Jour. Agric. Physics, Vol. 5, No. 1, pp. 46-56 (2005)

Simulating the Effect of Climate Change on Yield of Crops

RAMESH KUMAR, P., MANISH SINGH, NAVEEN KALRA, U.K. CHOPRA, M.S. NARANG[1], ANIL SHARMA, H.K. RAI, D. CHAKRABORTY, R.N. SAHOO, R.K. TOMAR, V.K. SEHGAL AND R.N. GARG

Division of Agricultural Physics, Indian Agricultural Research Institute, New Delhi-110 012
[1]Indian Agricultural Statistics Research Institute, Library Avenue, New Delhi-110 012

ABSTRACT

Effect of changes in seasonal temperature, rainfall and radiation on yield of various crops was studied on the pooled dataset of various agro-ecological regions. Food production at national scale (annual as well as *kharif*) had correspondence with the annual/south-west monsoon rains, whereas the food production during *rabi* season did not show significant relationship with the winter rains as most of the cereals grown during the *rabi*-season are usually under assured irrigated condition. The dependence of yield of wheat, barley, gram, rapeseed and mustard and maize with seasonal temperature was evaluated for north-western region of the country. Water-nitrogen interaction effect was characterized through simulation runs for New Delhi environment, and the N-doze to be applied depended on the extent of water availability through irrigation/ rainfall. The amount of winter rains received had significant effect on grain yield of wheat grown under limited moisture supply situation. The reduction factor for wheat, when grown under adequate inputs at research farm fields or the simulated outputs, was relatively higher than the value obtained at district level, which could be due to crops grown under the large extent of variations in biotic/abiotic stresses at regional scale. Optimal sowing date of wheat for various growing regions (at met-subdivision scale) was evaluated, and the extent of reduction in the attainable yield with pre-/post- sowing dates from the optimal date was evaluated using WTGROWS. The optimal dates were spatially variant, which mainly depended on the temperature during growing period of wheat. The adaptation strategy through delay in the date of sowing under various temperature rise scenarios was demonstrated for various growing locations. Wheat cultivars had differential response, in terms of growth and yield, with the temperature rise. The effect of aerosol or suspended particulate matter, through reduction in the amounts of solar radiation reaching the earth's surface, was evaluated through growth and yield response of wheat by running WTGROWS for New Delhi environment, and it could be concluded that the reduction in wheat yield was relatively lower for radiation reduction to the extent of 15 per cent from the normal.

Key words: Crop simulation model, climate change and its variability, climate-agronomic input interaction, sustainability and adaptation.

Introduction

Crop growth and yield is influenced by a number of biotic and abiotic stresses starting from sowing to harvest. Among abiotic stresses, climatic parameters (mainly temperature, rainfall and solar radiation) contribute more to change in yield of crops. Changes in seasonal temperature have a profound effect on the rate of physiological processes and ultimately on the yield of crops. As temperature rises, leaves are produced more quickly and the time taken to reach the harvestable maturity decline. Increased temperatures generally reduced yield because it shorten the duration of crop growth. Crops responded quite differently to temperature increase, higher magnitude of seasonal temperature during the different growth stages of the crop affects the yield of the crops. Crops like wheat is vulnerable to high temperature during reproductive stages (Nicoles *et al.* 1984; Wardlaw *et al.* 1989a; Tashiro and Wardlaw, 1990a; and Tashiro and Wardlaw, 1990b). In the present study, effects of temperature, water-nitrogen interaction, variability in winter rains and reduction in the solar radiation on growth and yields of various crops has been evaluated by using crop models.

Materials and Methods

Annual food production (total, *kharif* and *rabi*), on national scale, was related with seasonal and annual rains. Dependence of yield of various crops on temperature was evaluated at district scale in the north-western region. Long-term (1986-1997) datasets on yield of crops (at district level) and seasonal temperatures for the respective locations were compiled from various reports and meteorological observatories. From this relationship, reduction in yield per degree rise in temperature was computed for crops. Potential yield of wheat in various agro-environments was evaluated by running WTGROWS (Aggarwal and Kalra, 1994), and subsequently related with the seasonal temperature. The same model was used to work out the optimal sowing date and percent change in yield of wheat over maximum due to pre-/post- sowing from the optimal dates in different agro-environments. Subsequently, the model was used to evaluate the optimal dates of sowing in various locations under temperature rise scenarios. Water-nitrogen interaction effect was evaluated by using WTGROWS for New Delhi environment, for optimizing the N-input under variable water supply situation. Behaviour of different wheat cultivars under temperature rise was also simulated to judge their suitability. Effect of change in solar radiation on yield of wheat was also simulated for the same location. This was carried out to indirectly evaluate the effect of aerosol and suspended particulate matter on wheat yield through radiation reduction.

Results and Discussion

The effect of change in rainfall during *rabi* and *kharif* seasons on national food production was analyzed (Fig.1). During *rabi* season, no correspondence was noticed when per cent change in food production from trend line was related with per cent change in rainfall from normal. It was due to the reason that most of the *rabi* crops are generally grown under irrigated condition, and the rainfall does not show any significant relationship with the food production on national scale. But the results can be different in different segments of the country, particularly the rainfed and dry land regions. During *kharif* season, 0.64 % increase in food production was noticed with every 1 % increase in *kharif* rainfall from the normal. Annual food production also had one to one correspondence with the annual rains. This exercise has to be carried out for various agro-ecologies, production environments and crops.

The water-nitrogen interaction, for wheat grown under different combination of water and nitrogen inputs at New Delhi environment, was studied by using WTGROWS. Other inputs were assumed to be optimal for this location. There was a differential response of nitrogen for variable soil moisture availability during growth of wheat (Fig. 2). Under adequate irrigation supply, wheat yield was increased linearly up to 150-kg-N/ha. The optimal input of fertilizer-N decreased with the amount of irrigation. Rainfed wheat had relatively very low value of N and if the amount was increased resulted in reduction of the yield due to over-withdrawal of water in the initial stage of crop growth would result in almost dry condition during the post-anthesis phase of the crop. Nitrogen use efficiency has to be seen in relation to the stresses arising due to biophysical driving factors, mainly water and pests. It also depends upon the basal availability, primarily dependent upon the organic carbon content and prevailing weather condition.

Winter rains, as received in the north-west region are very useful to *rabi* crops (mainly wheat). The variability in the amounts received is significantly high, and a cause for concern under the climate change scenario (GHGs and aerosol). WTGROWS was used to evaluate the effect of the amount of winter rains on yield of wheat under adequate and limited water supply situation (Fig. 3). The response of the amount of winter rains was highly significant under rainfed and limited water supply situations (in particular relevant for eastern Rajasthan and Central region).

There is a need to generate technical coefficients / empirical functions to relate seasonal or inter-stage temperature and other climatic parameters with the growth and yield of crops, which can be conveniently linked with the climate change scenarios for evaluating the impact. For this purpose, the effect of increase in seasonal temperature on grain yield of different crops was evaluated. Results indicated differential response of

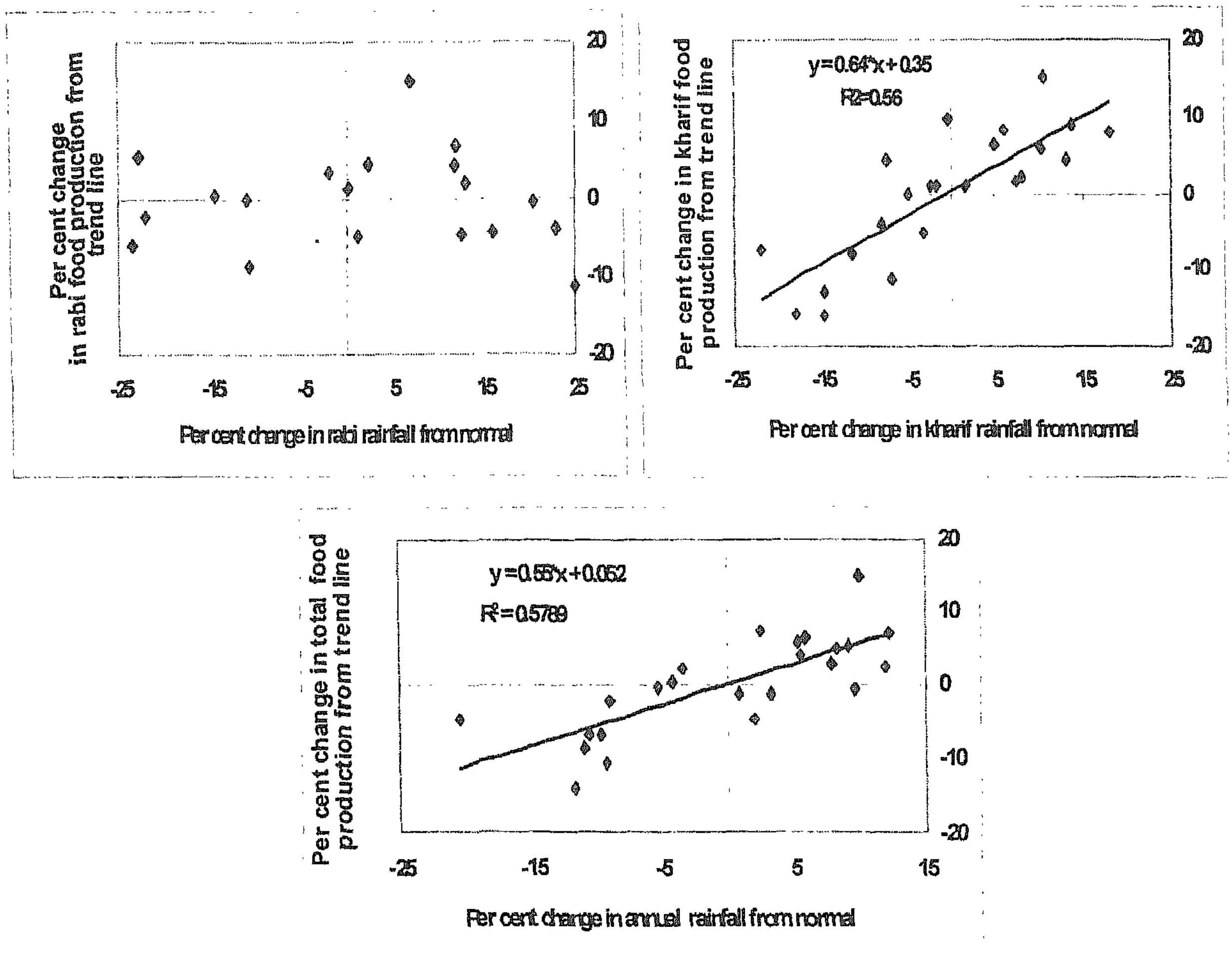

Fig. 1. Changes in food production with respect to rainfall

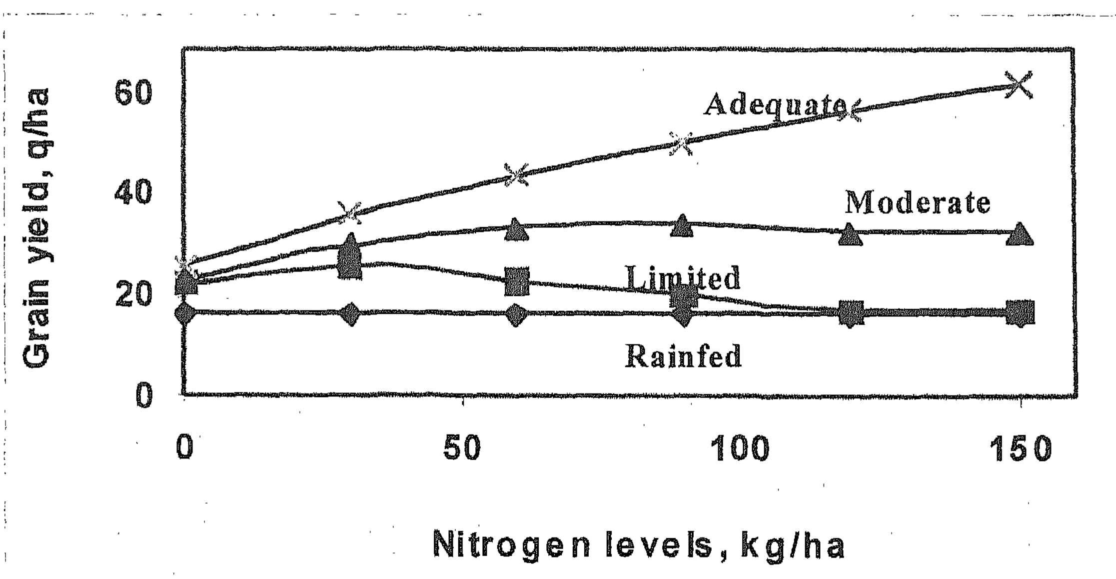

Fig. 2. Interaction effect of nitrogen and irrigation levels on wheat yield in New Delhi environment (WTGROWS)

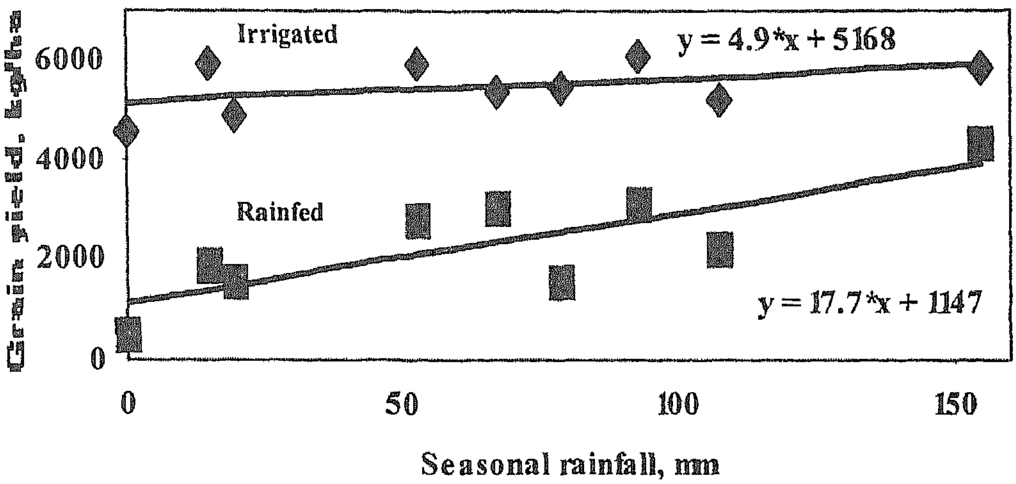

Fig. 3. Simulated wheat yields as a function of seasonal rains for irrigated and rainfed conditions in New Delhi environment

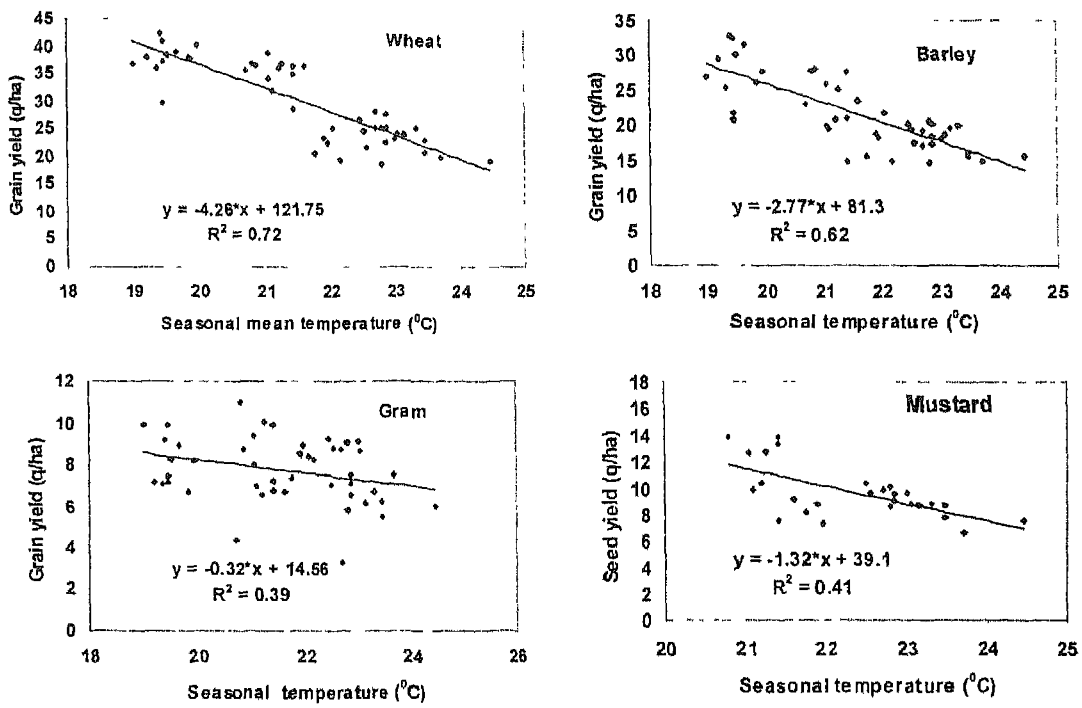

Fig. 4. Seasonal temperature dependence of yield of crops

crops to changes in seasonal temperature in various production environments. There was a decreasing trend in yield of all the five crops. The extent of reduction in wheat yield due to temperature rise was the highest (4.31q/ha/^{0}C) in Haryana followed by Rajasthan (2.78 q/ha/^{0}C), Punjab (0.45 q/ha/^{0}C) and Uttar Pradesh (0.37 q/ha/^{0}C). The similar trend was noticed for barley. The yield of gram was reduced due to rise in seasonal temperature and the extent of decrease was maximum (3.28q/ha/^{0}C) in Haryana followed by 2.49, 1.02 and 0.01 q/ha/^{0}C in Punjab, Rajasthan and Uttar Pradesh, respectively. The yield of rapeseed and mustard was reduced by 1.62 q/ha/^{0}C in Haryana followed by 0.17 and 0.97 q/ha/^{0}C in Uttar Pradesh and Rajasthan, respectively. Pooling of the datasets for all locations, in order to get the overall impact response in the northern region of the country, showed a decreasing trend in the yield of crops with the rise in temperature (Fig. 4). The reduction factors per degree rise in temperature were 4.26, 2.77, 0.32 and 1.32 q/ha/^{0}C rise for wheat, barley, gram and mustard, respectively. The effect of the temperature rise in case of gram was the lowest. These results can subsequently be linked with the climate change scenarios for evaluating the impact.

Effect of seasonal temperature change on yield of early, medium and late duration varieties of maize was evaluated (Fig. 5), which showed a decreasing trend in yield with temperature rise. Differential reduction in yield was noticed for different duration class varieties of maize. Decrease in yield was maximum (0.46 t/ha/^{0}C) in late duration, followed by medium duration (0.43 t/ha/^{0}C) and early duration classes (0.32 t/ha/^{0}C).

If these reductions in crops' yields are evaluated on the basis of research farm field results or by use of crop growth models, values may be relatively higher, primarily due to raising of most of the crops in research farm fields under adequate to moderate supply conditions or non-incorporation of the extent of spatial and dynamic course of variability in bio-physical and socio-economic inputs over a larger region. Potential yield of wheat in different regions of the country was simulated by the WTGROWS-model using the historic weather datasets on meteorological sub-division scales. Results revealed a large extent of differences in regions as well as large course of variability due to inter-annual climatic variations. Variability range happens to be more for higher productive regions, showing the vulnerability of climate change to these areas. Results were subsequently related to the seasonal temperature, which showed a decreasing yield trend due to rise in temperature with a slope of 634 kg/ha, that was relatively higher than the reduction factor evaluated on district scales by using the actual productivity records (Fig. 6). Since the reduction factor simulated with WTGROWS-model is for a potentially grown situation, the extent of reduction per degree rise in temperature is expected to be higher than the actual noted on regional scales where spatial temporal courses of variations exit in farmers' field.

There is a need to evolve a suitable methodology to extrapolate the results of research farm fields to regional level by capturing the extent of spatial and temporal variability in the bio-physical and socio-economic inputs in the farmers' fields. If the past historic datasets are used for a location, there is also a need to eliminate the technology growth rate trends from the historic productivity records to subsequently establish relationship with the climatic variability, which subsequently can help us in characterizing the impact in relation to climate change. Percent deviation in yield from the trend line, when plotted against the per cent deviation in seasonal temperature from the normal (Fig. 7), showed large scatter for all the four crops, indicating the need of inclusion of other bio-physical inputs to understand the system completely.

There is a need to screen the existing cultivars within a crop for the suitability under the climate change event. The cultivar's characterization is usually done through crop coefficients (genetic, physiologic and phenological), out of which thermal degree day requirement till a specific stage is important. The optimal thermal requirement for sustained cane yield under one degree celsius rise at Coimbatore, which clearly indicated the need to relatively longer duration cultivars for ensuring optimal vegetative phase in shown (Fig. 8). At our centre, pedigree analysis for various cultivars of important crops of this region is being done, to link with the relational layers of bio-physical and socio-

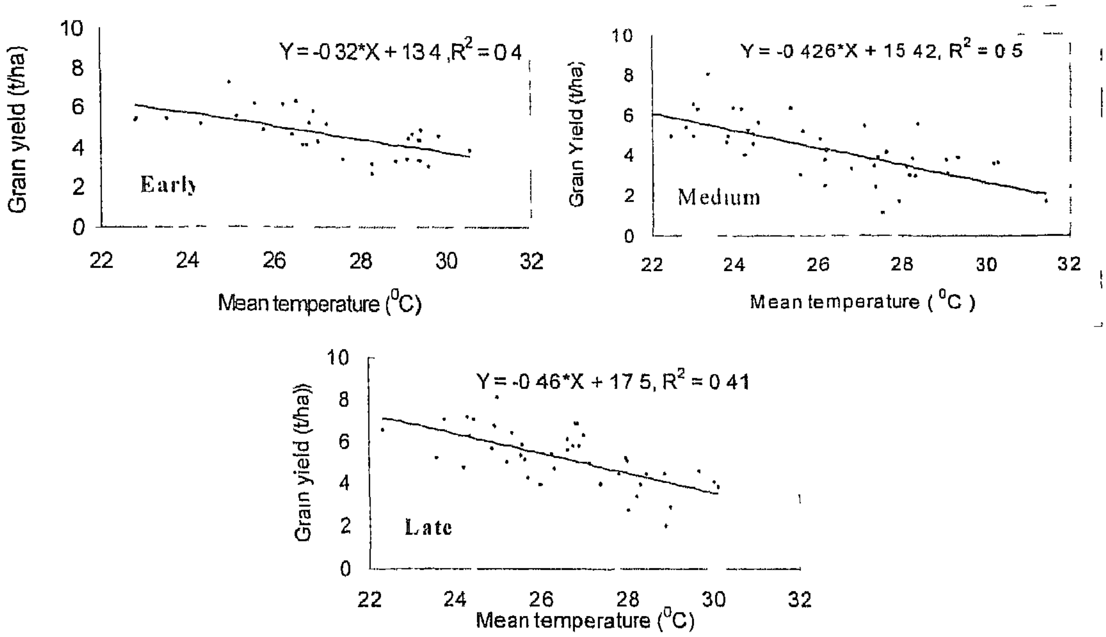

Fig. 5. Maize yield as influenced by seasonal temperature

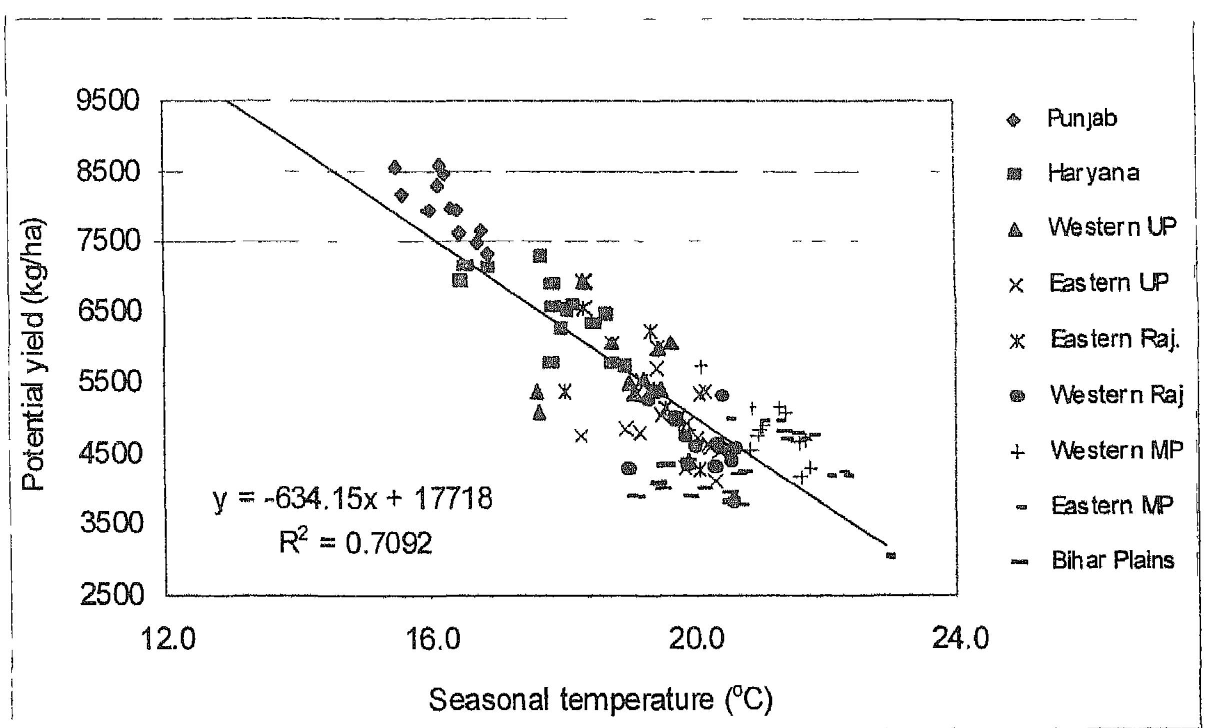

Fig. 6. Potential wheat yield as a function of temperature (simulated result)

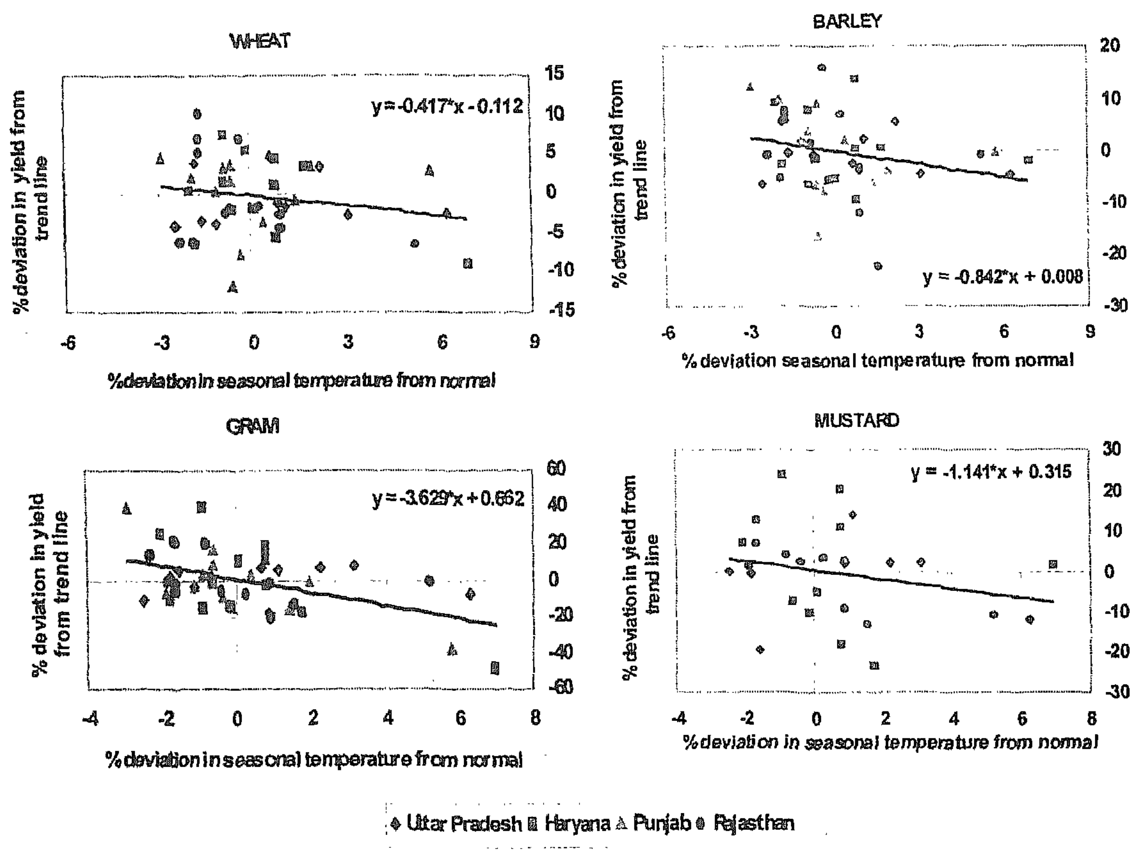

Fig. 7. Dependence of yield of crops on seasonal temperature change over normal

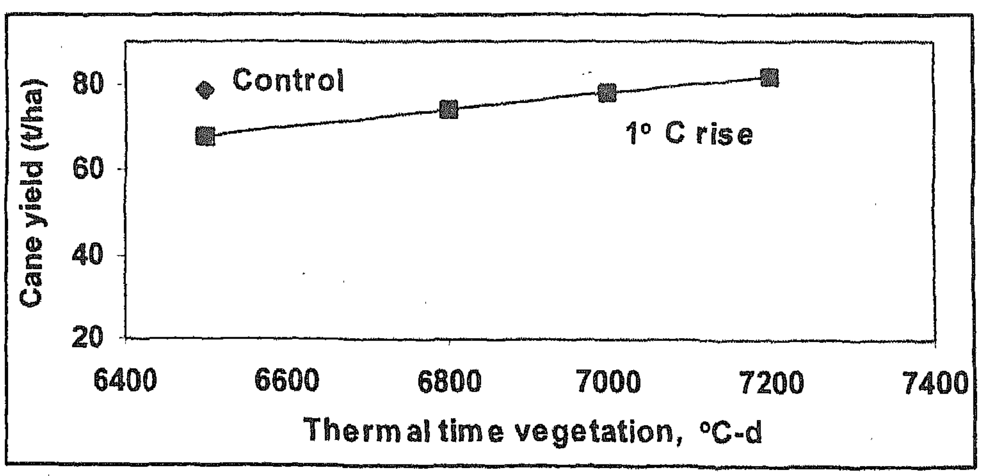

Fig. 8. Thermal degree day (till vegetation) requirement to sustain cane productivity for one degree celcius rise at Coimbatore

economic aspects for their suitability for a given region.

Effect of sowing date on wheat yield in various meteorological-sub divisions was evaluated using WTGROWS-model (Fig. 9). The model was run for optimally grown condition, i.e. adequate inputs of water, fertilizer etc. Normal weather of the location was employed for this purpose. The cultivars' characters (through heat degree days requirement, genetic coefficients) were used for the respective locations. Results indicated that optimum date of sowing for wheat was spatially dependent, mainly due to prevailing climatic conditions. Optimal dates were earlier in the north-west regions (Punjab and Haryana) when compared to central and eastern regions (M.P., Rajasthan, U.P. and Bihar). The large turn around time due to late harvest of basmati rice and tillage options for subsequent wheat poses problem in the Punjab, Haryana and Western U.P. There is a need to reduce the turn around time to match with the optimal dates for this region, and the zero tillage and bed plantings are becoming popular in this region. By adoption of these techniques, the reduction in the turn around time to the extent of 10-15 days is achieved in this region. Results further indicated significant reduction in yield over the optimal due to early or delay sowing of wheat from optimal date. Usually there is 1% reduction in the wheat yield per day delay in the sowing of wheat from the optimal date. Fig. 10 shows the optimal date of sowing for various locations under different levels of temperature rise (simulation results with WTGROWS under adequate inputs). In general, the date of sowing postponement by 5-7 days per degree rise in temperature, which is one of the important adaptation strategies for sustaining the crop yield.

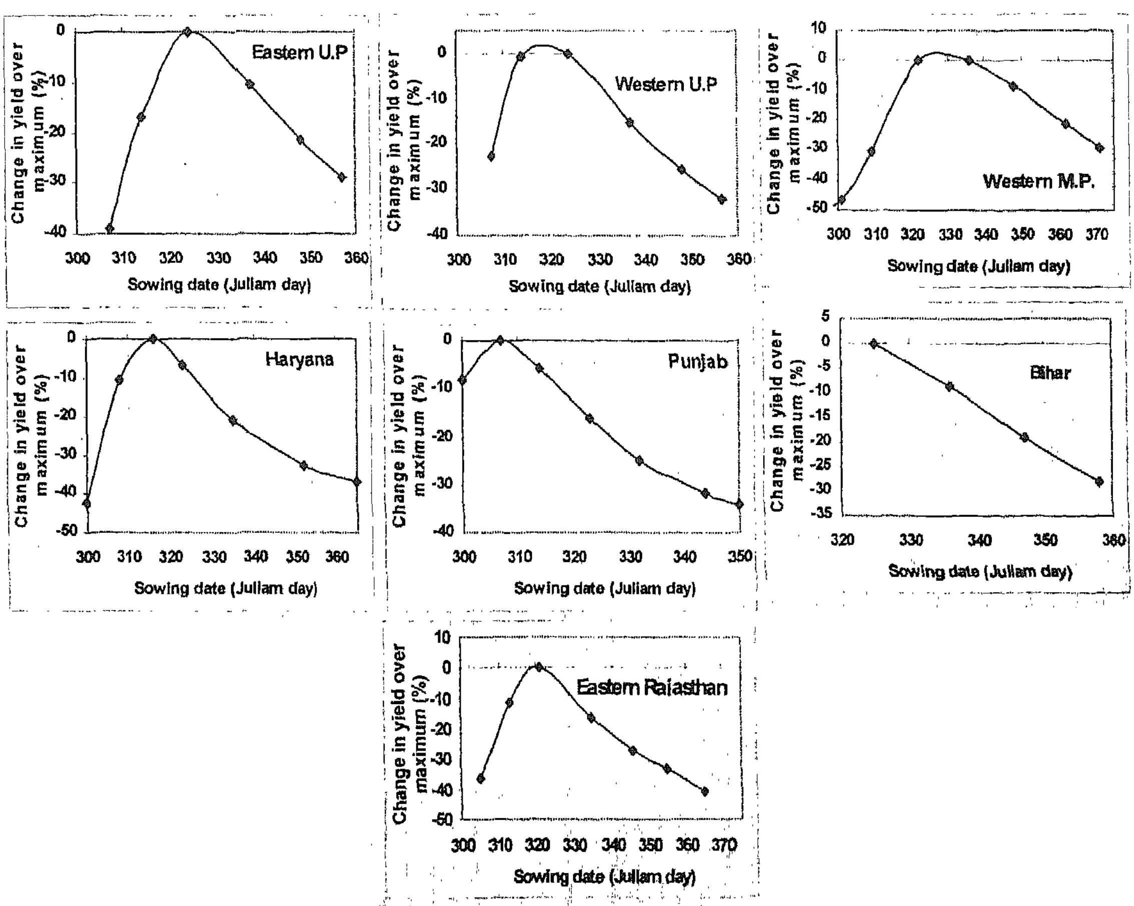

Fig. 9. Effect of sowing date on wheat yield under different met-sub divisions

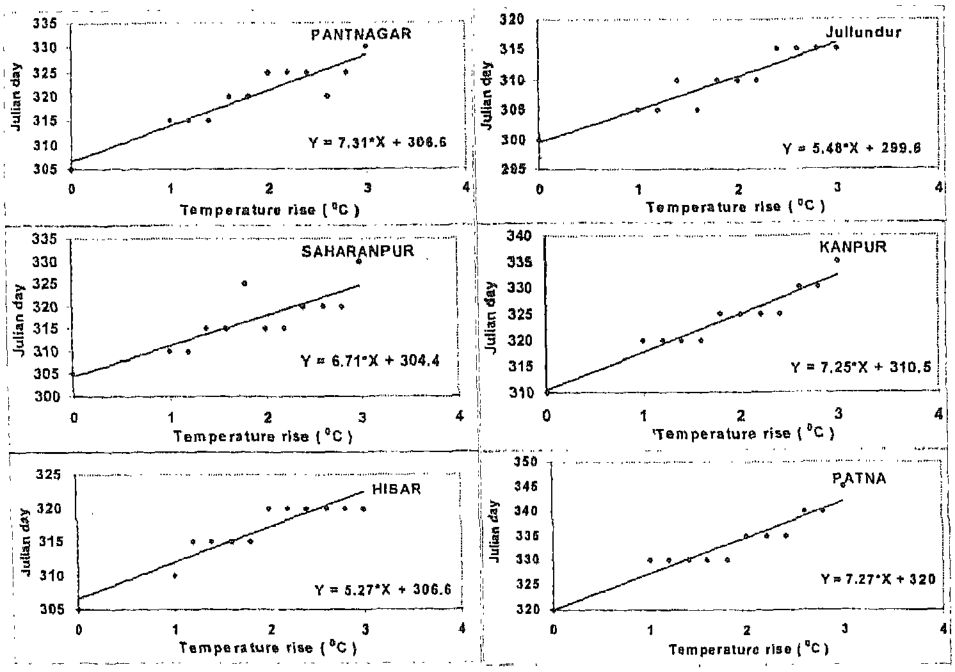

Fig. 10. Optimal date of sowing for wheat as influenced by temperature rise in various agro-environments

The effect of temperature rise (up to 3°C) on phenology, growth and yield of different wheat cultivars at New Delhi environment are presented in Fig. 11. Different cultivars showed varied response to temperature rise, in terms of phenology, growth and yield characters. Generally all the cultivars showed maximum grain yield production under the control (no temperature change), except the rainfed cultivar C306, which shows maximum grain yield production (32.72 q/ha) under 1°C rise in temperature, followed by no rise in temperature (31.75 q/ha) and 2°C rise in temperature (30 q/ha). Grain yield was drastically reduced under 3°C rise in temperature (25.2 q/ha). Among the irrigated triple gene dwarf cultivars, HD2285 showed maximum production of 57.1, 47.3 and 40.4 q/ha under control, 1 and 2°C rise, respectively. Where as under elevated temperature of 3°C rise, cultivar PBW343 produced the maximum grain yield of 34.9 q/ha, when compared with other test cultivars. Under 1 and 2°C rise in temperature also, cultivar PBW343 produced comparable yield of 46.8 and 39.7 q/ha, respectively, when compared with HD 2285. In production of total dry matter, PBW343 produced maximum dry matter of 74.6 q/ha under all the temperature rise treatments, whereas HD2285 produced the maximum total dry matter of 121, 102 and 87.7 q/ha under control, 1 and 2°C rise, respectively. Regarding the phenology, namely days to anthesis, HD2285 showed early flowering in all the four temperature treatments, with 80 days under control and 64 days under 3°C rise in temperature. Thus by increasing 3°C, flowering of the cultivar HD2285 can be advanced by 16 days with the average of 5 day per degree rise in temperature. Apart from HD2285, cultivar RAJ3765 showed comparatively early flowering when compared with other cultivars, with 84, 77, 72 and 67 days under control, 1, 2 and 3°C rise, respectively. Thus, there was 7 days reduction in flowering by increasing initial 1°C and thereafter 5 days reduction for each degree rise by 1°C. Cultivar C306 took long days to flower under all the treatments, ranging from 102 days under control to 78 days under 3°C rise in temperature. In case of post-anthesis duration, the trend got reversed with C306 taking less time (30 days under control and 33 days under 3°C rise in temperature), compared to rest of the cultivars. Under control, HD2285 took long time of 39 days to maturity from the anthesis, whereas RAJ3765 took long days to mature under elevated temperatures of 1 to 3°C. With increase in

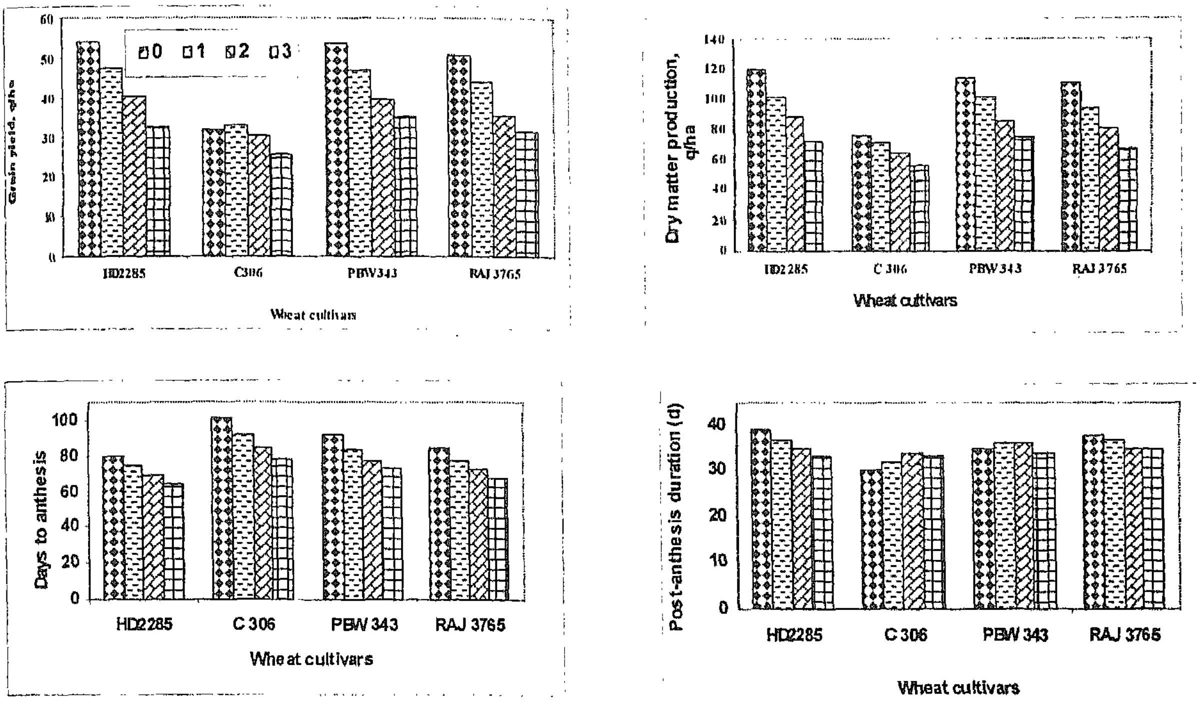

Fig. 11. Effect of temperature rise (upto 3 degree celcius) on phenology, growth and yield of wheat cultivars at New Delhi environment

temperature, rainfed cultivar showed increase in days to maturity (average of one day delay in maturity per degree rise in temperature) and irrigated cultivars showed decrease in days to maturity (average of two days early maturity per degree rise in temperature). Thus, rainfed (C306) and irrigated cultivars (HD2285, RAJ3765 and PBW343) behaved just opposite, when compared with pre-anthesis duration.

The effect of reduction in radiation on wheat yield in New Delhi environment was evaluated by using WTGROWS-model (Fig. 12). The optimal grown conditions were assumed for this exercise. Results indicated that reduction in radiation upto 15% was not having much effect on wheat yield. With 40% decrease in the radiation, the yields reduced by around 10%. Usually this problem of the radiation reduction happens in the months of December and January. But at that time, the crop is the early phases, i.e., early jointing, where the extent of radiation requirement by the crop is generally low. This event is due to foggy weather or the aerosol layer at a height of 3-4 km. Though there is a reduction in the direct solar radiation, that

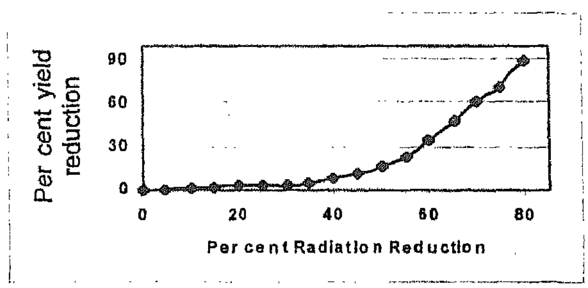

Fig. 12. Effect of radiation reduction on yield of wheat in New Delhi environment

also not exceeding by 10 %, but the diffused radiation component increases. This diffused component compensates for the reduction of the direct part, as it also contributes to the photosynthetic activity. There is a need to work out the photosynthetic efficiency of the diffused radiation for the crops. Presently, this part has not been delt in the model.

Conclusion

There is a need to relate the inter- and intra-seasonal variability in climatic parameters with growth and yield of important crops, which subsequently can help in evaluating the impact of climate change scenarios on agriculture. The seasonal temperature has one-to-one correspondence with the final yield of major crops, which can aid in extrapolating the results for evaluating the impact of climate change. There is a need to evolve a methodology for extrapolating the results obtained at research farm-field scales to regional levels, by including the extent of spatial and temporal course of variability in the farmers' fields so that the extensive research carried out in the research institutes can be utilized for regional impact studies. Large course of variability in the winter and south-west monsoon rains is clearly indicated through the national food production (annual and *kharif*), but this type of study has to be carried out in various agro-ecologies, production systems and crops. Winter rains play a major role in deciding the yields of rainfed *rabi* season crops. Crop growth simulation models capture the growth and yield of crops under various biotic as well abiotic stresses, but lack in extrapolating the results on regional scales. There is a need to link the crop growth models with the relational database layers through remote sensing and GIS platforms to understand the agricultural production at regional scale. Probability of occurrence of extreme climatic events has increased in the recent past, and we have to devise simple decision tools for evaluating the impact as well for defining the appropriate land use options for sustained agricultural productivity.

References

Aggarwal, P.K. and Kalra, N. 1994. Simulating the effect of climatic factors, genotype and management on productivity of wheat in India, I.A.R.I Publication, New Delhi, 156 pp.

Nicolas, M.E., Gladow, R.M. and Dalling, M.J. 1984. Effects of drought and high temperature on grain growth in wheat. *J. Plant Physiol.* **11**: 553-566.

Tashiro, T. and Wardlaw, I.F. 1990a. The effect of high temperature at different stages of ripening on grain set, grain weight and grain dimensions in the semi dwarf wheat 'Banks'. *Ann. Bot.* (London) **65**: 51-61.

Tashiro, T. and Wardlaw, I.F. 1990b. The response to high temperature shock and humidity changes prior to and during the early stages of grain development in wheat. *Aust. J. Plant Physiol.* **17**: 551-561.

Wardlaw, I.F., Dawson, I.A., Munibi, P. and Fewster, R. 1989a. The tolerance of wheat to high temperatures during reproductive growth. 1. Survey procedures and general response patterns. *Aust. J. Agric. Res.* **40**: 1-13.