Impacts of climate change on agriculture

Naveen Kalra, Subhash Chander, H. Pathak, P.K. Aggarwal, N.C. Gupta, Mukesh Sehgal and Debashis Chakraborty

Abstract: *Climate change has emerged as the most prominent of the global environment issues and there is a need to evaluate its impact on agriculture. Crop simulation models help greatly in this regard. Crop models such as WTGROWS, INFOCROP, ORYZA and DSSAT have been widely used for land use planning, agri-production estimates, impact of climate change and environmental impact analysis. Vulnerable regions under future scenarios of climate change and adaptation strategies (agronomic and input management) have been evolved for many important crops by using simulation techniques. One of the simple empirical techniques for evaluating the impact of future climate change is through historic analysis of the response of crops to inter-seasonal climatic variability. The impact of temperature rise is different for crops grown under variable production environments. Interactions exist for changes in temperature, carbon dioxide concentration, solar radiation and rainfall on growth and yield of crops. Adaptation strategies through the adoption of agronomic management options (such as altered date of sowing, scheduling of water and nutrients) can sustain agricultural productivity under climate change. The rapid changes in land use and land cover have to be included for impact analysis. Linking of the socioeconomic aspects needs to be strengthened.*

Keywords: *climate change; climatic variability; soil health; crop yield; crop model; pests*

Naveen Kalra, Subhash Chander and H. Pathak are with the Indian Agricultural Institute, New Delhi, where Dr Kalra is Head of the Division of Agricultural Physics, Dr Chander and Dr Pathak are Senior Scientists in the Unit of Simulation and Informatics, Dr Aggarwal is Head of the Environmental Sciences Division, and Dr Debashis Chakraborty is a Scientist in the Division of Agricultural Physics. Dr N.C. Gupta is a Lecturer in the Environment Management Group at the GGS Indraprastha University, New Delhi. Dr Mukesh Sehgal is a Senior Scientist at the National Centre for Integrated Pest Management, Pusa Campus, New Delhi. Contact: Dr Naveen Kalra, Head, Division of Agricultural Physics, Indian Agricultural Research Institute, New Delhi-110012, India. E-mail: nkalra@iari.res.in; kal_Naveen@yahoo.co.in.

The agricultural sector represents 35% of India's gross national product and sustains the livelihoods of almost 75% of the population. Food grain production has increased during the post-independence era from 51 to around 206 million tonnes. This has been possible by increasing the area under cultivation, enhancing crop yield through the use of high-yielding varieties and increasing resource inputs. India has numerous agro-ecological systems, with diversity in crops and cropping systems, climate, agronomic and resource management inputs and socioeconomic aspects. The soils of tropical Asia are low in N, P and K content, hence the sustainability of agricultural production and food security greatly depend upon climatic conditions.

The nation's food production is a gamble with the South-West Monsoon. In the last 50 years, there have been around 15 major droughts in the country, when productivity was affected. Although we have learnt to deal with this situation, especially since the severe drought of 1987, this problem still creates much social, political and cultural instability in the country. In the recent past, it has been observed that the productivity of the rice–wheat cropping system is declining in the most productive belt of the country. This is due to a lowering of the ground water table, reduced organic carbon content, introduction of new pests and delays in the sowing of wheat after late harvesting of rice.

Climatic variability

The climate has been changing naturally at its own pace since the beginning of time, but recently it has gained momentum due to man's interventions. The global mean annual temperatures at the end of the twentieth century were almost 0.7ºC above those recorded at the end of the nineteenth century. The diurnal temperature range has also increased, with night-time temperatures increasing at twice the rate of daytime maximum temperatures. The increase in mean temperatures over India is almost solely due to the increase in maximum temperatures (0.6ºC per 100 years), the minimum temperatures remaining practically stable, thus leading to an increase in the diurnal range of temperatures. The 1990s were, on average, the warmest decade since instrumental measurement of temperature started in the 1860s, and the 1900s constituted the warmest century of the last 1,000 years. The seven warmest years globally in the instrumental record occurred during the 1990s. The CO_2 concentration was 280 ppm between 1000 and 1750 AD, and today, this value has become 369 ppm. The Intergovernmental Panel on Climate Change (IPCC) Scenario indicates that CO_2 concentrations will be between 397 and 416 ppm by 2010, and between 605 and 755 by 2070. The estimated dry biomass production from agriculture in India is almost 800 million tons every year. This is equivalent to fixation of 320 Tg (10^{12} gram) of C. Only a part of this is retained over time as the body weight of human beings and other consumers, and the rest is released back into the atmosphere. Methane has increased since pre-industrial times from 700 to 1,750 ppb, accounting for about 15% of global warming. Methane concentration in the atmosphere is presently increasing at around 1% per year. India's total contribution to global methane emissions from all sources is only 18.5 Tg per year, compared with 535 Tg/year for the world. Rice paddies and ruminant animal production constitute a major (68%) source of these emissions. The main reason for low methane emissions from rice fields in India is that paddy is grown under soils with low organic carbon content and is subject to alternate wetting and drying conditions. Nitrous oxide, with its current concentration of 316 ppb in the atmosphere and increasing at the rate of 0.22% per year, is an important greenhouse gas accounting for approximately 5% of the total greenhouse effect, and is also responsible for the destruction of stratospheric ozone. Both fertilized and unfertilized soils emit N_2O, and estimates of total nitrous oxide released from Indian agriculture are low due to the generally low native soil fertility of our soils and the relatively lower amounts of fertilizers used compared with Western countries.

Inter- and intra-seasonal climatic variability is significantly evident in India. Sometimes these variations are confused with climate change. While the impact assessment of future climatic change is quite important, most crops in India, even in irrigated environments, are fairly sensitive to climatic variability. Winter rains in north-west India ranged from 0–12 cm in the past, and were generally received in smaller amounts at greater frequency, but benefited the *rabi* (winter season) crops, mainly wheat, of this region. The quantity of rainfall and its associated events has, however, become more uncertain In certain places, climatic extremes such as droughts and floods, the duration and timing of rainfall and snowmelt have increased.

It is often the case in climate change studies that the proposed scenarios are regarded as plausible, but have no further probability attached. Projected ranges of uncertainty can have probabilities attached to them and so are more likely to occur than individual scenarios. However, as significant uncertainty remains beyond the projected range, such projections cannot be regarded as forecasts and are without any degree of resolution.

Impact of climate change/variability on soil productivity

Soil organic carbon

Most regions in India can be described as tropical to subtropical, with most soils low to medium in organic carbon content. The possibility of carbon sequestration by incorporation of organic residues may not be feasible on a long-term basis, due to faster degradation under the prevailing higher temperatures. Regions such as Pantnagar, which previously had higher levels of organic matter, have now stabilized at 0.6–0.7%.

An increase of 1ºC in soil temperature may lead to increased liberalization of N, but N availability for crop growth may still decrease due to increased gaseous losses through processes such as volatilization. There are reports that crop residues under elevated CO_2 have a higher C:N ratio, and this may reduce their rate of decomposition in soils, leading to an increment in ecosystem carbon stock. Biological nitrogen fixation under elevated CO_2 may increase, provided other nutrients are not strongly limiting.

Soil fertility

Results of the All India Coordinated Long-Term Fertility Trials indicate that regions having an initial higher organic carbon content (> 0.6%), are showing a decline, whereas regions with lower organic carbon content have remained more or less static, or have demonstrated a slight increase in organic carbon content over a period of about 25 years.

The interaction of nitrogen, irrigation and seasonal climatic variability, particularly where there is low input of irrigation, has several implications. Where there is adequate moisture supply, such as in Punjab and Haryana, yields benefit from higher nitrogen application, whereas in regions of limited to moderate water supply, smaller increases in yield are noticed from N application. At low levels of water availability, it is difficult to determine optimal levels of N fertilizer application for maximizing yield returns in view of the uncertainty of N response. (Compare this with the substantial response to N applied during good post-monsoon rainfall received during the crop-growing period [Kalra and Aggarwal, 1996].)

Fertilizer and resource management options for enhancing crop productivity have been evaluated under interannual variations in weather conditions (Das and Kalra, 1995). The results revealed the sensitivity of crop yields to climatic variability and the need for inputs to be managed in relation to climatic variability.

Agricultural productivity trends

Annual food production shows an increasing trend, and deviations (those not related to technology use) can usually be related to seasonal rainfall. For instance, in the case of *rabi* season food production, which occurs at the time of the winter season's rainfall, no definite trend can be seen as the majority of food production in this season is in the irrigated areas.

The quality of surface and groundwater is deteriorating due to rapid growth in industrialization, and scheduling of common use of poor quality water, together with fresh water for crops and cropping systems, needs to be evaluated and subsequently linked with climate change scenarios for impact analysis.

Water availability

Under the climate change scenario, the onset of summer monsoons over India is projected to be delayed and often uncertain. This will have a direct effect not only on rainfed crops, but also on water storage, and hence the availability of irrigation water. Availability of water for agriculture will in future have to compete with demands for water for other uses, thereby placing additional strains on agriculture. Increases in temperature will also lead to increased evapotranspiration, which may result in a lowering of the groundwater table in some places. Increased temperature coupled with reduced rainfall may lead to upward water movement, resulting in accumulation of salts in the upper soil layers. Similarly, rises in sea level associated with increased temperature may lead to salt-water ingression in the coastal lands, making them unsuitable for conventional agriculture.

There is a large variability in interannual as well as inter-seasonal rainfall in this region, which is also well reflected in differential crop responses. Around New Delhi, where the winter rains of up to 12 cm in spells matching the critical growth stages of the crop, wheat yields of 75% rise to 90% of the attainable yield with three irrigation periods. Relating water availability and its use to crop yields helps in identifying critical growth stages when limited amounts of water can be applied to obtain the maximum benefits (Kalra *et al*, 1994).

Soil microbial activity and GHG emissions

Microbes have emerged as the major contributor as well as consumer of greenhouse gases (GHGs), as micro-organisms are the main intermediaries of C turnover in soil. They are also considered to be the sole agents of soil humus formation, cycling of nutrients, soil tilth and structure, amongst a myriad of other functions. What will happen to soil fertility in the event of global climate change needs to be addressed through examination of soil organic matter (SOM). Soil microbial biomass has been shown to respond rapidly to changes and perturbations, often before measurable changes occur in organic C and N, thus acting as an indicator of long-term changes in SOM content (Powlson and Brookes, 1987). However, the measurement of microbial biomass (C_{mic}) alone will not serve the purpose because it is generally influenced by climatic variables. Hence, for real measurement of the impact on soil processes, the proportion of total organic C or N (C_{org}) within the microbial biomass, ie the microbial quotient, needs to be considered. Under conditions of equilibrium, the C_{org} of agricultural soils contains 2.3– 4% C_{mic}. Soils exhibiting a C_{mic} to C_{org} ratio higher or lower than these values at equilibrium would be either accumulating or losing C respectively (Anderson and Domsch, 1986). Different climatic conditions, in particular precipitation/evaporation, influence the equilibrium C_{mic} to C_{org} ratio, and a very high correlation was found in which a 73% variation could be explained with the quadratic function, thereby enabling the prediction of soil fertility in terms of accumulation or losses of C (Insam, 1990).

CO_2 effluxes from tropical systems will increase markedly with small changes in temperature without any increase in inputs from the above-ground communities, thereby leading to rapid losses over a short period of a few decades, and later the system will sustain a balance because of the shortage of substrate for decomposition as well as the adaptation of microbial communities to climatic change.

Soil degradation

Increased rainfall will accelerate the rates of soil loss and further reduce farm productivity. Erosion is also likely to increase sedimentation in streams and reservoirs. Wind erosion is another possibility in dry soils (Parry *et al*, 1999). If erosion goes unchecked, continued soil impoverishment will eventually force farmers to abandon their lands. All IPCC scenarios indicate rises in sea level with global warming, and low-lying areas around the coast would be submerged, thereby reducing the opportunities for crop cultivation in these areas. At the same time, other neighbouring areas might become more saline, further reducing the current coastal land available for producing crops.

It is evident from all this that climate change can influence food availability through its direct effect on growth and yield of crops, and indirectly through changes in rainfall (irrigation availability), soil organic matter transformation, soil erosion, changes in pest profiles, and a decline in arable areas due to submergence of coastal lands. There are also other likely indirect influences, which cover changes in the socioeconomic environment including government policies, capital availability, prices and returns, infrastructure, land reforms, and inter- and intra-national trade. Rising carbon dioxide and temperature and changes in rainfall are of direct physiological consequence to plant growth, development and yield. Temperature and rainfall most obviously affect the morphology and physiology of plants, and changes in CO_2 affect plant morphology, photosynthesis and transpiration. Environmental control, especially of CO_2, is very difficult and expensive, and even worldwide there have been only a few studies. But lately, a facility has been developed at the Indian Agricultural Research Institute (IARI) in collaboration with international scientific agencies, which will be useful for quantifying the response to CO_2 of agriculturally important crops in the region. The interaction effects of CO_2, rainfall and temperature can also be best studied though the use of crop growth simulation models.

There have been very few attempts to study the possible impact of climate change on non-cereal crops. Increases in temperature may have significant effects on the quality of cotton, fruits, vegetables, tea, coffee, aromatic and medicinal plants. The nutritional quality of cereals and pulses may also be moderately affected, which in turn will have consequences for nutritional security. In hill country, the low temperature and shorter growing period limit the productivity of crops. Global warming is likely to prolong the growing season, which could result in higher crop yields, provided water remains available.

The rising temperatures and carbon dioxide and uncertainties in rainfall associated with global climatic change may lead to serious direct and indirect consequences on crop production and hence food security (Sinha and Swaminathan, 1991). We recently witnessed such an impact of climatic events on food availability in 1998 in the form of a crisis in the supply of onions, potatoes, cauliflower and tomato, which triggered some unprecedented social and political impacts. These demonstrated once again how little we understand about the integrated relationships of weather and agriculture and how little we have developed the back-up for policy support in such unfortunate and unforeseen circumstances. It is, therefore, important to have an assessment of the direct and indirect consequences of global warming on different crops contributing to our food security. It is also important to develop a policy response to address such concerns in future with a more mature scientific understanding and also to provide back-up support for our negotiations in international conventions. Future agricultural planning thus has to take note of the overall goal of attaining congruence in productivity, stability, sustainability, profitability and equity in Indian agriculture in the coming decades.

Impact of climate change/variability on crop productivity

The dependence of crop yields (wheat, barley, gram and mustard) on seasonal temperature was established for the northern region of the country by compiling historic datasets on meteorological subdivisional scales (Figure 1). Reduction in yield associated with increases in temperature was characterized for these important crops for the northern region during the *rabi* season. The reduction factors per degree rise in temperature, on average, were 4.26, 2.77, 0.32 and 1.32 q/ha for wheat, barley, gram and mustard respectively. There is also a need to eliminate the growth rate trends due to changing technology from the historic productivity records to establish their relationship with climatic variability, which can subsequently help us in characterizing the impact in relation to climate change.

The wheat growth simulator (WTGROWS) developed at IARI, New Delhi, has been extensively tested using different agro-environments (Aggarwal and Kalra, 1994). It has been successfully used for resource management, forecasting of wheat yields and climate variability-related studies. Using this model, a strong linear decline in wheat yield was noticed with the increase in January temperatures. For every degree increase in mean temperature, grain yield decreased by 428 kg/ha. Inter-seasonal climatic variability analysis for wheat yield indicated that the impact of the variability was lowest for Kota and highest for Solapur. Inter-seasonal climatic variability has been characterized through growth and yield response under different production environments.

WTGROWS was used to discover the optimal date of sowing at various locations of Indo–Gangetic alluvial plains when temperatures were rising – see Figure 2 (Aggarwal and Kalra, 1994). Places having higher potential yields of wheat had greater reductions in yield per day with delays in sowing from the optimal date. A few locations (north-eastern areas) showed a small yield reduction with delayed sowing. In practice, as the temperature rises, adjustments can be made to the date of sowing to ensure similar weather conditions, but this can lead to imbalances in the cropping system schedule.

Aggarwal and Kalra demonstrated, by using WTGROWS, the shift of iso-yield lines of wheat yield northward at concentrations of 425 ppm of CO_2 and a 2ºC rise in temperature. The rise in carbon dioxide concentration in the atmosphere effectively influences the productivity of the crop plants.

(For these studies, open-top chamber facilities have been developed at various institutes in India. In these chambers, the coupled weather and canopy environments also change along with CO_2, and thus the differences in growth and yield of crops become a complex function of these parameters. To work out the impact of carbon dioxide and temperature only, Free Air Carbon Dioxide Enrichment (FACE) facilities have been established at the Indian Agricultural Research Institute, New Delhi in collaboration with the National Physical Laboratory.)

Enhanced carbon dioxide concentration has been shown to affect the carbon dioxide assimilates and their partitioning within the source leaf and transport to the sink in mung bean and wheat. Carbon dioxide elevation partially compensates for the negative effect of moisture stress in *Brassica* plants. All the yield components in rice, namely panicle number (effective tillers), filled grains per panicle and grain weight, responded positively to enhanced carbon dioxide levels. Increased photo-assimilate supply possibly increased the percentage maturity of the seeds (Uprety, 1998).

WTGROWS was used to evaluate the interaction of radiation with temperature for wheat in New Delhi and Patna environments (Figure 3). The range of variation among treatments for above-ground biomass was narrower, except for temperature rises of 3ºC, whereas the differences were wider in the case of grain yield, where the interaction effect was more pronounced. In general, the above-ground biomass and grain yield fell gradually with reductions in radiation, the trend being more consistent in Patna than in the New Delhi environment. Temperature rises of 1ºC had some positive effects compared with the control (no temperature rise) both for

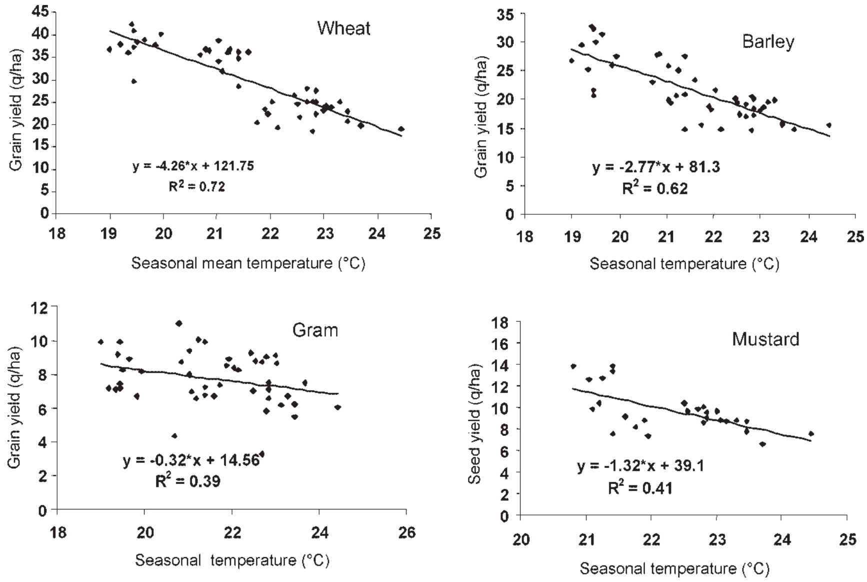

Figure 1. Yield (q/ha indicates 100 kg/ha) of various *rabi* (winter) season crops, as related to seasonal temperature (northern environment).

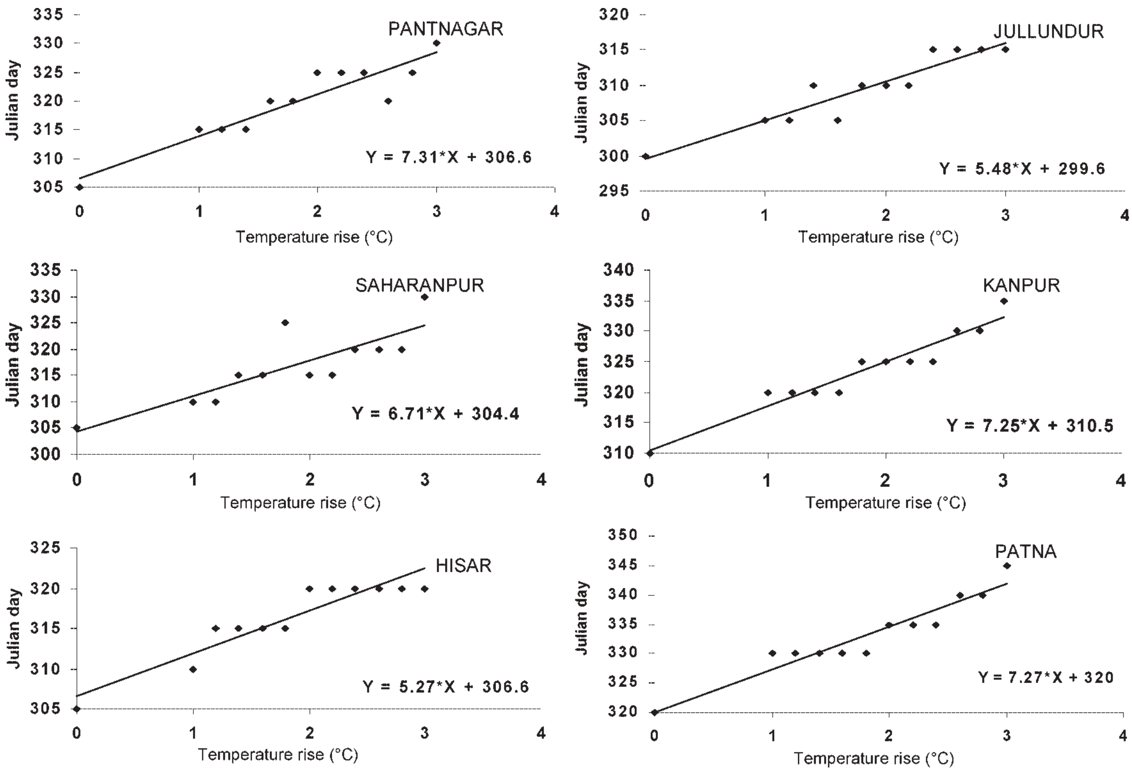

Figure 2. Optimum sowing date for wheat, as related to temperature rise at various locations in the Indo–Gangetic alluvial plains.

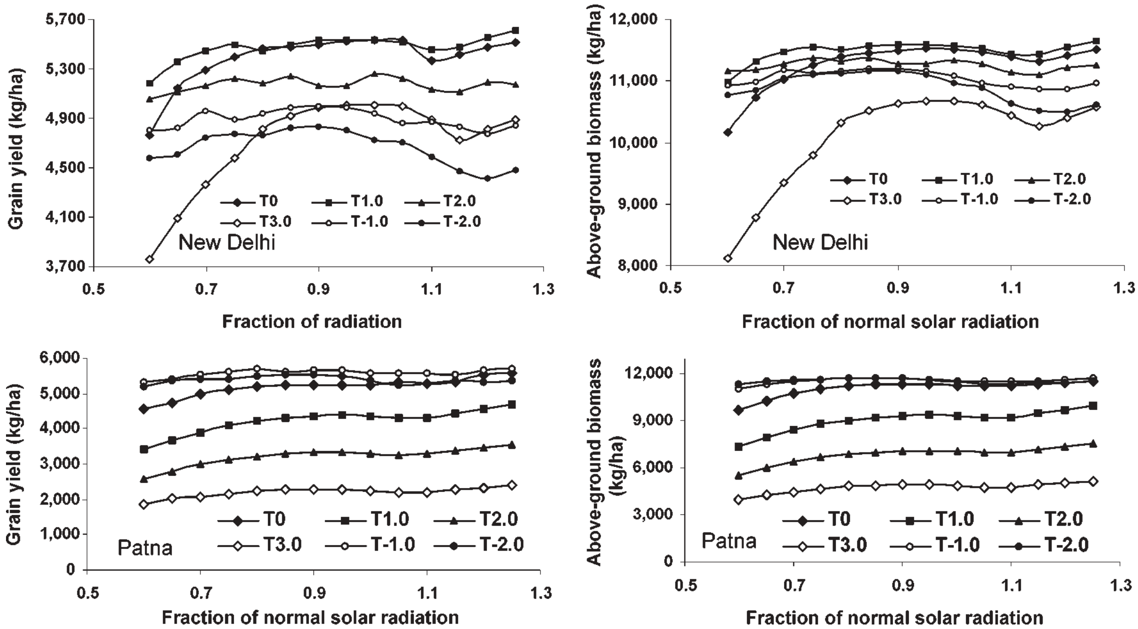

Figure 3. Interaction effect of temperature and radiation changes on grain yield and above-ground biomass of wheat in New Delhi and Patna environments.

above-ground biomass and grain yield in the New Delhi environment. Subsequent rises in temperature reduced the biomass and yield over the control treatment, and the extent of the reduction was quite large for a 3ºC rise. Reductions in temperature of 1º and 2ºC enhanced the grain yield and biomass for the Patna environment due to the relatively higher temperatures during the growth of wheat crops under normal conditions. The amount of reduction in yields associated with reductions in radiation is not large until radiation decreases by around 20% from the normal values.

Gadgil and her group (Gadgil, 1995; Gadgil *et al*, 1999a and b) used the PNUTGRO model to determine the sowing window for rainfed groundnut. Variation in the model yield with sowing date showed that a broad sowing window of 22 June to 17 August was the optimum for minimizing the risk of failure. It was also shown that the incidence of locally triggered pests/diseases, namely *leaf miner* and late leaf spot (*tikka*) was smaller when sowing was postponed until after mid-July, and thus did not involve much risk. It was also seen that moisture availability was critical for the pod-filling stage.

Lal *et al* (1999) projected significant increases in yield for soybean with the doubling of CO_2 in central India. However, a 3ºC rise in surface air temperature almost cancels out the positive effects of a doubling of carbon dioxide concentration. A decline in daily rainfall amount by 10% restricts the grain yield to about 32%. Hundal and Kaur (1996) examined climate change impact on the productivity of wheat, rice, maize and groundnut crops in Punjab. If all other climate variables were to remain constant, temperature increases of 1º, 2º and 3ºC from present-day conditions would reduce the grain yield of wheat by 8.1, 18.7 and 25.7%, rice by 5.4, 7.4 and 25.1%, maize by 10.4, 14.6 and 21.4% and the seed yield of groundnut by 8.7, 23.2 and 36.2% respectively. Lal *et al* (1998) examined the vulnerability of wheat and rice crops in north-west India and found that under elevated CO_2 levels, yields of rice and wheat increased significantly (15% and 28% for a doubling of CO_2). However, a 3ºC rise in temperature cancelled out the positive effect of elevated CO_2 on wheat (2ºC for rice). The combined effect of enhanced CO_2 and imposed thermal stress on the wheat crop leads to a 21% increase in yield (4% for rice) with the irrigation schedule presently practised in the region. While the adverse impacts of likely water shortage on wheat crops would be less severe under elevated CO_2 levels, they would largely be maintained for the rice crops, resulting in a net decline in rice yields.

INFOCANE has been developed at IARI for simulating the growth and yield of sugarcane and understanding the climate change impact in three contrasting agro-ecologies. The model was tested in farmers' fields and thereafter used for suggesting resource management options and for evaluating the impact of temperature rise, carbon dioxide increase and rainfall changes in the contrasting environments.

Mandal (1998), Chatterjee (1998) and Sahoo (1999) calibrated and validated the CERES-maize, CERES-sorghum and WOFOST models for the Indian environment and subsequently used them to study the impact of climate change (CO_2 levels: 350 and 700 ppm; temperature rise from 1–4ºC) on the phenology, growth and yield of different cultivars.

Mandal (1998) observed that increases in temperature of up to 2ºC did not influence the potential and irrigated yields and biomass of chickpea. Pre-anthesis and total crop duration were reduced with the temperature rise. Nitrogen uptake and total water use were not significantly different up to a 2ºC rise. Raised CO_2

increased grain yield under potential, irrigated and rainfed conditions. There was a linear increase in grain yield as the CO_2 concentration increased from 350 to 700 ppm. Potential grain yield of pigeon pea (using WOFOST) decreased over the control when the temperature was increased by 1ºC.

Chatterjee (1998) observed that increases in temperature consistently decreased maize and sorghum yields from the contemporary conditions. Increasing the temperature by 1º and 2ºC decreased sorghum potential yields by 7 and 12% on average. Increases of 50 ppm of CO_2 increased yields by only 0.5%.

Sahoo (1999) looked at the simulation of climate change on maize under irrigated and rainfed conditions. Rises in temperature lowered the yield in both environments. At a CO_2 level of 350 ppm, grain yield decreased continuously with temperature rise up to 4ºC. This was possibly due to a reduction in days by 50% to silking and physiological maturity. At CO_2 levels of 700 ppm, grain yields increased by about 9%. The temperature rise effect on yield reduction was noticed in several cultivars. The effect of elevated carbon dioxide concentration on growth and yield of maize was established, but was less pronounced than for crops such as wheat, chickpea and mustard.

Experiments with the CERES-rice model on the effects of CO_2 concentration indicated that, over Kerala state, an increase in CO_2 concentration would lead to yield increases due to its effect on fertilization and also its enhancement of water use efficiency (Saseendran *et al*, 1999). For every one degree Celsius rise in temperature, the decline in yield was about 6%. Also, in other experiments it was noted that the physiological effect of ambient CO_2 at 425-ppm concentration compensated for the yield losses due to increases in temperature of up to 2ºC.

Specific effects of direct radiation reduction in all parts of the country during January–March 1999 were not evident in records of crop yields. This may be due to associated weather conditions, which could have compensated for any slight reduction in yields of wheat, rice and sugarcane due to reduced radiation alone. The effect of reduced solar radiation on the yield of irrigated wheat in the New Delhi environment was evaluated by using WTGROWS, and the results clearly indicated reductions in grain yield of the order of 5% with reductions in radiation of 15–20%. The response may be different under rainfed and water-limited environments.

Aggarwal and Mall (2002) studied the impact of climate change on grain yields of irrigated rice with two popular crop simulation models – CERES-rice and ORYZA1N at different levels of N management. The climate change scenarios used were a 0.1ºC increase in temperature and 416 ppm CO_2 (2010 scenario) and a 0.4ºC temperature increase and 755 ppm CO_2 (2070 scenario) as the optimistic scenarios of climate change, and increases of 0.3ºC temperature and 397 ppm CO_2 (2010 scenario) and 2.0ºC increase in temperature and 605 ppm CO_2 (2070 scenario) as the pessimistic scenarios (after Watson *et al*, 1998). The results showed that the direct effect of climate change on rice crops in different agroclimatic regions in India would always be positive, irrespective of the various uncertainties. Depending upon the scenario, rice yields increased between 1.0 and 16.8% in pessimistic scenarios of climate change, according to the level of management and model used. These increases were between 3.5 and 33.8% in optimistic scenarios.

Table 1. Temperature increases (ºC) that will cancel out the positive effect of CO_2 in different regions at the current level of management practices in irrigated rice.

CO_2 concentration		
450 ppm	*550 ppm*	*650 ppm*
1.9	2.7	4.8
1.2	3.5	>5.0
2.0	4.4	>5.0
0.9	1.8	2.8
1.0	2.1	3.4
1.0	2.3	4.4

Table 1 shows the temperature increment that would cancel out the positive effect of elevation in carbon dioxide concentration for irrigated rice, which clearly reflects the nullification of the CO_2 fertilization with the rise in temperature.

INFOCROP, a mechanistic crop growth model, has been developed at the Institute and is capable of simulating the yield of several crops under different production environments. It has sub-routines for water, nitrogen and insects and pests, and is widely used for climate change impact analysis.

Screening of cultivars for tolerance to sterility under enhanced temperatures during the post-anthesis phase needs to be evaluated for the major crops in the phytotron (control chambers) to allow the choice of appropriate cultivars for sustained productivity under climate change. Quality aspects of important crops such as wheat (*aestivum* and durum), basmati rice and mustard under climate change need to be addressed. There is also a need to develop selection criteria for screening cultivars for adaptation to drought and temperature stresses.

Crop–weed competition will be affected depending upon their photosynthetic pathway. Since most crops are C3 and most weeds are C4 plants, increased CO_2 would favour crops over weeds, reducing the need for weed control. The accompanying temperature increase may further alter the competition, depending upon the threshold ambient temperatures.

Direct effects of global changes, as projected now, would be small on *kharif* crops, but overall, *kharif* agriculture may become more risky due to increased climatic variability and pest incidence and virulence. Production of *rabi* crops is more seriously threatened due to projections of large increases in temperature and higher uncertainties in winter rainfall arising due to western disturbances and north-east monsoons. Central and southern Indian regions may be more seriously affected than northern India.

Weather watch groups should be established for each crop (including vegetables and fruits) and for livestock/fisheries at the respective commodity institutes to review the state of various crops/livestock/fisheries continuously (including assessing the prospects for production) on a real-time basis and to provide this feedback to the government to enable it to develop appropriate policy responses.

Impact of climate change on insect pests and diseases

The development of diseases and pests is strongly dependent upon temperature and humidity. Any change in these factors, depending upon their base value, can significantly alter the scenario, which ultimately may result in yield loss. For every insect species there is a range of temperatures within which it remains active from egg to adult stage. Lower values of this range are called 'threshold of development' or 'developmental zero'. Within the favourable range, there is an optimum temperature at which most of the individuals of a species complete their development. Exposure to temperatures on either side of the range exerts an adverse impact on the insect by slowing down the speed of development (Pradhan, 1946).

If ambient temperatures remain favourable for the pest after temperature increases, the pest incidence may be expected to rise due to increased rates of development, which may result in the completion of more pest generations. However, the pest population would be adversely affected once the ambient temperature exceeded the favourable range.

Studies have shown that insects remain active within a temperature range from 15º to 32ºC (Phadke and Ghai, 1994). In the case of red cotton bug at constant temperatures of 20, 25 and 30ºC, the average duration of life-cycle was found to be 61.3, 38.3 and 37.6 days respectively, while at 12.5 and 35ºC the pest did not show any development (Bhatia and Kaul, 1966). The most congenial temperatures for insect development have been suggested by Phadke and Ghai (1994). For the mustard aphid, *Lipaphis erysimi,* a maximum temperature ranging from 19–24ºC is suggested, with a mean of 12–15ºC; for rice stink bug, a maximum temperature between 26.9 and 28.2ºC with a relative humidity of 80.6–82.1%; for rice green leafhopper, a temperature from 20–28ºC; for the brown plant hopper, a temperature from 24.8–28.6º; for aphids, thrips and leaf weevils, a mean temperature around 27.5–28.5ºC; and a maximum temperature from 23–27.8ºC is required for the gram pod borer.

Monocyclic diseases such as stem rot, sheath rot and false smut are less influenced by ambient weather conditions. Epidemics of monocyclic diseases are relatively rare in the sense of an explosive increase in their population. In contrast, polycyclic diseases such as blast, brown spot, bacterial leaf blight and rice tungro virus, which invade the aerial parts of the plants, are subjected to constant interaction with the weather. They easily attain epidemic proportions to cause heavy losses (Abrol and Gadgil, 1999).

Forecasting the appearance of aphids *(Lipaphis erysine* Kalt) on mustard crops grown during the winter season in the northern part of India based on the movement of western monsoon disturbances has been achieved (Ramana Rao *et al*, 1994). Western disturbances bring in cold and humid air from the Mediterranean region, resulting in cloudy and favourable weather conditions for the occurrence of aphids on mustard crops. It was shown that there was a sharp increase in the population of aphids when the mean daily temperature ranged from 10º to 14ºC, with a relative humidity of 67–85% and cloudiness greater than 5 octas.

The swarms of locust produced in the Middle East usually fly eastwards into Pakistan and India during the summer season and lay eggs during the monsoon period. The swarms resulting from this breeding return during autumn to the area of winter rainfall, flying to all parts of India and influencing *kharif* crops (Rao and Rao, 1996). Changes in rainfall, temperature and wind speed may influence the migratory behaviour of locusts.

Pests such as the armyworm, *Mythimna separate,* achieve higher population growth leading to outbreaks after heavy rains and floods. On the other hand, pests such as *Pyrilla perpusilla* become more damaging under drought conditions. Less frequent but intense rains in future will cause floods as well as droughts, which will thus influence the incidence of pests.

Some pests, such as the cabbage white butterfly, *Pieris brassicae,* migrate to the plains in winter and back to the hills in summer. With milder winters in the hills and increasing temperatures, such migrations will also be affected. With shorter cold seasons, the onset of diapause will be delayed in autumn, while its termination may be hastened in spring, thereby increasing the period of activity of pests.

Aphid infestations on barley from 1985/86 to 1999/2000 were analysed in relation to climatic variability. The aphid population on barley declined with time. The aphid population showed a negative relationship with January's mean minimum temperature and with February's total rainfall.

Pest population dynamics simulation models can be used to simulate population dynamics and assess the impact of climate change on pest incidence. A dynamic simulation model was developed for the rice stink bug, *Leptocorisa acuta,* using a thermal time concept – see Figure 4 (Reji *et al*, 2003). It was found that up to a 2ºC rise in daily average temperature over 2001's weather would increase the pest population, while further increases in temperature would have an adverse effect on pest populations.

The INFOCROP model was validated for stem borer, leaf folder, bacterial leaf blight and weed effects in rice, and for stem borer, leaf rust and weed damage in wheat. The validated model was then used to establish economic injury levels and also to formulate iso-loss curves for the pests, which can be used for rationalizing pesticide use on crops.

Danger of error propagation in assessing the agricultural impacts

How great the extent of climate change will be and where and in what time frame remains uncertain. In India, historic climatic analysis shows there to be a mixed trend in temperature change, some locations showing increases and others having lower temperatures. Similar trends are being noticed in various seasons. Such scenarios are not relevant for today's policy planning, especially in the agricultural sector, which is continuously undergoing transformation due to changing demands, markets and

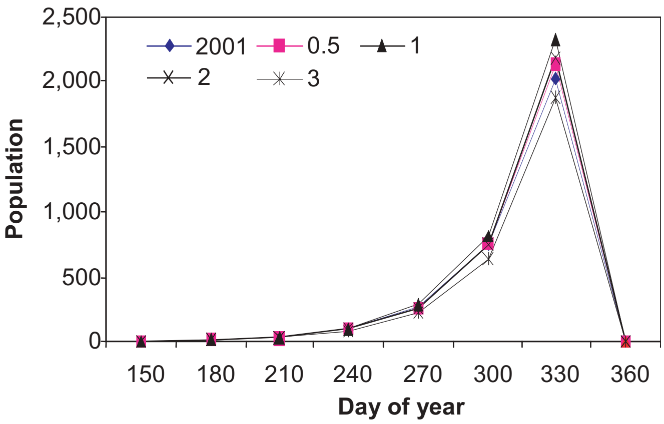

Figure 4. Simulation of the effect of temperature rise on the rice stink bug population.

agricultural technologies. The pace of these changes is expected to increase very rapidly in the coming years, and the whole agricultural scenario may be quite different in the next 10 to 20 years, irrespective of whether climate change takes place. Extrapolation of the point results of the impacts, as obtained through the use of simulation models, to a larger scale may bring in more errors, if the spatial and temporal variability in the socioeconomic and biophysical aspects are not included. This kind of study is effective only if an interdisciplinary team of researchers works together on a common mission of climate change-related studies.

Conclusion

The occurrence of extreme climatic events in this region has increased. Researchers have identified options to sustain agricultural production under these extreme events, and farmers have also adopted them quickly for their benefit. Inter-seasonal climatic variability at various locations has been characterized by using historic weather datasets and relating them to the growth and yield of crops. Simulation models greatly help in linking with the climate change scenarios to evaluate the impact on crops. Crop growth models such as WTGROWS, ORYZA and INFOCROP have been used extensively to examine the likely impact of climate change on crops and to suggest suitable agro-management options to sustain the productivity of crops. Regions vulnerable to climate change have been identified for various crops. The impact of climate change and its variability on the incidence of pests has been evaluated for various crops. There is a need to link the socioeconomic database layers with the biophysical aspects and simulation models to evaluate the impact of climate change. Climate change scenarios are needed at higher resolutions (temporal and spatial) for calculating accurate estimates of the impact. Food security policy in relation to climate change can be designed to account for changing crop yields as well as shifting boundaries for crops, impacts on food supply, imports/exports, loss of livelihoods with changes in crops/cropping systems and related implications for water demand. There is a need to evaluate the impact on a regional scale, taking into account the extent of spatial and temporal courses of variability in the biophysical and socioeconomic aspects. The boundary conditions under which the results have been obtained and the chances of error propagation in evaluating the impact should be described.

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