cardinal temperatures for wheat growth at different phenological stages

Phenological stages	Minimum Temperature	Maximum Temperature	Optimum Mean Temperature
	(°C)	(°C)	(°C)
Germination	3-4.5	30-32	20-25
Tillering	4	37	25
Vegetative	12	30-35	15-20
Reproductive	20	25-31	20-25

High night temperatures have significant influences on physiology, growth, and yield traits of wheat. High night-time temperatures (>14 °C) has decreased photosynthesis after 14 days of exposure to stress; and grain yields linearly decreased with increasing night-time temperatures, leading to lower harvest indices at 20 and 23 °C. High night-time temperature (>20 °C) has also reduced spikelet fertility, grains per spike, and grain size. Compared to the control (14 °C), grain-filling duration was decreased by 3 and 7 days at night temperatures of 20 and 23 °C, respectively (Prasad *et al*., 2008).

In plants grown under controlled conditions, high temperature is a major determinant of wheat development and growth, decreasing yields by 3 to 5% per 1 °C increase above 15 °C (Gibson and Paulsen, 1999). Growth chamber studies have revealed that high temperatures during kernel filling (10 days after anthesis until ripeness) decrease wheat yield by reducing kernel weight (Warrington *et al*., 1977; Tashiro and Wardlaw, 1990; Stone and Nicolas, 1994). About 23% reduction in kernel weight has been reported, compared to normal temperature, when temperature is raised from 20/15 (day/night temperature) to 40/15 °C for 3 days beginning 30 days after anthesis (Stone and Nicolas, 1994). When high temperature (35/20 °C, day/night) is applied at early reproductive stage i.e. 15 days after anthesis until ripening, it reduced grain yield by 18% compared to control (20/20 °C, day/night) (Gibson and Paulsen, 1999).

Any biological system has its own physiological mechanism to respond to environmental stresses and within certain limit they show a tendency to go back to the original conditions once the stress is withdrawn. High temperature stress tolerance in plants is related to membrane stability, increased compatible solutes, increased protein stability and synthesis of heat shock proteins. High night temperature has also a role in enhancing the expression of chloroplast protein synthesis elongation factor in wheat cultivars suggesting possible involvement of this protein in plant response to stress. By virtue of being a biological system, the crop plants are well equipped to modify their own physiological mechanisms to adapt to the environmental stress conditions, but sometimes at the cost of the ultimate economic yield. If exposure to stress is prolonged, the mechanism of elasticity fails and economic yield is severely affected (Ellis, 1990; Prasad *et al*., 2008).

Information on interaction of intensity of thermal stress and duration with yield is often limited and important to understand. This present analysis is aimed at quantifying the interaction of exposure to high thermal stress for a specific duration during the reproductive stage with yield, which can lead to certain amount of yield loss in wheat. Here, we seek to specifically quantify the spatial impacts of increasing temperature on wheat productivity to assist strategic planning of crop layout on regional basis.

2. Materials and methods

2.1. Locations

Four locations representing major wheat producing states of India have been selected for the study, *viz.*, Ludhiana (Punjab), Hisar and Karnal (Haryana) and Kanpur (Uttar Pradesh). At all the locations, wheat is sown almost simultaneously around mid-November and the crop duration extends for an average 150 days between 46th and 15th standard meteorological weeks (SMW). The locations are part of fertile Indo-Gangetic plains, enjoy more or less assured irrigation and hence, the uncertainty associated with rainfall is not a major limiting factor in wheat production in these areas. Among the stations, Ludhiana represents the highest productivity level of wheat with lowest average prevailing maximum temperature (24.9 ^{0}C) between 46th to 15th SMWs. Though minimum temperature does not indicate any particular trend, the difference in maximum temperature between Ludhiana and Kanpur is 3 ^{0}C and impact of it is reflected in the yield difference of about 1500 kg/ha.

The average yield is decreasing by about 497 kg/ha with every unit increase of average temperature in a range of 17.5 °C at Ludhiana to 20.4 °C at Kanpur during the wheat season (Table 2). Ludhiana also receives highest rainfall (142.6 mm) during the wheat season due to intense western disturbance activity and may positively influence the yield through reduction of temperature and clearing of smog to facilitate better photosynthetic activity (Pathak and Wassmann, 2009).

Table 2. Average climatic conditions during wheat season (46th to 15th SMW), acreage and yield of wheat from 1971-72 to 2005-06 at different locations in this study

Parameters	Ludhiana	Karnal*	Hisar	Kanpur
Latitude (N)/ Longitude (E)	30.9/75.8	29. 4/77. 0	29.1/75.7	26.4/80.3
Average maximum temperature (°C)	24.9	25.4	26.7	27.9
Average minimum temperature (°C)	10.1	10.8	9.5	12.8
Average temperature (°C)	17.5	18.1	18.1	20.3
Average rainfall (mm)	142.6	125.8	63.5	60.4
Rate of change of maximum temperature (°C/annum)	0.02	-0.009	-0.007	0.026
Rate of change of minimum temperature (°C/annum)	0.07	0.004	0.002	-0.027
Net area under wheat (000 ha)	260	187	210	186
Irrigated area under wheat (000 ha)	260	181	201	153
Yield (kg/ha)**	4325	3831	3829	2830

Note: *Data ranged from 1972-73 to 2004-05; ** Averaged from 1984-85 to 2004-05

2.2. Crop and climatic data

Data pertaining to annual wheat area and yield (district-wise) for different locations have been collected from Centre for Monitoring Indian Economy (CMIE), New Delhi, India from 1971-72 to 2005-06 except for Karnal, where data availability was limited from 1972-73 to 2004-05. Daily climatic data for the wheat growing season have been collected from the Agrometeorological Data Bank maintained at CRIDA, Hyderabad for the required duration.

2.3. Phenological stages of wheat

As sowing and harvesting of wheat for different locations are almost uniform, the phenological development for commonly grown wheat varieties in the region, more or less, coincide (Table 3). This would help to have a comparative analysis among the locations. Late vegetative (from 1st January to start of heading) and reproductive (from start of heading to reaching of dough stage) are the two stages to which the present analysis is made for studying temperature impact on wheat yield. The reproductive stage is covered in average 56 days from heading to attainment of physiological maturity.

Table 3. Phenological stages of wheat with their period of occurrence considered in this study

Phenological stages	Between Dates	Between Julian Days	Between SMW's	Days required
Vegetative				
Emergence to CRI	15 November - 4 December	319-338	46-49	20
CRI to Heading	5 December -18 February	339-49	49-8	75
Reproductive				
Heading to Anthesis	19 February - 27 February	50-58	8-9	9
Anthesis to Milking	28 February - 8 March	59-68	9-10	9
Milking to Dough	9 March - 18 March	69-78	10-11	10
Dough to Physiological Maturity	19 March - 15 April	79-106	12-15	28
Total Duration	15 November - 15 April	319-106	46-15	151

Note: SMW represents standard meteorological week

2.4. Analysis

2.4.1. Selection of temperature stress periods

Average maximum, minimum and mean temperatures prevailed during late vegetative and reproductive stages at different locations have been presented in Table 4. In relation to the optimum mean temperature suggested in Table 1, all the locations have been found within the range and hence, it may be assumed that fluctuations in year to year yield can not be effectively explained through the mean temperature. Again, minimum temperatures at different locations were also not found to exceed the specified cardinal values for both vegetative and reproductive stages. In all probability, it is the maximum temperature that may cross the upper threshold particularly in most sensitive anthesis and milking stages at most of the places and hence, maximum temperature may be singled out as the most important thermal function regulating the annual wheat yield variation in most of the years.

In North Indian wheat belt, a simulation study showed no significant impact of 1 ^{0}C rise in the average temperature on potential yield of wheat though an increase of temperature by 2 ^{0}C, above the normal temperature, has reduced potential yield in many places (Aggarwal and Sinha, 1993). This observation forms the basis of our consideration for mean daily positive departure of temperature, above long term normal, by 2 ^{0}C, which may have some negative impact on productivity. Positive departure of temperature has been considered in place of their absolute values to avoid difference between impacts that may be caused by higher maximum or minimum temperature in isolation i.e. higher maximum or minimum temperature if prevailed for certain period of days continuously, are assumed to cause identical amount of negative impact on wheat yield. In this study, a continuous 5 days or longer spell of high temperature (departure by 2 ^{0}C above long term mean) was considered as the period to qualify for selection as stress duration.

Table 4. Normal temperatures at different locations during late vegetative and reproductive stages of wheat

Phenological stages	Ludhiana	Hisar	Karnal	Kanpur
		(Maximum/Minimum/Mean) ^{0}C		
Late vegetative	19.1/6.1/12.6	20.6/5.3/12.9	20.4/7.1/13.7	21.9/8.2/15.0
Heading to Anthesis	22.1/8.4/15.2	23.9/7.9/15.9	23.5/9.1/16.3	26.0/11.2/18.6
Anthesis to Milking	23.7/9.2/16.4	25.7/8.7/17.2	25.4/10.5/17.9	27.7/12.5/20.1
Milking to Dough	25.8/11.2/18.5	28.2/11.1/19.6	27.5/12.4/19.9	30.1/14.5/22.3

The maximum and minimum temperatures for (a) 1st January to 18th February and (b) 19th February to 18th March, corresponding to late vegetative stage and reproductive stage, respectively, are screened out on yearly basis to identify the continuous durations with temperature exceeding the daily long term average by at least 2 ^{0}C. Gaps were observed in data sets and low values of yield due to some other factors apart from climate prior to 1984-85 and hence the present analysis is confined to the period from 1984-85 to 2004-05 to bring uniformity and avoid any kind of undetectable bias. If both maximum and minimum temperatures showed average positive departures by at least 2 ^{0}C concurrently, in that case, the one with comparatively higher departure and longer duration have been taken into consideration. One or two days of break within a long spell of such stress were considered part of the total stress duration assuming such short period may not nullify the negative impact already set in motion.

2.4.2. Development of empirical relationships and temperature-duration based response factor

Among all the places with low temperature regime and highest productivity, Ludhiana's location assumed to represent ideal growing condition for wheat. The 'yield-temperature departure-stress duration' relationships have been developed for both late vegetative and reproductive growth stages for Ludhiana. The relationships have been extended to other locations through introduction of a 'response factor' (RF), which takes care of the wheat yield variability due to combined effect of temperature departure (T) and the duration of the stress period (D). This is done with a view that the variability of yield due to temperature and duration of stress can be manipulated through the response factor once the relationships have been developed for the best possible sets of atmospheric thermal regimes i.e. for Ludhiana in this case. The response factor (RF) has been expressed as the ratio between the average wheat yield difference between Ludhiana and a given place to the average yield at Ludhiana due to combined effect of temperature departure and stress duration (T x D). The response factor has been calculated for both the phenological stages under study. It is unitless.

For estimation of annual wheat yield the response factor has been incorporated in the original equations and comparison with the actual yield has been done to assess the suitability of the regression functions. The applicability of the procedure to estimate wheat yield at other locations have been validated following standard statistical procedures, viz., Kolmogorov-Smirnov test of normality of errors, Skewness, kurtosis, root mean square error (RMSE) and coefficient of determination (R^2).

3. Results

3.1. Trend of temperature at different locations for late vegetative and reproductive stages of wheat

Trend of temperature change exhibits a mixed result with respect to both location and phenological stages (Table 5). At the late vegetative stage, between 1st January and 18th February, an annual rate of increase of minimum temperature by 0.02 ^{0}C has been observed at Ludhiana. But at other locations both maximum and minimum temperatures showed a decreasing trend in this stage. The rate of decrease of maximum temperature is more noticeable and ranging from 0.09 ^{0}C per annum at Kanpur to 0.15 ^{0}C per annum at Hisar. Same trend of decreasing temperature has also been observed between 28th February and 8th March corresponding to the anthesis to milking stage at all the locations including Ludhiana. On the contrary, increase of maximum temperature has been observed in two other important phases of reproductive stage i.e. from heading to anthesis and milking to dough phases at all the locations. Kanpur experiences an annual rate of increase of maximum temperature by 0.12 ^{0}C between 19th and 27th February. The rate of increase between 9th and 18th March is highest at Ludhiana with 0.10 ^{0}C per annum for maximum temperature. Minimum temperature rise is of concern at Ludhiana at heading to anthesis stage, where it is increasing at the rate of 0.08 ^{0}C per annum. At rest of the places minimum temperature is generally showing a decreasing trend.

Table 5. Rate of change of temperature at various phenological stages for different locations between 1971-72 and 2005-06

Phenological stages	Rate of change of maximum/minimum temperature (^{0}C per annum)			
	Ludhiana	Karnal	Hisar	Kanpur
Late Vegetative				
1st January to Heading (1st January - 18th February)	-0.11/0.02	-0.13/-0.03	-0.15/-0.05	-0.09/-0.15
Reproductive				
Heading to Anthesis (19th February - 27th February)	0.03/0.08	0.04/-0.01	0.04/0.03	0.12/-0.01
Anthesis to Milking (28th February - 8th March)	-0.10/-0.04	-0.08/-0.05	-0.13/-0.07	-0.01/-0.10
Milking to Dough (9th March - 18th March)	0.10/-0.02	0.01/-0.06	0.01/-0.15	0.002/-0.10

3.2. Screening of temperature stress periods and quantification of yield-temperature departure-stress duration relationship

To find out thermal stress periods following the criteria set in the study, yearly temperature data (maximum and minimum) are screened for both the phenological stages. The late vegetative stage is of total 49 days in duration from 1st January to 18th February. The reproductive stage spans from Heading (19th February) to Reaching of Dough stage (18th March), which is completed in 28 days on an average (Table 5).

Following the criteria for screening we find average positive temperature departure in both the stages at various locations ranging between 2.74 and 4.20 ^{0}C (Table 6). Range of average continuous stress exposure is more at reproductive stage (9.94 to 12.4 days) than at late vegetative stage (12.9 to 14.7 days). Out of 21 years (1984-85 to 2004-05) Ludhiana experiences temperature stress in 17 years in each of the phenological stages. In case of Karnal, lowest stress period of 12.9 days of 5 days duration has been observed with an average temperature departure of 2.74 ^{0}C in the late vegetative stage. Highest average temperature departure of 4.20 ^{0}C has been observed at Hisar with an average 11.9 days exposure at the reproductive stage. Wheat at the reproductive stage is exposed to least duration of stress period at Ludhiana followed by Hisar, Kanpur and Karnal.

Table 6. Average positive temperature departure of 2 ^{0}C, above long term normal, and their durations during late vegetative and reproductive stages of wheat at different locations between 1984-85 and 2004-05

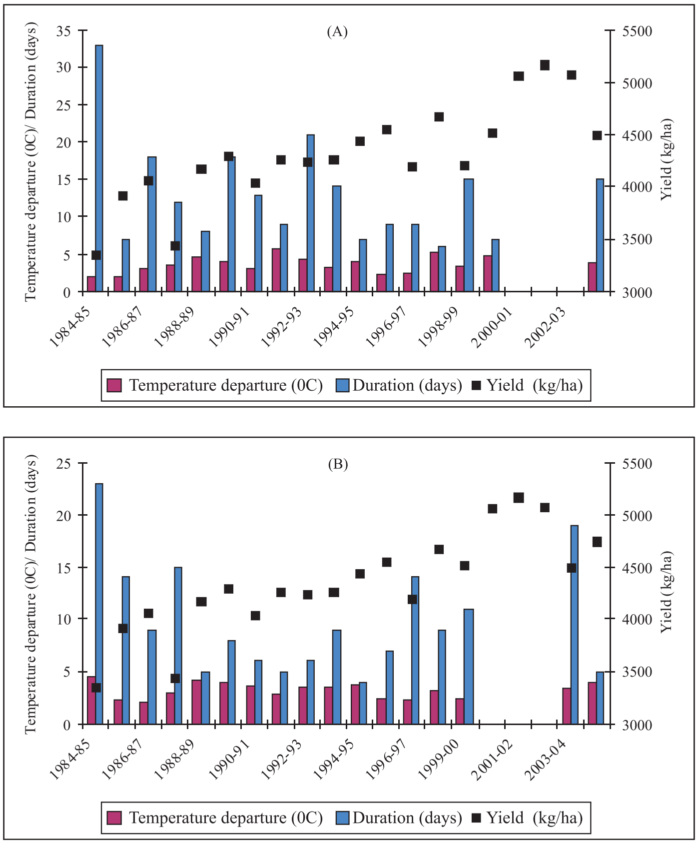
Locations	Late vegetative stage			Reproductive stage		Combined effect of temperature and Duration	Yield (kg/ha)	Difference in yield compared to Ludhiana due to effect of (T x D)
	Average temperature departure (^{0}C)	Average stress duration (days)	Combined effects of temperature and duration	Average temperature departure (^{0}C)	Average stress duration (days)			
			(^{0}C-days)					(kg/ha)
	(T)	(D)	(T x D)	(T)	(D)	(T x D)		
Ludhiana	3.63 (17)	13.0	47.19	3.24 (17)	9.94	32.21	4325	---
Hisar	3.25 (10)	14.7	47.78	4.20 (12)	11.9	49.98	3829	-496
Karnal	2.74 (18)	12.9	35.35	3.53 (16)	12.4	43.77	3831	-494
Kanpur	3.17 (17)	14.6	46.28	3.54 (14)	12.1	42.83	2830	-1495

Note: Values in parentheses represent the total number of years, between 1984-85 and 2004-05, where average temperature departure exceeds by 2 ^{0}C in at least 5 continuous days.

The applicability of (T x D) effect on yield depends on the prevailing thermal conditions at different locations. Because of this factor, though the average (T x D) for Karnal (35.35) is lesser in magnitude than for Ludhiana (47.19) in the late vegetative stage, but it does not imply a better environmental condition for wheat production than that of Ludhiana.

The yield, average temperature departure and stress duration data for Ludhiana have been used, between 1984-85 and 2003-04 (late vegetative) and 1984-85 and 2004-05 (reproductive stage), to quantify 'yield-temperature departure-stress duration' relationships (Fig. 1). Due to inconsistency in data 2004-05 (late vegetative) and 1998-99 (reproductive) are not considered for development of the multiple regression equations. Highest yield of wheat is recorded in three consecutive years, viz., 2000-01 (5066 kg/ha), 2001-02 (5170 kg/ha) and 2002-03 (5074 kg/ha), where no temperature stress periods have been detected at any of the stages. In the late vegetative stage, the average stress temperature departure is ranging from 2.01 (1985-86) to 5.70 ^{0}C (1991-92) and duration from 33 days (1984-85) to no stress in three years between 2000-01 and 2002-03. Similarly, during the reproductive stage, in 1984-85 highest temperature departure (4.57 ^{0}C) and stress duration (23 days) have been observed. Wheat growth in 1984-85 is subjected to altogether 56 days of temperature stress in both the thermally sensitive phenological stages and records the lowest yield of 3350 kg/ha.

Fig. 1. Annual wheat yield, average positive temperature departure and stress duration for Ludhiana (A) late vegetative stage, (B) reproductive stage



Note: In 2000-01, 2001-02 and 2002-03 no thermal stress periods were observed according to the defined assumptions.

The multiple regression equations developed to estimate wheat yield based on 'temperature departure and stress duration' for Ludhiana are as below:

(a) Late vegetative stage (1st January to 18th February)

$$Y = 4910.506 - (41.438X_1) - (41.411X_2) \text{ ---------------------------- } (1)$$

$(R^2 = 0.574^{**}$, d. f. = 18)

(b) Reproductive stage (19th February to 18th March)

$$Y = 5045.532 - (117.026\,X_1) - (43.919X_2) \text{ -------------------------- } (2)$$

$(R^2 = 0.626^{**}$, d. f. = 18)

In both the relationships, Y is the estimated yield (kg/ha), X_1 (^{0}C) is the temperature departure above average by 2 ^{0}C for any continuous duration X_2 (days, ≥ 5). The value of X_2 is ≥ 5 days in a continuous stretch. The high temperature departure and the stress duration is found to influence yield by equal magnitude at the late vegetative stage but at the reproductive stage the influence of temperature departure has increased by almost three fold over the second factor. Both the equations exhibit highly significant (1% level) statistical probabilities with respect to yield estimation.

3.3 Development of response factors and wheat yield estimation at different locations

The changes in average yield of wheat due to unit change in combined effect of 'positive temperature departure and its duration' (T x D) are 17.7 and 18.5 kg/ha for late vegetative and reproductive stages, respectively (Table 6). From this we have calculated the response factors for different magnitudes of (T x D) and standard equations are being given to calculate response factor for any given value of (T x D) (Table 7). The values of response factors at reproductive stage are comparatively higher than at the late vegetative stage. For example, at (T x D) level 50, the response factors are 0.205 and 0.214 at late vegetative and reproductive stages, respectively.

Wheat yield has been estimated on annual basis for Hisar, Karnal and Kanpur using equations (1) and (2) after deducting the proportionate yield by introducing the response factor, which takes care of the (T x D) effect of the respective places. For that purpose, the original yield estimate from the equations is multiplied with the response factor and the resultant value is deducted from the original yield estimate.

On annual basis, the actual yield, temperature departure and stress duration data of Hisar from 1985 to 2002 at late vegetative stage (excluding 1986) and from 1985 to 2005 at reproductive stage (excluding 1996 to 1998, 2001); Karnal from 1985 to 2004 at late vegetative stage (excluding 1986, 1991 to 1992, 1995 to 1996, 1998 to 2003) and from 1985 to 2005 at reproductive stage (excluding 1986, 1996 to 2003) and Kanpur from 1985 to 2004 at late vegetative stage (excluding 1986-87, 2001) and from 1985 to 2004 at reproductive stage (excluding 1992, 1996 to 1997, 1999 to 2003) are used for yield estimation using the equations (Fig. 2 a, b, c). The stress criteria set for this study are found not fulfilled in the excluded years. Good Agreement between observed and estimated yield has been established through Kolmogorov-Smirnov test of normality of errors. The finding of the analysis suggests that the errors (difference between observed and estimated yield) are normally distributed and that confirms the suitability of the derived equations in other wheat growing areas when the response factor is introduced. The low RMSE values also support the methodology we have used (Table 8).

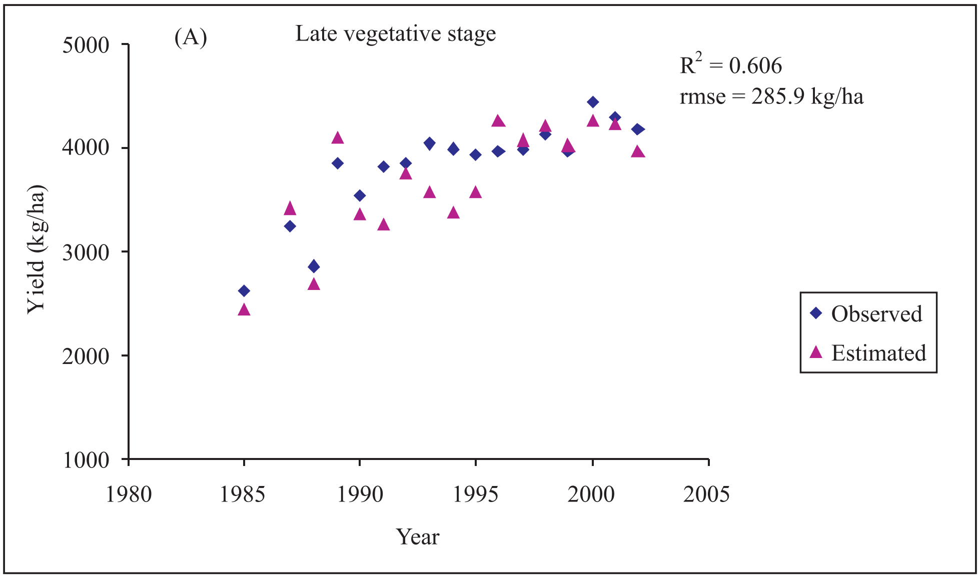
Table 7. Response factors derived as a function of combined effect of temperature departure (T) and stress duration (D) at late vegetative and reproductive stages of wheat.

Combined effect of (T x D) (^{0}C-days)	Response factor	
	Late vegetative stage	Reproductive stage
1.0	0.004	0.004
10	0.041	0.043
20	0.082	0.086
30	0.123	0.128
40	0.164	0.171
50	0.205	0.214
60	0.245	0.257
70	0.286	0.300
80	0.327	0.342
90	0.368	0.385
100	0.409	0.428
Standard equations	$Y = 0.0041x - 1E^{-16}$	$Y = 0.0043x - 1E^{-16}$

Note : 'Y' represents response factor, 'x' represents magnitude of (TXD)

Using the regression equations and following reverse calculation procedure, we determine minimum stress exposure requirement to have a 10% yield reduction from the average observed yield for the stressed years for which yield estimation is done (Table 9). The difference in average observed yield for the stressed years at late vegetative and reproductive stages differs due to the fact that yield variation caused by occurrence of thermal stress during late vegetative stage in some of the years and reproductive stage in others. The estimated stress duration ranges from 9 days at Ludhiana, 14 days at Hisar to 17 days each at Karnal and Kanpur during the late vegetative stage. In the reproductive stage, same amount of yield reduction can be affected in 11 days of stress at Ludhiana, 10 days at Hisar, 13 days at Karnal and 15 days at Kanpur.

Fig. 2 (A). Time series for the estimated and observed wheat yield at Hisar



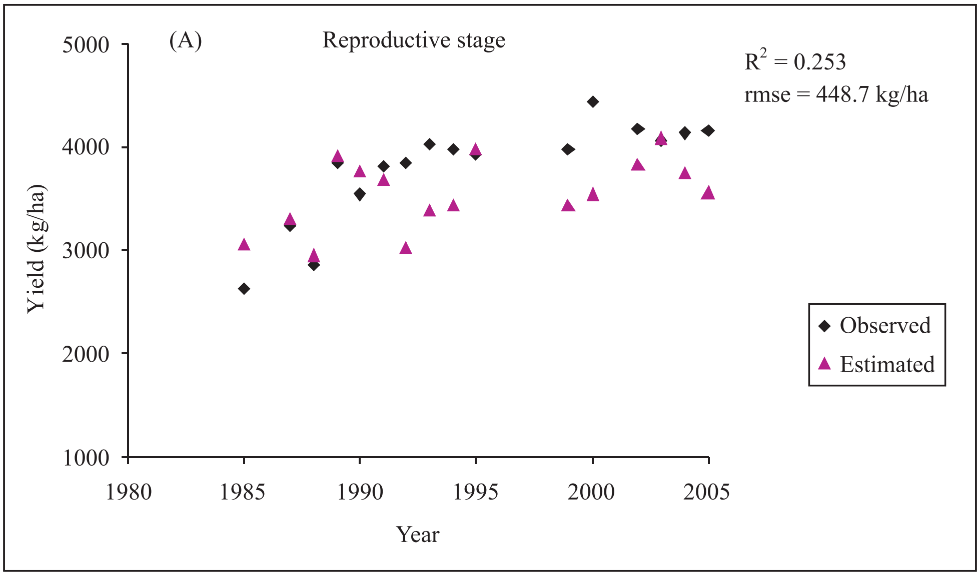
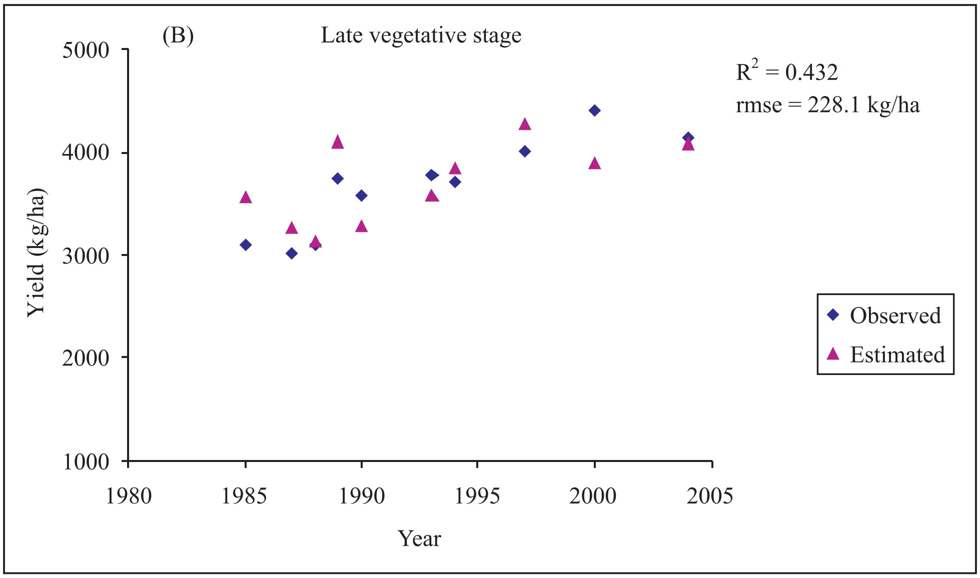


Fig. 2 (B). Time series for the estimated and observed wheat yield at Karnal



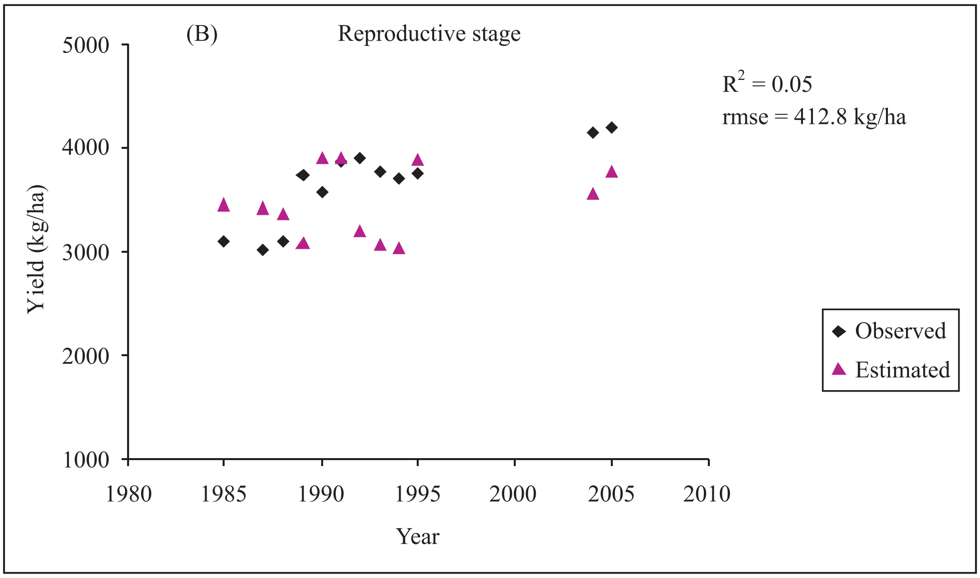
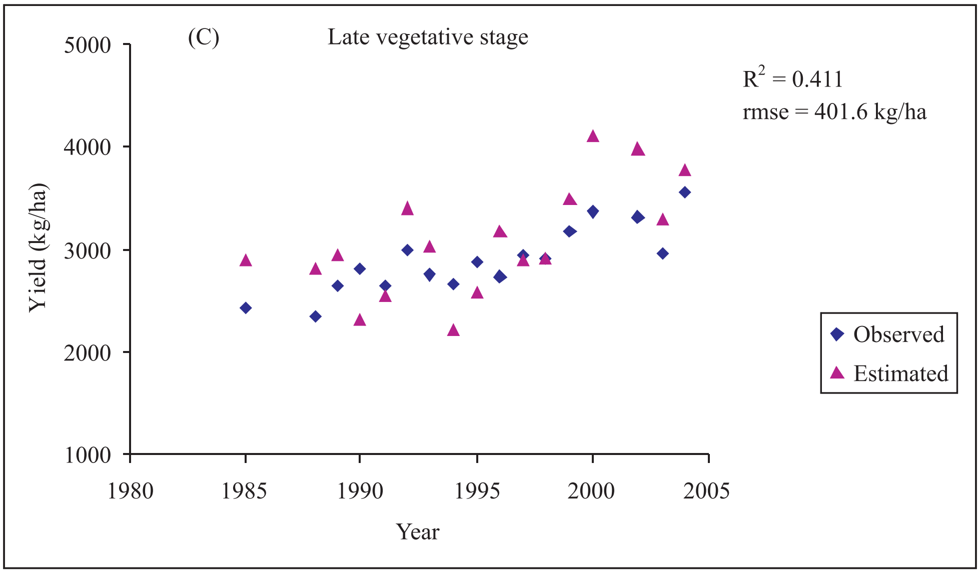


Fig. 2 (C). Time series for the estimated and observed wheat yield at Kanpur



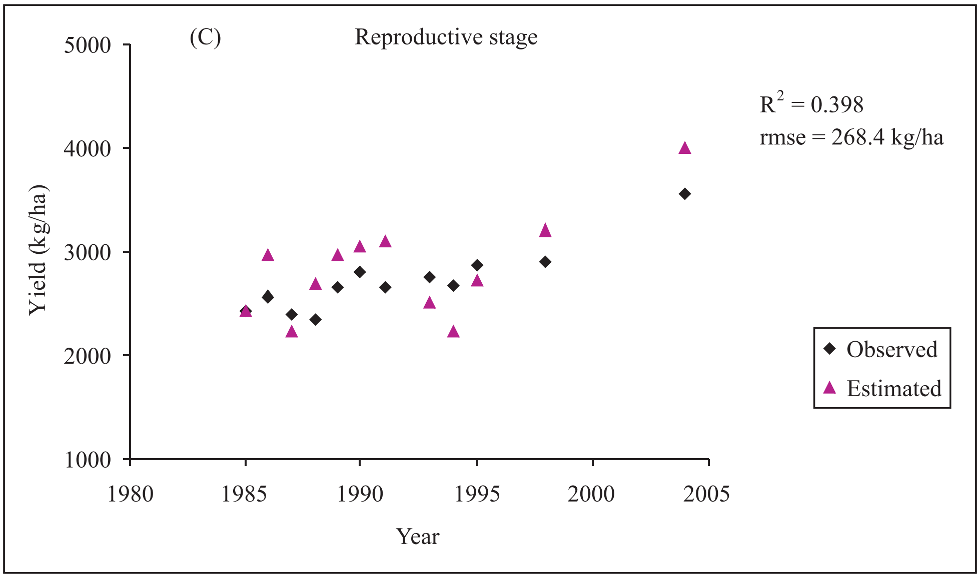


Table 8. **Kolmogorov-Smirnov test of normality of errors (obtained by subtracting estimated yield values from observed values), Skewness, Kurtosis, RMSE and R^2 values for estimated yields obtained from regression equations for various locations**

Location	Crop stage	Statstic	P ($P<0.05$)	Skewness	Kurtosis	RMSE (kg/ha)	R^2
Hisar	Late vegetative	0.162	0.200	0.268	-0.618	285.9	0.606**
	Reproductive	0.185	0.145	0.086	-1.153	448.7	0.253*
Karnal	Late vegetative	0.138	0.200	0.446	-0.673	228.1	0.432*
	Reproductive	0.222	0.107	-0.060	-2.131	412.8	0.050
Kanpur	Late vegetative	0.190	0.103	0.615	-0.460	401.6	0.411**
	Reproductive	0.243	0.049	0.603	-1.192	268.4	0.398*

Table 9. **Minimum exposure to thermal stress required to have 10% yield reduction from the average observed yield at different locations**

Locations	Average observed yield for the stressed years (kg/ha)	Average stress temperature experienced (^{0}C)	Estimated stress exposure to have 10% yield reduction from the average observed values (days)
Late vegetative stage			
Ludhiana	4188	3.63	9
Hisar	3806	3.25	14
Karnal	3652	2.74	17
Kanpur	2889	3.17	17
Reproductive stage			
Ludhiana	4219	3.24	11
Hisar	3792	4.20	10
Karnal	3650	3.53	13
Kanpur	2716	3.54	15

Impact on wheat production and productivity in India due to change in thermal regime during the reproductive stage have been explored following two different kinds of projections. In 'Scenario A' we have assumed that the current conditions of thermal stress would prevail and in 'Scenario B' the exposure to thermal stress will increase by average 5 days (current + 5) in future. Aggarwal (2007) projected average loss of wheat production in India to be 4-5 million tonnes with every degree increase in temperature in its entire growth period. In our projection, we present the impact in terms of 'limitation to achieve the potential yield due to rise in temperature'.

Projected temperature increase by IPCC, at the end of 21st century, is likely to be in the range of 2 to 4.5 ^{0}C with a best estimate of about 3 ^{0}C, and is very unlikely to be less than 1.5 ^{0}C (IPCC, 2007). From this analysis we have seen that, wheat, at reproductive stage, is already experiencing the elevated temperature of around 3 ^{0}C at different locations with variation in the duration of exposure. At the current level the total wheat production in India would be limited by 1.170 million tonnes every year due to exposure to stress temperature during the reproductive stage (Table 10).

If we assume that the exposure to thermal stress would increase by average 5 days (current + 5) in future with the current level of stress temperature, the gap between actual average yield and achievable potential yield may rise further. The gap may increase from current -11.22% in 'Scenario A' to -23.03% in 'Scenario B' leading to average gap of 2.392 million tonnes every year. In both the scenarios the average area sown under wheat has been considered as 26 million ha, which is the average wheat area sown in India between 2002-03 and 2006-07. Besides, the places already exposed to high degree of thermal stress, eg. Kanpur, may respond in a lesser magnitude in terms of change in wheat production and productivity.

4. Discussion

Climate sets the limit to the productivity of crops. Spatial and temporal variation of climate directly affects the economic and environmental performances of agricultural system in a region. Quantification of the spatial impact of climate can effectively assist in the strategic crop planning at a regional level. Assessment of the potential value of seasonal climate forecasts spatially helps to understand to what extent climate risk can be managed and whether responsive management strategies can be developed. A better understanding of how regional wheat productivity is influenced by the spatial variation of climate and how much value seasonal forecasts can add to management practices that can contribute to future cropping and management strategies. However, the complex interactions between agricultural systems performance, climate, soil, and management practices make it difficult to assess the impact of individual factors (Enli *et al*. 2009)

High temperature stress is of major concern for wheat production in India. Among different locations, Ludhiana represents best environmental conditions for wheat production. But maximum and minimum temperatures increases at the rate of 0.02 and 0.07 ^{0}C per annum, respectively, may cause reduction of productivity in the coming years by affecting the normal physiological mechanism of grain setting and development adversely. Heat stress starting from anthesis mainly affects assimilate availability, translocation of photosynthates to the grain and starch synthesis and deposition in the developing grain. This results in a lower kernel weight. The 'heading to anthesis' (19 to 27 February) stage is of primary concern as of now, as it coincides with important grain filling period and subjected to maximum risk of temperature stress at most of the locations. Over the range of 12 to 26 ^{0}C increase in average temperature during grain filling, grain weight is reduced at a rate of 4 to 8 percent/^{0}C (Wardlaw *et al*., 1980; Wiegand and Cuellar, 1981). Acevedo *et al*. (1991) reported an average reduction of 4 per cent in grain weight per degree increase in average temperature during grain filling. Shortened grain filling duration is partially offset by increased grain filling rate (Sofield *et al*., 1977), but the effects are much more complex. Hastened senescence, on the other hand, reduces assimilate supply to the grain.

The 'yield-temperature departure-stress duration' relationships developed for Ludhiana exhibit equal importance of rise in temperature and its prevailing duration in influencing the yield variability at the late vegetative stage. But at the reproductive stage, the influence of high temperature on yield increases by almost three fold compared to the duration of stress exposure. The sensitivity to high temperature increases with growth period of wheat and it exerts a differential effect on both vegetative and reproductive stages (O'Toole and Stockle, 1991). As the period between 'heading to end of milking' is of only 28 days, high temperature even if prevails for shorter duration may cause heavy yield loss.

The effect of latitudinal positions of the places also governs the thermal regime during the wheat season. The places close to the equator have relatively high temperature regimes and that sets the potential wheat productivity at lower levels in Hisar, Karnal and Kanpur compared to Ludhiana. Low rainfall receipt in the wheat season and comparatively more crop area under rainfed (33,000 ha) cultivation might be additional causes of poor yield realization, at Kanpur. We also found that a given magnitude of exposure to thermal stress may cause more wheat yield loss in cooler climatic conditions than relatively warmer places. This implies high vulnerability of yield reduction of wheat at relatively cooler climates under rising temperature conditions.

The approach we followed in this study is an empirical one but the essence of generalization has been imparted through introduction of a temperature based response factor to the original equations for extending their applicability to other wheat growing areas within the same wheat zone instead of developing individual sets of equations for each location. The method has the potentiality to be used as a handy yield forecasting tool, where the observed yield is likely to fall close to the probabilistic yield values obtained from two yield-temperature relationships.

Table 10. Impact on wheat production and productivity due to change in thermal regime in the reproductive stage: *Scenario A*: Current conditions of thermal stress duration would prevail in future; *Scenario B*: The exposure to thermal stress will increase by average 5 days (current + 5) in future

Scenario A: Current conditions of thermal stress would prevail in future						
Location	**Average stress temperature currently experienced**	**Average stress duration currently experienced**	**Average present yield**	**Estimated yield with current set of thermal stress**	**Yield limitation in terms of Absolute values**	**Yield limitation in terms of relative values**
	(^{0}C)	(days)	(kg/ha)	(kg/ha)	(kg/ha)	(%)
Ludhiana	3.24	9.94	4325	3797	-528	-12.21
Hisar	4.20	11.90	3829	3353	-476	-12.43
Karnal	3.53	12.40	3831	3486	-345	-9.01
Kanpur	3.54	12.10	2830		Not affected	
Average					-450	-11.22

Current loss of total wheat production per year, in India, due to exposure to thermal stress in reproductive stage:11,70,000 kg ≃ 1.170 million tonnes (Assuming, wheat area sown in India = 26 million ha)

Scenario B: The exposure to thermal stress would increase by average 5 days (current + 5) in future						
Location	**Average stress temperature currently experienced**	**Project stress duration**	**Average present yield**	**Estimated yield with project set of thermal stress**	**Yield limitation in terms of Absolute values**	**Yield limitation in terms of relative values**
	(^{0}C)	(days)	(kg/ha)	(kg/ha)	(kg/ha)	(%)
Ludhiana	3.24	14.94	4325	3326	-999	-23.10
Hisar	4.20	16.90	3829	2866	-963	-25.15
Karnal	3.53	17.40	3831	3033	-798	-20.83
Kanpur	3.54	17.10	2830		Not affected	
Average					-920	-23.03

Projected loss of total wheat production, per year, in India due to exposure to thermal stress in reproductive stage: 23,92,000 kg ≃ 2.392 million tonnes (Assuming, wheat area sown in India = 26 million ha)

The projection of yield due to change in one or a few related production factors is a very sensitive issue due to the complexities and uncertainties involved in the farm production. Besides, assumption of rise of temperature throughout the growth season at a uniform pace is a contentious one, as we have seen that in different phases of reproductive stage the trend of temperature tends to incline on both positive and negative directions. Again, by virtue of the inherent genetic characteristics, the plant itself would exhibit tolerance to environmental stresses and due to mechanism of bio-chemical flexibility, to some extent, they can undo the harmful effects. Based on the analysis performed, we suggest that though the stress on wheat productivity, due to temperature, will be increasingly felt in the coming years, but the resultant losses in production and productivity may not be to that degree as suggested by Aggarwal (2007), provided water and other resources do not become limiting factors.

5. Summary

Wheat is a highly thermo-sensitive crop, particularly during its reproductive stage. In India, the 'North West Plain Zone' is the most productive wheat area with more or less assured irrigation, but yield fluctuations are observed across the zone. The average yield decreases by about 497 kg/ha with every unit increase of average temperature from 17.5 ^{0}C at Ludhiana to 20.3 ^{0}C at Kanpur during the wheat season. The study is aimed at quantifying the interaction of exposure to high thermal stress for a specific duration during the reproductive stage with yield, and resultant loss in production.

Rising trend of maximum temperature in 'heading to anthesis' and 'milking to dough' stages in the entire zone is of major concern due to high sensitivity of these stages to temperature rise and subsequent negative impact on yield. Quantified relationships for 'average daily temperature departure, from long term normal, by 2 ^{0}C for minimum 5 days duration' with district wise annual wheat yield were developed for two phenological stages at Ludhiana and the applicability of the relationships are extended to estimate yield in other locations through introduction of a response factor {RF = f(temperature departure x stress duration)}.

We found that a given magnitude of exposure to thermal stress may cause more wheat yield reduction in cooler climatic conditions than relatively warmer places. In the reproductive stage, a 10% reduction from the average yield is expected under 11 days of continuous thermal stress exposure at Ludhiana, 10 days at Hisar, 13 days at Karnal and 15 days at Kanpur if exposed to average daily positive temperature departure, from long term mean, by 3.24, 4.20, 3.63 and 3.54 ^{0}C, respectively.

Though water availability, so far, is not a limiting factor for wheat production but it is projected to decline in the near future due to increasing demands from various sectors (CWC, 2001). In such conditions, temperature stress coupled with water stress may exacerbate the negative effects on wheat production. However, the method used by the authors demonstrates satisfactory yield estimations in relation to atmospheric thermal regime in spite of complexities and uncertainties involved in actual farm production.

The projection of yield due to change in one or few related production factors is a complex exercise due to involvement of multiple factors, directly or indirectly and individually or interactively. Besides, assumption of rise of temperature throughout the growth season at a uniform pace is a contentious one, as we have seen that in different phases of reproductive stage, the trend of temperature tends to incline on both positive and negative directions. Again, by virtue of the inherent genetic characteristics, the plant itself would adapt to environmental stresses over time and to some extent undo negative effects. Based on the analysis performed, we suggest that though the stress due to rising temperature will be felt increasingly in the coming years, but the resultant productivity loss in wheat, in future, may be limited to 25% of the current level provided water and other resources do not become limiting factors.

The 2nd fortnight of February has been identified with marked increase in both maximum and minimum temperatures over all the locations corresponding to the crucial 'heading to anthesis' stage. Our findings confirm the concept of advancement of wheat growing period by at least 15 days, from the normal mid-November sowing to minimize the harmful effects due to rising temperature. Besides, concerted breeding effort to impart thermo-tolerance in high yielding wheat cultivars is of urgent need to sustain wheat productivity in near future.

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