Impact of Climate Change on Indian Agriculture: A Review

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IMPACT OF CLIMATE CHANGE ON INDIAN AGRICULTURE: A REVIEW

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Abstract. During the recent decade, with the growing recognition of the possibility of climate change and clear evidence of observed changes in climate during 20th century, an increasing emphasis on food security and its regional impacts has come to forefront of the scientific community. In recent times, the crop simulation models have been used extensively to study the impact of climate change on agricultural production and food security. The output provided by the simulation models can be used to make appropriate crop management decisions and to provide farmers and others with alternative options for their farming system. It is expected that in the coming decades with the increased use of computers, the use of simulation models by farmers and professionals as well as policy and decision makers will increase. In India, substantial work has been done in last decade aimed at understanding the nature and magnitude of change in yield of different crops due to projected climate change. This paper presents an overview of the state of the knowledge of possible effect of the climate variability and change on food grain production in India.

1. Introduction

There is now clear evidence for an observed increase in global average temperatures and change in rainfall rates during the 20th century (Easterling, 1999; IPCC, 2001; Jung et al., 2002; Balling Jr and Cerveny, 2003; Fauchereau et al., 2003) around the world. The most imminent climatic changes in recent times is the increase in the atmospheric temperatures due to increased levels of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_2O) and chlorofluoro carbons (CFC_s). Because of the increasing concentrations of those radiative or greenhouse gases, there is much concern about future changes in our climate and direct or indirect effect on agriculture (Garg et al., 2001; IPCC, 2001; Krupa; 2003; Aggarwal, 2003; Bhatia et al., 2004).

In India, studies by several authors shown that during last century there is observed increasing trend in surface temperature (Hingane et al., 1985; Srivastava et al., 1992; Rupa Kumar et al., 1994; De and Mukhopadhyay, 1998; Pant et al., 1999; Singh and Sontakke, 2002; Singh et al., 2001), no significant trend in rainfall on all India basis (Mooley and Parthasarathy, 1984; Thapliyal and Kulshrestha,

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1991; Pant and Rupakumar, 1997; Pant et al., 1999; Stephenson et al., 2001), and decreasing/increasing trends in rainfall in regional basis (Chowdhury and Abhyankar, 1979; Rupa Kumar et al., 1992; Kripalani et al., 1996, 2003; Singh and Sontakke, 2002). Table I shows the silent features of the selective reports on observed climate trend during the 20th century over India.

In recent years, with the growing recognition of the possibility of global climate change, an increasing emphasis on world food security in general and its regional impacts in particular have come to forefront of the scientific community. Crop growth, development, water use and yield under normal conditions are largely determined by weather during the growing season. Even with minor deviations from the normal weather, the efficiency of extremely applied inputs and food production is seriously impaired. The carbon dioxide (CO_2) concentration was in the steady state at 280 ppm till the pre industrial period (1850). It is rising since then at the rate of 1.5 to 1.8 ppm per year. The concentration of CO_2 is likely to be doubled by the end of 21st century (Keeling et al., 1995). Open top chambers and FACE technology are currently being used for the study of the response of crop plants to the elevated CO_2. Results from such studies have shown an increase in plant photosynthetic rate and crop yield (Kimball, 1983). Measurement in Delhi also showed similar trend (Uprety, 2003). In an experiment in New Delhi, Uprety et al., 2003 observed increase in rice grain yield due to increase in CO_2 concentration. The increased net photosynthetic rate and greater accumulation of sugar contributed significantly to the accelerated development of leaves and tillers and finally grain yield. The increasing CO_2 concentration in the atmosphere and the anticipated climate change due to global warming are likely to affect future global agricultural production through changes in rate of plant growth (Lemon, 1983; Cure and Acock, 1986; Rotter and Van de Geijn, 1999), transpiration rate (Morison, 1987; McNaughton and Jarvis, 1991; Jacobs and DeBruin, 1992).

Agriculture plays a key role in overall economic and social well being of India. Though the share of agriculture in both Gross Domestic Product (GDP) and employment has declined over time, the pace of decline in its share in employment has been much slower than that of GDP. The share of agriculture in GDP is declined from 39% in 1983 to 24% in 2000–01 compared with much lower rate of decline in its share in total employment from 63% to 57% during the same period. Declines in the share of agriculture in GDP were not commensurate with the fall in dependency in agriculture. Such trends have resulted in fragmentation and decline in the size of land holdings which leads to agronomic inefficiency, a rise in unemployment, a low volume of marketable surplus. These factors could contribute to increase vulnerability to global environmental change (Aggarwal et al., 2004). In India, average food consumption at present is 550 gm per capita per day whereas the corresponding figures in China and USA are 980 gm and 2850 gm respectively. Present annual requirement based on present consumption level (550 gm) for the country is about 210 Million Tonnes (Mt), which is almost equal to the current production. While the area under food grain, for instance,

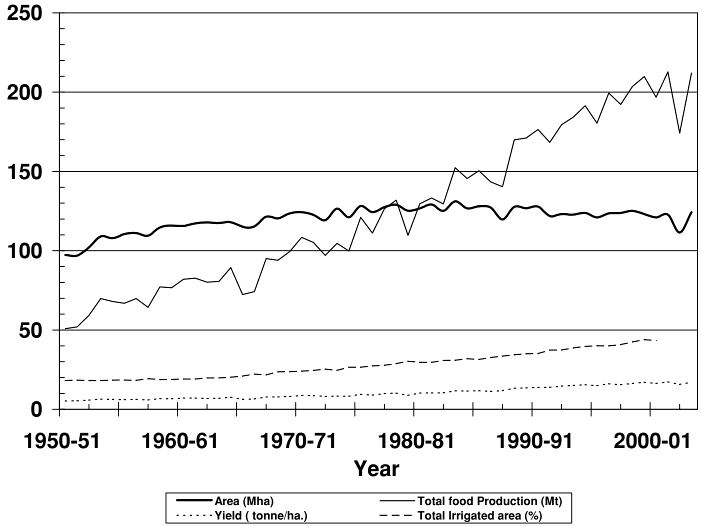

Figure 1. All-India area, production and yield of food grain from 1950–51 to 2003–04 along with percentage coverage under irrigation (Source: DES, 2004).

fell from 126.67 mha to 124.24 mha during the period from 1980–81 to 2003–04, the production registered as increase from 129.59 Mt. to 212 Mt. during that period. The food grain production looked quite impressive in 2003–04, which is more than 4 times the production of 50.82 Mt in 1950-51 (Figure 1). However the country faces major challenges to increase its food production to the tune of 300 million toones by 2020 in order to feed its ever-growing population, which is likely to reach 1.30 billion by the year 2020. To meet the demand for food from this increased population, the country's farmers need to produce 50% more grain by 2020 (Paroda and Kumar, 2000; DES, 2004). The problem has became acute because urbanization and industrialization have rapidly dwindled the per capita availability of arable land from 0.48 ha in 1950 to 0.15 ha by 2000 and is likely to further reduce to 0.08 ha by 2020. As against the national average of 40% of the total cropped area being irrigated, 60% of the total cropped area is still rain-fed and dependent on uncertainties of monsoon. This shows the dependency of Indian agriculture on climate (Figure 1). Moreover, if certain climate change scenarios come to pass, agricultural production in some areas may decrease. How can productivity be increased while ensuring the sustainability of agriculture and the environment for future generations? Decision makers need information supplied by research to make informed choices about new agricultural technologies and to devise and implement policies to enhance food production and sustainability. There is now a great concern about decline in soil fertility, change in water table, rising salinity, resistance to many pesticides and degradation of irrigation water quality in north-western India (Sinha et al., 1998; CGWB, 2002). It is clear that over time more nutrients have been removed than added through the fertilizers, and the farmers have to apply more fertilizers to get the same yield, they were getting with less fertilizers 20–30 years ago. Climate change will further affect soil conditions. Changes in temperature and in precipitation patterns and amount will influence soil water content, run-off and erosion, salinisation, biodiversity, and organic carbon and nitrogen content. The increase in temperature would also leads to increased evapotranspiration. There is need to quantify the specific regional soil-related problems and that affect the global environmental change will have on soil fertility and its functioning for crop growth and production.

There are two major crop growing season in India as for climate point of view. The summer or '*kharif'* crop growing season (June–September) coincides with southwest monsoon. The major '*kharif'* crops are rice, maize, sugarcane, cotton, jute, groundnut, soybean and Bajra etc. Depending on crop duration, '*kharif'* crops can be harvested during the autumn (October–November) or winter (December–February) months. The southwest monsoon is critical to the *kharif* crop, which accounts for more than 50% of the food-grain production and 65% of the oilseeds production in the country. The interannual monsoon rainfall variability in India leads to large-scale droughts and floods, resulting in a major effect on Indian food grain production (Parthasarathy and Pant, 1985; Parthasarathy et al., 1992; Selvaraju, 2003; Kumar et al., 2004) and on the economy of the country (Gadgil et al., 1999a; Kumar and Parikh, 2001). The winter or '*rabi*' crop-growing season starts after the summer monsoon, and continues through to the following spring or early summer. Rainfall occurring at the end of the monsoon season provides stored soil moisture and often irrigation water for the *rabi* crop, which is shown in the post-monsoon season (October–November). The summer monsoon therefore, is responsible for both kharif and rabi crop production in India. The major '*rabi*' crops are wheat, mustard, Barley, potato, onion and gram etc.

Global warming may also threaten India food security if there is a negative effect on agriculture. Although, the effect of increasing CO_2 concentrations will increase the net primary productivity of plants, but climate changes, and the changes in disturbance regimes associated with them, may lead either to increased or decreased net ecosystem productivity. In many tropical and subtropical regions, potential yields are projected to decrease for most projected increases in temperature. The impacts of elevated CO_2 should be considered among others, in the context of, (A) changes in air temperature, particularly nocturnal temperature due to increase in CO_2 and other trace gases and changes in moisture availability and their effect on vegetative versus reproductive growth; (B) need for more farm resources (e.g. fertilizers); and (C) survival and distribution of pest populations, thus developing a new equilibrium between crops and pests (Krupa, 2003). Indirectly, there may be considerable effects on land use due to snow melt, spatial and temporal rainfall variability, availability of irrigation, frequency and intensity of inter- and intra-seasonal droughts and floods, soil organic matter transformations, soil erosion, change in pest profiles, decline in arable areas due to submergence of coastal lands, and availability of energy. All these can have tremendous impact on agricultural production and hence, food security of any region (Aggarwal, 2003). The rising temperatures and carbon dioxide and uncertainties in rainfall associated with global warming may or may not have serious direct and indirect consequences on crop production. It is, therefore, important to have an assessment of the direct and indirect consequences of global warming on different crops especially on cereals contributing to the food security (Gadgil et al., 1995, 1999a,b). Mechanistic crop growth models are now routinely used for assessing the impacts of climate change. There are several crop models now available for the same crop that can be employed for impact assessment of climate change (Mall and Aggarwal, 2002). Crop models, in general, integrate current knowledge from various disciplines including agrometeorology, soil physics, soil chemistry, crop physiology, plant breeding, and agronomy, into a set of mathematical equations to predict growth, development and yield of a crop (Aggarwal and Kalra 1994; Hoogenboom, 2000). In most climate change applications, long-term historical weather data are used as input for the crop models. In general, at least 30 years of historical weather data are preferred to represent annual weather variability; different climate change scenarios can then be applied to these data records. The simplest approach is to assume a fixed climate change and to modify the data with a constant number, such as an increase or decrease of 1, 2, 3°C etc. for temperature. Similarly, rainfall and solar radiation can be changed with a certain percentage, such as an increase or decrease of 10, 20, 30% etc. These changes are then applied to the daily water data and the crop simulation models are run with these modified inputs. A more realistic approach is to use the outputs from the General Circulation Models (GCMs) to modify the historical weather data (Lal et al., 1998; Hoogenboom, 2000; Mall et al., 2004).

Studying the potential socioeconomic impacts of climate change involves comparing two future scenarios, one with and one without climate change. Uncertainties involved in such an assessment include: (1) the timing, magnitude and nature of climate change; (2) the ability of ecosystems to adopt either naturally or through managed intervention to the change; (3) future increase in population and economic activities and their impacts on natural resources systems; and (4) how society adapts through the normal responses of individual, businesses and policy changes that after the opportunities and incentives to respond. The uncertainties, the long periods involved and the potential for catastrophic and irreversible impacts on natural resources systems raise questions as to how to evaluate climate impacts, investments, and other policies that would affect or be affected by changes in the climate.

In India, substantial work has been done in last decade aimed at understanding the nature and magnitude of change in yield of different crops due to possible climate change. The objective of the present review is to a) examine the present status of the knowledge of climate change impact on Indian agricultural production, b) discuss the uncertainties and limitation of these studies in Indian conditions and identifying future research needs.

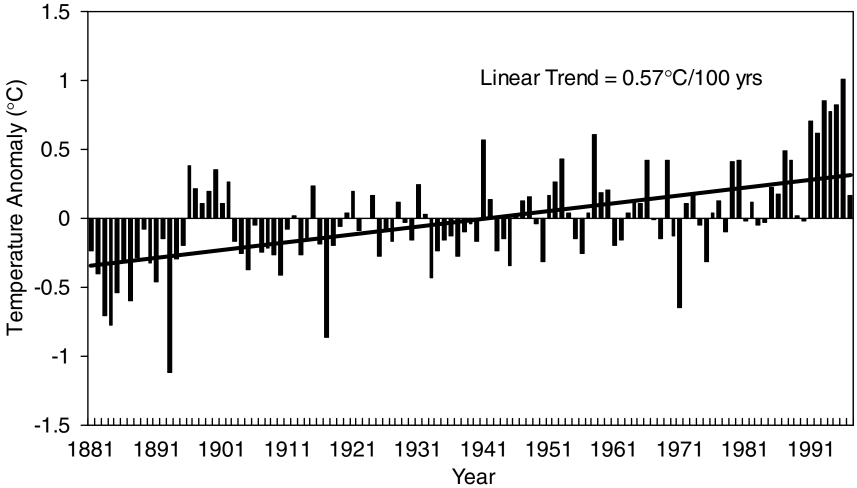

Figure 2. All-India Mean Annual Surface Air Temperature Anomalies (1881–1997). (Source: Pant and Rupakumar, 1997)

2. Climate Variability and Food Production

Climatic variability and occurrence of extreme events are major concerns for the Indian subcontinents. There is need to quantify the growth and yield responses of important crops and also identify suitable land use options to sustain agricultural productivity under this large range of climatic variations. In India, the analysis of seasonal and annual surface air temperatures (Pant & Kumar, 1997) has shown a significant warming trend of 0.57°C per hundred years (Figure 2). The warming is found to be mainly contributed by the post-monsoon and winter seasons. The monsoon temperatures do not show a significant trend in any major part of the country. Similar warming trends have also been noticed in Pakistan, Nepal, Sri Lanka and Bangladesh (Ahmed and Warrick, 1996; Chaudhari, 1994; Rupakumar and Patil, 1996; IPCC, 2001). The rainfall fluctuations in India have been largely random over a Century, with no systematic change detectable in summer monsoon season (Figure 3). However, areas of increasing trend in the seasonal rainfall have been found along the West Coast, North Andhra Pradesh and Northwest India and those of decreasing trend over East Madhya Pradesh, Orissa and Northeast India during recent years (Table I; Rupa Kumar et al., 1992).

Extreme weather conditions, such as floods, droughts, heat and cold waves, flash floods, cyclones and hailstorm, are direct hazards to crops. More subtle fluctuation in weather during critical phases of crop development can also have substantial impact on yields. Cultivated areas are subject to a broader range of influences, including changes in commodity prices, costs of inputs and availability of irrigation water. Climate may have indirect and possibly lagged influences on harvested areas. For

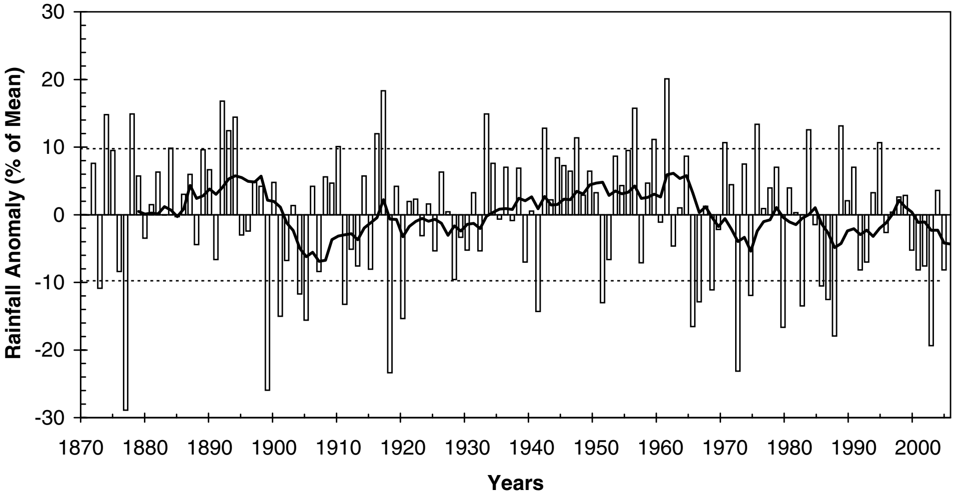

Figure 3. All-India Summer Monsoon Rainfall (SMR) Anomalies (1871–2004). Dark line shows 10 year running average (Source: Ranjeet Singh et al., 2005 (Unpublished)).

example, shortfalls in rainfall can reduce irrigation water supplies, leading to reduce areas under irrigated crops and potentially increased areas under rain-fed crops in the subsequent season (Kumar et al., 2004). A typical example of summer monsoon rainfall and food grain production relation in India is visible in figure 1. After an adverse agro-climatic condition faced by Indian Agriculture during 2002–03 (due to 19% decline in summer monsoon rainfall in 2002), resulting in steep decline in the foodgrains production by about 18 percent from the preceding year. The country's foodgrains production during 2002–03 had slumped to 174.19 Mt, due to widespread drought, from the record level of 212.02 Mt in 2001–02.

Mall and Singh (2000) observed that small changes in the growing season temperature over the years appeared to be the key aspect of weather affecting yearly wheat yield fluctuations. Pathak et al. (2003) concluded that the negative trends in solar radiation and an increase in minimum temperature, resulting in declining trends of potential yields of rice and wheat in the Indo-Gangetic plains of India. In Delhi the minimum and maximum temperature shows a rising trend both in summer or '*Kharif' growing season* (June–October) as well as winter or '*rabi*' growing season starts after summer monsoon. There was also a small declining trend in solar radiation during *rabi* and *Kharif* season after 1980. These changes indicate warming trend. Since solar radiation is closely related to crop growth, any decrease in this will significantly reduce agricultural productivity. The accompanied increase in minimum temperatures increases maintenance respiration requirement of the crops and thus further reduces net growth and productivity (Aggarwal, 2003).

Selvaraju (2003) analyzed the relationship between Indian Summer Monsoon rainfall (SMR) and food grain production in India. He found that the inter-annual variations in SMR and total food grain production anomalies are closely related (Figure 4). However, the magnitude of change in foodgrain production is smaller than the rainfall (Figure 4(a)). During the years of deficit monsoon (1966, 1972, 1974, 1979, 1982 and 1987) the foodgrain production declined, and during the years of excess or normal rainfall (1970, 1975, 1978, 1983 and 1988) it was certainly higher. The correlation between SMR and foodgrain production (0.71) was significant at the 1% level. The SMR is responsible for 50% of the variability in total foodgrain production anomalies (Figure 4(b)). The SMR shows a high correlation ($r = 0.80$) with *Kharif* foodgrain production and a moderate correlation ($r = 0.41$) with *Rabi* foodgrain production anomalies. Among the individual crops, rice ($r = 0.66$), wheat ($r = 0.49$) and chickpea ($r = 0.49$) production had significant association with SMR.

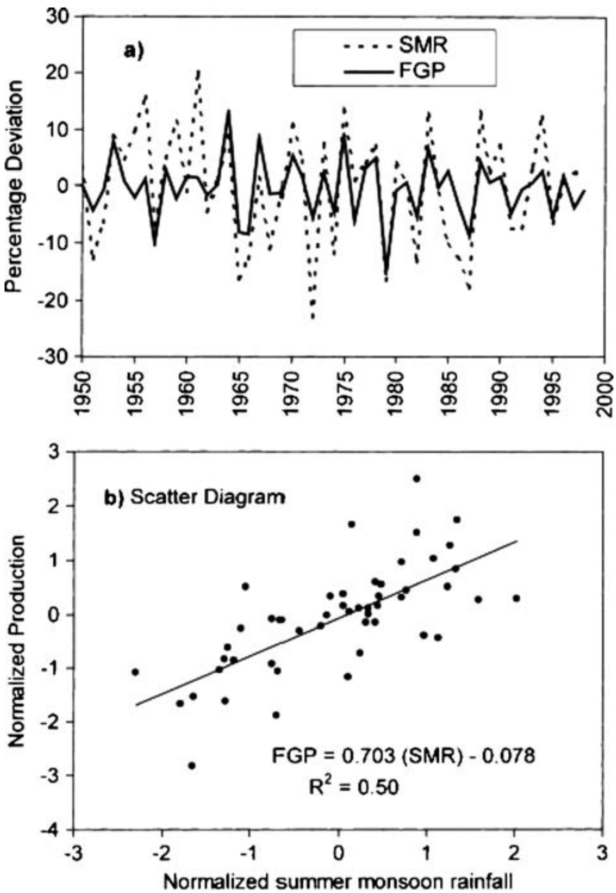

Figure 4. Relationship between SMR and total foodgrain production: (a) percentage deviation from normal; (b) scatter diagram showing the relationship between normalized SMR and normalized total foodgrain production (FGP). (Source: Selvaraju, 2003)

Recently, Kumar et al. (2004) analyzed the crop-climate relationships for India, using historic production of statistics for major crops (rice, wheat, sorghum, groundnut, and sugarcane) and for aggregate food grain, cereal, pulses and oilseed production. All India annul total production (except sorghum and sugarcane), production in the monsoon (except sorghum) and post-monsoon seasons (except sorghum and rice) were significantly correlated to all India summer rainfall.

Productivity of some of the important cropping systems has either become static or shown a decline in some locations. Recent trends of a decline or stagnation in the yield of rice-wheat cropping system in Indo-Gangetic plain and north western India have raised serious concern about the regions food supply (Aggarwal et al., 2000; Mall and Srivastava, 2002; Pathak et al., 2003). This trend clearly indicates the reduced factor of productivity in case of the rice-wheat cropping systems. These variations in trends of productivity indicate the effects of other biophysical and socio-economic components, which needs to be eliminated before embarking on assessing the impacts of climate change and its variability on growth and yield of crops.

3. Projected Climate Change Scenarios over Indian Subcontinent

Climate change is no longer a distant scientific prognosis but is becoming a reality. The anthropogenic increases in emissions of greenhouse gases and aerosols in the atmosphere result in a change in the radiative forcing and a rise in the Earth's temperature. The bottom-line conclusion of the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001) is that the average global surface temperature will increase by between 1.4° and 3°C above 1990 levels by 2100 for low emission scenarios and between 2.5° and 5.8°C for higher emission scenarios of greenhouse gases and aerosols in the atmosphere.

The UKMO GCM model (Bhaskaran et al., 1995) predicts a total precipitation increase of approximately 20% and increase in winter or *rabi* crop season temperature by 1–4°C with increased CO_2 concentration. Specific humidity increases by 19%, indicating that the increased monsoon rainfall is largely due to increased water content of the atmosphere. The model also predicts a greater number of heavy rainfall days during the summer monsoon or *kharif* period, and an increased interannual variability. Lonergan (1998) estimates that India's climate could become warmer under conditions of increased atmospheric carbon dioxide. The average temperature change is predicted to be in the range of 2.33°C to 4.78°C with a doubling in CO_2 concentrations. Lal et. al. (1995) presents a climate change scenario for the Indian subcontinent, taking projected emissions of greenhouse gases and sulphate aerosols into account. It predicts an increase in annual mean maximum and minimum surface air temperatures of 0.7°C and 1.0°C over land in the 2040s with respect to the 1980s. Since the warming over land is projected to be lower in magnitude than that over the adjoining ocean, the land-sea thermal contrast that drives the monsoon mechanism could possibly decline. However, there continues to be considerable uncertainty about the impacts of aerosols on the monsoon.

Recently, Lal et al., 2001 estimated that CO_2 level will increase to 397–416 ppm by 2010s from the present CO_2 level of 371 ppm and this would further increase by 605–755 by 2070s. They projected between 1 to 1.4°C & 2.23 to 2.87°C area-averaged annual mean warming by 2020 & 2050 respectively. Comparatively, increase in temperature is projected to be more in *rabi* than in *kharif* crop growing season. A large uncertainty is associated with projected *rabi* rainfall than *kharif* rainfall in 2050s (Table II). Moreover, the standard deviation of future projections of area-averaged monsoon rainfall centered around 2050s is not significantly different relative to the present-day atmosphere implying thereby that the year-to-year variability in mean rainfall during the monsoon season may not significantly change in the future. More intense rainfall spells are, however, projected over the land regions of the Indian subcontinent in the future thus increasing the probability of extreme rainfall events in a warmer atmosphere.

Rupa Kumar and Ashrit (2001) have projected 13% increase in monsoon or *kharif* season rainfall in India using ECHAM4 model, while HadCM2 suggests reduction in *kharif* rainfall by 6% in the greenhouse gas simulation. Both GCMs suggest an increase in annual mean temperature by more than 1°C (1.3°C in ECHAM4 and 1.7°C HadCM2). Rupa Kumar (2002) concluded that coupled models indicate general warming and enhanced rainfall conditions over India towards the later half of the 21st century, in a GHG increase scenario; however, there is some disagreement among the models on rainfall changes. Regional climate models display good skills in reproducing local features. Preliminary results with HadRM2/HadCM2 indicate general warming into 2050s, but no substantial change in monsoon rainfall. He showed decrease in rainfall in some states (viz. Jammu and Kashmir, Himachal Pradesh, Bihar, Gujarat and Rajasthan etc.) in India. May (2002) predicts an intensification of the rainfall in the Indian region during the monsoon season a sa consequences of the anticipated increase in the greenhouse gases concentrations. The increase of the regional rainfall is found to be related to an intensification of the stmospheric moisture transport into the Indian region. Observation also indicates a weakening of the large scale aspects of the Indian summer monsoon (Stephenson et al., 2001).

Rupa Kumar et al. (2003) concluded that under future scenarios of increased greenhouse gas concentrations (GHG) indicate marked increase in both rainfall and temperature into the 21st century, particularly becoming conspicuous after the 2040s in India. Over the region south of 25°N (south of cities such as Udaipur, Khajuraho and Varanasi) the maximum temperature will increase by 2–4°C during 2050s. In the northern region the increase in maximum temperature may exceed 4°C. This study also indicates a general increase in minimum temperature up to 4°C all over the country, which may however exceed over the southern peninsula, northeast India and some parts of Punjab, Haryana and Bihar. There is an overall decrease in number of rainy days over a major part of the country. This decrease is more in western and central part (by more than 15 days) while near the foothills of Himalayas (Uttaranchal state) and in northeast India the number of rainy days may increase by 5–10 days. However, increase in GHG may lead to overall increase in the rainy days intensity by 1–4 mm/day except for small areas in the northwest India where the rainfall intensities decrease by 1 mm/day. Table II shows the selective reports about projected climate changes using GCMs and Regional Climate Models (RCMs) over India during later part of 21st century. Generally all reports shows changing patterns in rainfall and an increase in temperature during different crop season or annual basis.

4. Vulnerability of Crop Production

Estimating the effect of a changing climate on crop production in the India is difficult due to the variety of cropping systems and levels of technology used. However, the use of crop growth models is one way in which these effects can be studied, and probably representing the best method we have at present for doing so. Although a large number of simplifying assumptions must necessarily be made, these models allow the complex interaction between the main environmental variables influencing crop yields to be understood.

There have been a few studies in India which aimed at understanding the nature and magnitude of yield gains or losses of crops at selected sites under elevated atmospheric CO_2 and associated climatic change (Abrol et al., 1991; Sinha and Swaminathan, 1991; Aggarwal and Sinha, 1993; Aggarwal and Kalra, 1994; Gangadhar Rao and Sinha, 1994; Mathauda and Mavi, 1994; Gangadhar Rao et al., 1995; Mohandass et al., 1995; Lal et al., 1998,1999; Francis, 1999; Saseendran et al., 1999, Rathore et al., 2001; Mall and Aggarwal, 2002; Aggarwal and Mall, 2002; Aggarwal, 2003; Attri and Rathore, 2003, Mall et al., 2004)

Saini and Nanda (1986) showed that there was a decline of 600–650 grains m^{-2} in wheat crop with every 1°C increase in mean temperatures above 17–17.7°C during the terminal spikelet initiation to anthesis. Integrated impact of a rise in temperature and CO_2 concentration on yield of crops may be negative (Sinha and Swaminathan, 1991). They estimated that a 2°C increase in mean air temperature could decrease rice yield by about 0.75 ton/hectare in the high yield areas and by about 0.06 ton/hectare in the low yield coastal regions. Further, a 0.5°C increase in winter temperature would reduce wheat crop duration by seven days and reduce yield by 0.45 ton/hectare. An increase in winter temperature of 0.5°C would thereby translate into a 10% reduction in wheat production in the high yield states of Northern India. Achanta (1993) simulated irrigated yields for Pantnagar district under doubled CO_2 and increased temperature and concluded that the impact on rice production would be positive in the absence of nutrient and water limitations.

Aggarwal and Sinha (1993) reported that at 425 ppm CO_2 concentration and no rise in temperature, wheat grain yield at all levels of production (i.e. potential, irrigated and rainfed) increased significantly. In northern India, a 1°C rise in mean temperature had no significant effect on potential yields but irrigated and rainfed yields increased in most places. An increase of 2°C in temperature reduced potential wheat yields at most places. The effect on irrigated and rainfed productivity varied with location. The natural climatic variability also had considerable effect on the magnitude of response to climate change. Evapotranspiration was reduced in irrigated as well as rain-fed environments.

Gangadhar Rao and Sinha (1994) studied the impact of climate change on wheat performance of India and showed that wheat yields decreased due to the adverse effects of temperature during grain filling and maturity stages of the growth. The results of this study indicate that crop characteristics such as sensitivity of grain filling duration to temperature, play a major role in determining the effects of climate change on crop productivity.

In a detailed study, Aggarwal and Kalra (1994) developed and evaluated the WTGROWS crop simulation model to estimate the effect of climate change on productivity of wheat in India was simulated for normally sown crops at three levels of production (potential, irrigated and rainfed). The CO_2 level of 425 ppm and temperature rise options of 0, 1 and 2°C were assumed. At 425 ppm CO_2 concentration and no rise in temperature, grain yield at all levels of production increased significantly at all places. One degree Celsius rise in mean temperature had no significant effect on potential yields. Irrigated yields however showed a small increase in most places where current yields were greater than 3.5 t/ha. In central and peninsular India, where current irrigated yields were between 2 to 4 t/ha, the response varied from a significant decrease to a significant increase. Rainfed yields, however, showed a significant increase. An increase of 2°C in temperature reduced potential yields at most places. The magnitude was, however, less at places with low potential productivity. In fact, for a few locations there was a small increase or no significant effect. In sub-tropical (above 23°N) environments there was a small decrease in potential yields (1.5 to 5.8%) but in tropical locations the decrease was 17–18%.

In the same study, mean simulated yield of wheat for current and changed climate scenario (2°C rise and CO_2 level of 425 CO_2 ppm) in different latitudinal ranges was evaluated (Table III). Irrigated yields slightly increased for latitudes greater than 27°N but were reduced at all other places. The decrease in yield was much higher in lower latitude. Several locations, particularly where current rainfed yields were greater than 2 t/ha showed a very significant increase in rainfed yields with climate change. These locations are mostly above 27°N; the mean increase here was 28.6%. Between 25°N and 27°N although rainfed yields in current weather were high, there was a significant decrease in changed climate. These results were closely related to the effects of changed climate on crop duration. Depending upon the magnitude of temperature increase, crop duration, particularly the period up to anthesis was reduced. In northern India, because of this reduction in pre-an thesis duration, grain filling was often shifted to relatively cooler temperature of February thus enabling the crop to maintain reasonable grain filling duration in changed climate. On addition, the improved water use efficiency and growth rates helped the crops to maintain adequate rates of growth. The simulation analysis showed that if crops were allowed to maintain same crop duration as in current weather, the effects of climate change are significant. Figure 5 shows the isolines of the simulated irrigated wheat yields under current climate and under climate change scenarios. There was no effect of climate change in northern India but yields were reduced in Central India by 10–15%. This reduction in productivity under changed climate unless accompanied with suitable research and policy interventions may reduce wheat production options in central India (Kalra and Aggarwal, 1994; Aggarwal, 2000).

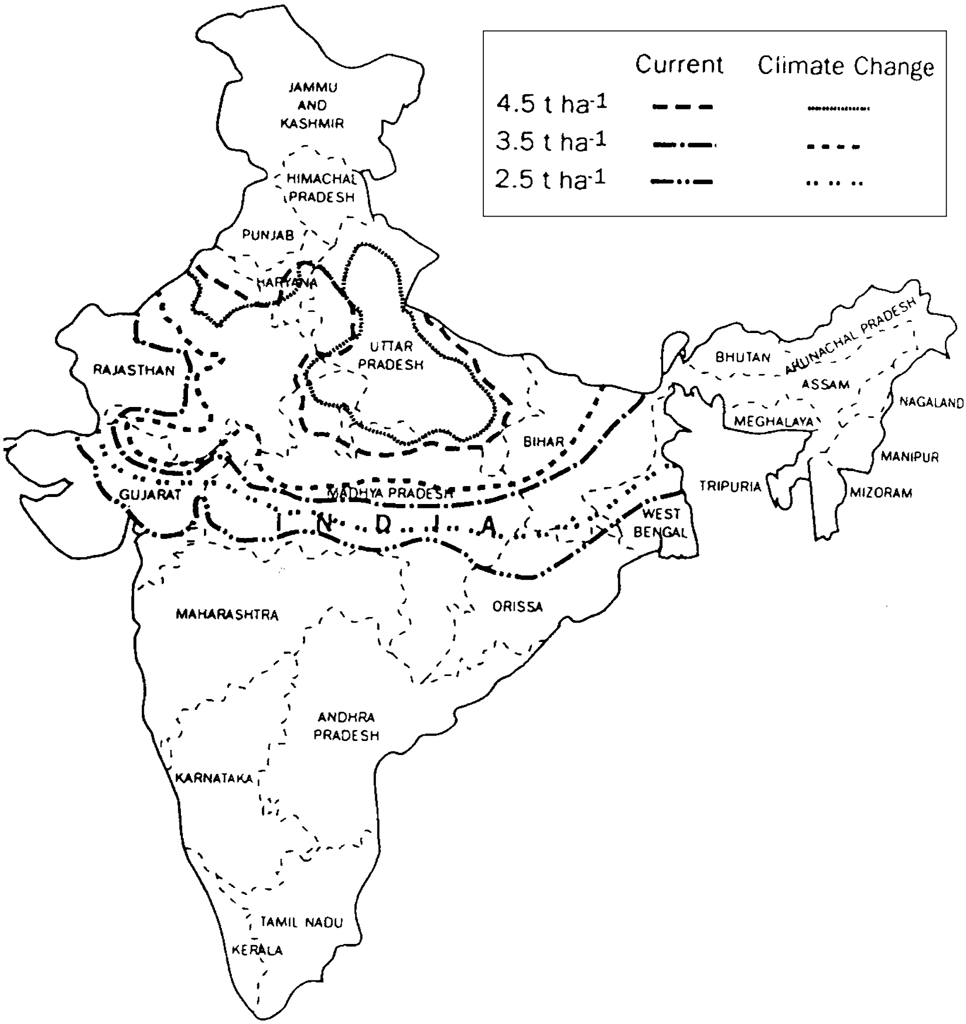

Figure 5. Impact of climate change on shift in irrigated wheat productivity zones. Climatic change scenarios was 425 ppm CO_2 and a 2°C rise in mean temperature. (Source: Aggarwal, P. K., 2000)

Gangadhar Rao et al. (1995) studied the impact of climate change on the crop productivity of Sorghum [*Sorghum bicolor* (L.) Moench] in three diverse sorghum growing areas in India i.e. Hyderabad, Akola and Solapur. Crop growth was simulated using the CERES-sorghum (Ritchie and Alagarswamy, 1989) simulation model with climate change scenarios generated by the three GCM s namely; Goddard Institute of Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and United Kingdom Meteorology Office (UKMO). The simulated results indicated a decrease in yield and biomass of rainy season sorghum at Hyderabad and Akola under all climate change scenarios. Post rainy season sorghum grown at Solapur on stored soil water showed a marginal increase in yield. The positive effects of increased CO_2, if any, were masked by the adverse effects of predicted increase in temperature resulting in shortened crop growing seasons. The study also has shown that the effects of climate change on the same crop would depend upon the season it is grown.

Mohandass et al. (1995) used ORYZA1 model (Kropff et al., 1994) to simulate rice production in India under current and future climates. They predicted increase in rice production under the GCMs scenarios used. This was mainly due to an increase in yields of main season crops where the fertilizing effect of the increased CO_2 level is more than able to compensate the crop for any detrimental effects of increased temperatures. Although large decreases were predicted for second season crops at many of the locations due to high temperatures being encountered, the relatively low proportion of total rice produced in this season meant that its overall effect on the rice production was small.

Uprety et al. (1996) concluded that with the type of climate we have in the northern belt of Indian subcontinent, viz, variation in temperatures and CO_2 concentration, the production of Brassica crop (a oilseed crop) is likely to increase and is likely to be shifted in some more relatively drier regionas than where it is grown presently. Hundal and Kaur (1996) examined the climate change impact on productivity of wheat, rice, maize and groundnut crop in Punjab using CERES-wheat (Godwin et al., 1989), CERES-rice (Singh et al., 1993), CERES-maize (Ritchie et al., 1989) and "PNUTGRO" (Kaur, 1993) crop simulation models. They concluded that, if all other climate variables were to remain constant, temperature increase of 1, 2 and 3°C from present day condition, 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 seed yield in groundnut by 8.7, 23.2 and 36.2%, respectively. In general, the simulation results indicates that increasing temperature and decreasing radiation levels pose a serious threat in decreasing growth and yields of cereals and oilseeds crop. Increased CO_2 levels are expected to favour growth and increase crop yields and, therefore, will be helpful in counteracting the adverse effects of temperature rise in future.

Lal et al. (1998) examined the vulnerability of wheat and rice crops in northwest India to climate change through sensitivity experiments with CERES-wheat and CERES-rice models 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 3°C (2°C) rise in temperature cancelled out the positive effect of elevated CO_2 on wheat (rice). The combined effect of enhanced CO_2 and imposed thermal stress on the wheat (rice) crop is 21% (4%) increase in yield for the irrigation schedule presently practiced in the region. While the adverse impacts of likely water shortage on wheat crops would be minimized to a certain extent under elevated CO_2 levels, they would largely be maintained for the rice crops resulting in about 20% net decline in the rice yields.

Chatterjee (1998) used CERES-sorghum model and observed increase in temperature consistently decreased the sorghum yields from the present day conditions. Increase in temperature by 1 and 2°C sorghum decreased the grain yields by 7 to 12%, on an average. A further increase in temperature drastically reduced the potential yields by 18 to 24%, on an average. The magnitude of decrease in yield with increase in temperature was, in general, proportional to the increase in temperature in most years, indicating that there was no large interaction effect between yearly climatic variation and increase in temperature. Increase in 50-ppm CO_2 increase yields by only 0.5%. This was nullified when the temperature increased by 0.08°C. Similarly the small beneficial effect of still higher CO_2 concentrations was nullified by further increase in temperature. The beneficial effect of 700-ppm CO_2 was nullified by an increase of only 0.9°C in temperature. Further increase in temperature always resulted in lower yields than control irrespective of the increase in CO_2.

Mandal (1998) used CROPGRO-chickpea model and observed increase in temperature up to 2°C did not influence potential yield of chickpea as well as above ground biomass significantly. Pre-anthesis and total crop duration got reduced by 10 and 12 days with 2°C rise. Irrigated yield, which averaged around 58% of the potential yield, in general increased with temperature rise upto 2°C. Total crop duration got reduced only by 4 days with 2°C rise. Nitrogen uptake and total water use (as evapo-transpiration) were not significantly different upto 2°C rise. Crop yield under rain-fed condition was much lower, but the effect of temperature rise on crop growth processes and subsequent yield were more or less similar as noticed in case of irrigated condition. The elevated 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 under all the three levels. The response seemed to be more pronounced under moisture limiting condition. Potential grain yield of pigeonpea (using WOFOST crop model) decreased greatly over the control when the temperature was increased even by 1°C. The results indicated the differential response of production levels to temperature rise, which need to be understood through climate change effects on phenology, crop and soil processes.

Lal et al. (1999) projected 50% increased yield for soybean for a doubling of CO_2 in Central India by using CROPGRO-soybean model. However, a 3°C rise in surface air temperature almost cancels out the positive effects of doubling of carbon dioxide concentration results in reducing the total duration of the crop (and hence productivity) by inducing early flowering and shortening the grain fill period. Soybean crops in Central India are found to be more vulnerable to increase in maximum temperature than in minimum temperature. A decline in daily rainfall amount by 10% restricts the grain yield to about 32%. They concluded that acute water stress due to prolonged dry spells during monsoon season could be a critical factor for the soybean productivity even under the positive effects of elevated CO_2 in the future.

Sahoo (1999) used CERES-maize crop model and carried out simulation for irrigated and rainfed conditions. Rise in temperature decreased the maize yield both the environments. At CO_2 level of 350 ppm, grain yield decreased continuously with temperature rise till 4°C, where the yield decreased by about 30% over the present day condition. This was possibly due to reduction in days to 50% silking and physiological maturity. At CO_2 level of 700 ppm, grain yield increased by about 9% over the present day condition. The temperature rise decreased the yield continuously in all the cultivars, which was around 8% per degree rise in temperature. Effect of elevated carbon dioxide concentration on growth and yield of maize was established, but less pronounced when compared with crops like wheat, chickpea and mustard crop. The beneficial effect of 700 ppm CO_2 was nullified by an increase of only 0.6°C in temperature. Further increase in temperature always resulted in lower yields than control. For one of the IPCC scenario (an increase of 1.8°C temperature for India and 425 ppm CO_2 by the year 2030), potential maize yields would be severely effected (about 18%).

The sensitivity experiments of the CERES-rice model to CO_2 concentration changes by (Saseendran et al., 1999) indicated that over the Kerala State, an increase in CO_2 concentration leads to yield increase due to its fertilization effect and also enhance the water use efficiency. The temperature sensitivity experiments have shown that for a positive change in temperature up to 5°C, there is a continuous decline in the yield. For every one-degree increment the decline in yield is about 6%. Also, in another experiment it was noticed that the physiological effect of ambient CO_2 at 425-ppm concentration compensated for the yield losses due to increase in temperature up to 2°C

Kumar and Parikh, 2001, estimated the functional relationship between farm level net revenue and climate variables, introduced through linear, quadratic, and interaction terms, to understand the climatic sensitivity of Indian agriculture. They found that the overall impacts due to the climate change scenario for a 2°C rise in temperature and a 7 percent increase in precipitation are negative and about 8.4% of the total farm level net-revenue for India. The temperature increase results in significant negative impacts, while the higher precipitation considered under the scenario increases the net-revenue. On the whole the negative impacts due to temperature change more than compensate for the small positive impact due to precipitation change. Impacts estimated for a range of temperature changes revealed that the temperature response function is of inverted ‘U’ shape, i.e., with higher climate changes the loss would be greater. The spatial distribution of impact is shown in figure 6. The northern states of Haryana, Punjab, and western Uttar

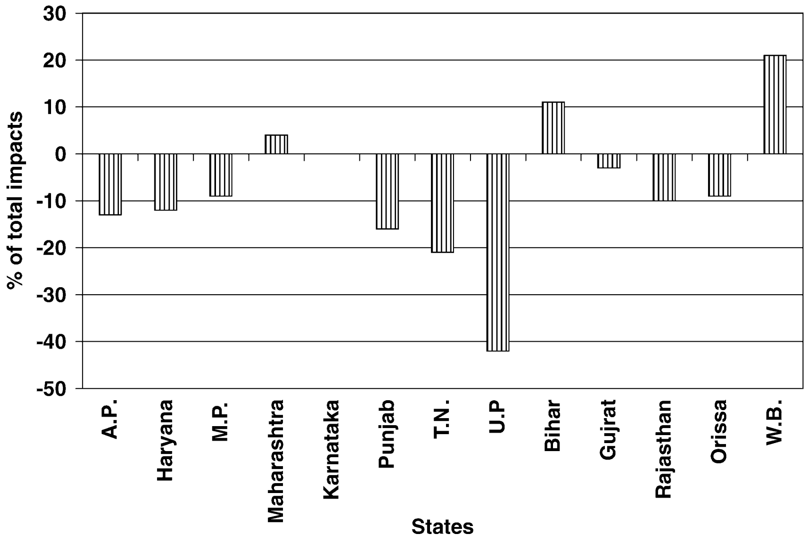

Figure 6. Distribution of impacts on net revenue accorss various states (as percentage of total absolute impacts). (Source: Kumar & Parikh, 2001)

Pradesh, which grow predominantly wheat in the winter season, experience most negative effects, along with the coastal districts of Tamil Nadu. On the other hand the, the eastern district of West Bengal and parts of Bihar, seem to benefit from the changes in future (Kumar and Parikh, 2001).

Rathore et al. (2001) used CERES-rice model and analyzed the impact of climate change on rice production in India. They concluded that by the middle of the 21st century in Central and South India, an increase in rice yield is possible under the projected climate change scenarios by Lal et al. (1995). In North West India a decrease in yield under irrigated conditions may take place as a result of the significant decrease in rainfall during the monsoon season under climate change. Also, reduction in crop duration may occur at all locations in the country due to increase in temperature associated with the build up of greenhouse gases in the atmosphere.

Aggarwal and Mall (2002) reported the results of a study where the impact of various climate change scenarios has been assessed on grain yields of rice with two popular crop simulation model – CERES-rice and ORYZA1N (Aggawal et al., 1997) at different levels of management. Figure 7 Shows the change in rice yields at current level of management (refers to application of 150 Kg N/ha in 3 split doses and frequent irrigations, a common practice in irrigated rice growing areas in several parts of the country) with change in temperature and CO_2. Increase of 1 to 2°C temperature without any increase in CO_2 resulted in a 3–17% decrease in grain yield in different regions. In general, as the temperatures increased rice yields in eastern and western India were less affected, moderately affected in north whereas

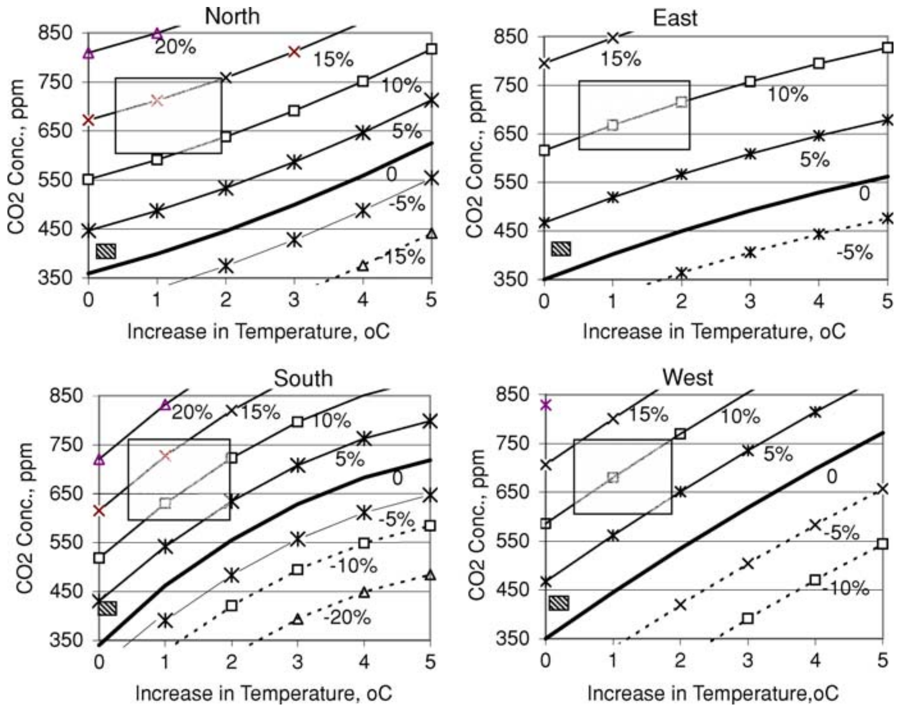

Figure 7. Effect of increase in temperature and CO_2 on simulated grain yields of irrigated rice with current level of N management (150 kg N ha-l) in different regions of India. Lines refer to the equal change in grain yield (% change, labeled) at different values of CO_2 and increase in temperature. Large, shaded box refers to bias in impact assessment due to uncertainties in IPCC scenario of 2070 and the small, hatched box refers to the bias due to uncertainties in the scenario of 2010. (Source: Aggarwal and Mall, 2002)

severely affected in southern India. Grain yields increased in all regions as the CO_2 concentration increased. A doubling of CO_2 resulted in 12 to 21% increases in yield in different regions. The beneficial effect of 450 ppm CO_2 was nullified by an increase of 1.9–2.0°C in northern and eastern regions and by 0.9-1.0°C in southern and western regions. In improved level of management (analogues to potential production environment) increase of 1 to 4°C temperature without any increase in CO_2 resulted in a 5–30% decrease in grain yields in different regions. A 28–35% increase in yields of rice was obtained as atmospheric CO_2 doubled. The beneficial effect of 450 ppm CO_2 was nullified by an increase of 1.2–1.7°C in northern and eastern regions and by 0.9–1.0°C in southern and western regions.

Most of the simulation studies have shown a decrease in duration and yield of crops as temperature increased in different parts of India. Such reductions were, however, generally, offset by the increase in CO_2; the magnitude of these crops varied with crop, region and climate change scenario. In north India, irrigated wheat yields decreased as temperature increases, a 2°C increase resulted in 17%

decrease in grain yield but beyond that the decrease was very high. These decreases were compensated by increase in CO_2 due to letter's fertilizing effect on crop growth. CO_2 concentration ha to rise tp 450 ppm to nullify the negative effect of 1°C increase in temperature. The effect of climate change scenario of different periods can be positive or negative depending upon the magnitude of change in CO_2 and temperature (Aggarwal, 2003). He has also developed two scenarios based on IPCC (2001) as optimistic (low increase in temperature; high increase in CO_2) and pessimistic scenarios (high increase in temperature; low increase in CO_2) for different years. The possible impact of these studies showed that the irrigated wheat and rice yields in north India will not be significantly affected due to direct effect until 2050. It is only in 2070 when the temperature increases are very large, that the crops show large reduction in yield.

Recently Attri and Rathore (2003) used CERES-wheat dynamic simulation model and climate change scenarios projected by the middle of the current century, based on the latest studies, and analyses the impacts of concurrent changes of temperature and CO_2 on the growth, development and yields of wheat in northwest India. Table IV Shows the change in yield of different genotype of wheat under modified climate in rainfed and irrigated conditions. They found increase in wheat yield between 29–37% and 16–28% under rainfed and irrigated conditions especially in different genotypes were observed under a modified climate as shown in table. A 3°C increases in temperature or more shall cancel out the positive effects of CO_2.

Mall et al. (2004) used the CROPGRO-soybean model to simulate the impact of climate change on soybean production in India. Climate change scenarios for the selected regions of the Indian subcontinent were developed using three GCMs namely, Goddard Institute of Space Studies Model (GISS-2, Russell and Rind, 1999), Geophysical Fluid Dynamics Laboratory Model (GFDL-R30, Knutson et al., 1999) and United Kingdom Meteorological Office – Hadley Climate Prediction Centre Model (UKMO – HadCM3, Mitchell et al., 1998). For the crop growth model used in this study, the probable changes in surface air temperature during the growing season were estimated at the selected sites in the region following standard rationalization techniques suggested by IPCC (Carter et al., 1999; Mearn et al., 2001). Probable changes in precipitation, cloudiness and solar radiation under the climate changes scenarios were not taken into consideration in this analysis in view of the significant uncertainties associated with non-linear, abrupt and threshold rainfall events projected by GCMs over the Indian subcontinent. In this study, all the GCM projected climate change scenarios (at the time of doubling of CO_2 concentrations) predicted decreased yields for almost all locations. Mean decline in yields across different scenarios ranged from 14% in Pune (West India) to 23% in Gwaliar (Central India). Decline in soybean yield is found to be less in west and south India as compared to other parts of the country. The mean yield was found to be significantly affected under UKMO model generated climate scenarios for both current and doubled CO_2 atmosphere.

These studies have indicated that the direct impacts of climate changes would be small on *kharif'* crops but *kharif* agriculture will become vulnerable due to increased incidence of weather extremes such as change in rainy days, rainfall intensity, duration and frequency of drought and floods, diurnal asymmetry of temperature, change in humidity, and pest incidence and virulence. *Rabi* crop production may become comparatively more vulnerable due to larger increase in temperature, asymmetry of day and night temperature and higher uncertainties in rainfall. The impacts of the climate change on Indian agriculture would be small in near future, but in long run the Indian agriculture may be seriously affected depending upon season, level of management, and magnitude of climate change.

5. Uncertainties due to Scenarios and Crop Models on Impact Assessment

Estimates of impact of climate change on crop production could be biased depending upon the uncertainties in climate change scenarios, region of study, crop models used for impact assessment and the level of management. So it is very important to give these uncertainties due importance while assessing the impacts of possible climate change on crop productivity for formulating response strategies.

The environmental factors such as cloudiness and solar radiation at the earth's surface will also change but the GCMs are less consistent in their predictions, particularly on a regional basis (Mitchell et al., 1995; IPCC, 2001). Climate models, in general, are subject to several uncertainties, which are especially pronounced at regional scales. Models are also known to be inadequate in their representation of physical processes related to rainfall. It should be noted here that the projected changes in climatic elements by the end of the 21st century is sensitive to assumptions concerning future concentrations of greenhouse gases and aerosols. Because there is still considerable uncertainty in our understanding of how the climate system varies naturally and reacts to emissions of greenhouse gases and aerosols, current estimates of the magnitude of future warming are subject to future adjustments (either upward or downward). These caveats need to be kept in view while interpreting the possible impacts associated with the projected climate change scenarios presented in section 3.

Aggarwal and Mall (2002) reported that there was considerable difference in the impact of climate change on rice yields calculated by the two crop models (Figure 8 and Table V). This difference was magnified depending upon the N management and uncertainty of the climate change scenario. In the scenario of 2010, CERES-rice responded to climate change at 0 kg Nha-l by an increase of 1–2% only, rising to 2–5% at 150 kg Nha-l and remained at that level at higher N (Figure 8). By comparison, rice yields simulated with ORYZAIN showed a slightly higher response to climate change (3–4% at 0 kg Nha-l and 3–7% at 150 kg Nha-l). This was true irrespective of the regions (Table V). This was due to the assumption of greater response of photosynthesis to increase in CO_2 in ORYZAIN relative to Ceres-rice (Mall and

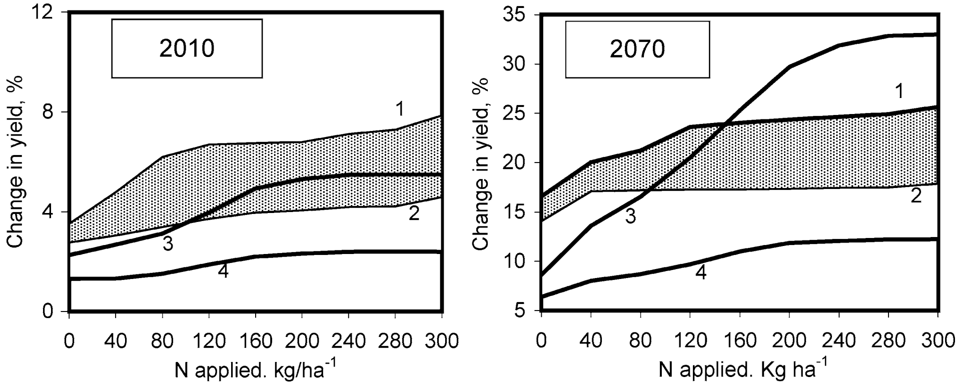

Figure 8. Response of irrigated rice yields (% change in yield in climate change over the control yield) in northern India to different levels of N availability for IPCC's optimistic and pessimistic scenarios of climate change for 2010 and 2070. The simulations were done using two crop models – Ceres-rice and ORYZA1N. The difference between lines 1 and 2 and between 3 and 4 refers to uncertainties in impact assessment due to climate change scenarios as simulated by ORYZA1N and Ceres-rice, respectively. The difference between the top and bottom lines in each figure refers to the total uncertainties due to crop models and climate change scenarios. (Source: Aggarwal and Mall, 2002).

Aggarwal, 2002). It is interesting to note that despite considerations of all uncertainties, the simulated rice crop always responded positively to climate change. Thus, the impact of climate change scenarios of 20 10 was nominal and varied between 1–7% depending upon the scenario of climate change, level of N management and impact assessment model used for the analysis and the regions of study.

In the scenarios of 2070, simulation analysis by CERES-rice showed a large sensitivity of grain yields to uncertainty in climate change at higher levels of N, particularly in the optimistic scenario of climate change (Figure 8 and Table V). Rice grain yields increased 6% in the pessimistic scenario and 9% in the optimistic scenario at 0 kg Nha-l. At the same N level, rice yields simulated by ORYZAIN showed a much higher response (14–16%). This was due to the greater response of photosynthesis to increase in CO_2 and also due to the assumption photosynthesis remains insensitive to temperatures up to 37°C in ORYZAIN as compared to 32°C in Ceres-rice (see Mall and Aggarwal, 2002, Part 1). At 80 kg Nha-l, grain yields increased between 16–21% for ORYZAIN and between 7–16% for CERES-rice. At 150 kg Nha-l, Ceres-rice showed a response of 9% only in the pessimistic scenario of climate change, whereas ORYZAIN showed a response of 16%. However, for the optimistic scenario of climate change, both models showed a similar response of approximately 24% increase in grain yields. As the N level increased further to 240 kg ha-l, the maximum response simulated by ORYZAIN was only 24% compared to 32% by CERES-rice. Overall, the response varied between 4–34% in the 2070 scenario depending upon the uncertainties in climate change, model used, level of N management and regions (Mall, 2003).

The differential response of the two models was due to their contrasting structure. Ceres-rice showed a relatively lower response to climate change at low levels of N applications because the model did not show any response in grain number. By comparison, at the same level of N management, rice yields simulated by ORYZAIN showed a small increase. This was due to an increase in grain number caused by the increased growth rate related to CO_2 enrichment. As more N was applied, CERES-rice showed a higher response in grain yield than ORYZAIN due to setting a sink limitation (grain weight reached its potential) in the latter.

This study shows that the direct effect of climate change in irrigated and well management rice crops will always be positive in different agroclimatic regions in India irrespective of the various uncertainties. Southern and western India, which are at present relatively cooler during the rice season compared to northern and eastern regions, are likely to show a greater sensitivity to climate change. As a consequence, current yield differences in irrigated rice crops across regions are likely to disappear after the climatic change.

Aggrawal and mall (2002) concluded that several studies are being done to develop an integrated assessment of climate change impact on regional and global food supplies and demand. Some of these could also find use in directing food policy. These studies use specific GCM based scenarios and a specific crop model. While integrated assessments of climate change on food availability are very much needed, conclusions based on the average simulated grain yields and mean changes in climatic parameters should be used with caution.

6. Mitigation and Adaptation Strategies

Examination of relatively recent weather of the last century at many parts of the country indicates warming trends although statistically may not be significant, but there are enough indicators to suggest a modest increase in CO_2 and temperature. In spite of the uncertainties about the precise magnitude of climate change on regional scales due to scenarios and crop models on impact assessment, an assessment of the possible impacts of climate change on India's agricultural production under varying socioeconomic conditions is important for formulating response strategies, which should be practical, affordable and acceptable to farmers. The identification of suitable response strategies is key to sustainable agriculture. The important mitigation and adaptation strategies required to cope with anticipated climate change impacts include adjustment in sowing dates, breeding of plants that are more resilient to variability of climate, and improvement in agronomic practices (Attri and Rathore, 2003).

Attri and Rathore (2003) suggested the adaptation strategies for sustainable production of wheat and ensuring food security. Adaptation measures to mitigate the potential impact of climate change included possible changes in sowing dates and genotype selection. Enhancement of sowing by 10 days in late-sown cultivars and delaying of sowing by 10 days in normally sown cultivars resulted in higher yields under a modified climate, whereas a reduction in yield was observed.

The results obtained by Mall et al. (2004) on the mitigatory option for reducing the negative impacts of temperature increases indicate that delaying the sowing dates would be favorable for increased soybean yields at all the locations in India. Sowing in the second season would also be able to mitigate the detrimental effects of future increases in surface temperature due to global warming at some locations. However, the proposed shift in soybean production from the current main season to a second season may necessitate additional planning and change in management practices.

However, it should be noted that changing of sowing dates is a no-cost decision that can be taken at the farmer level; a large shift in sowing dates probably would affects the agrotechnological management of other crops, grown during the remaining part of the year. Changes in the cropping sequence, irrigation and agriculture land use can be additional alternative options for adaptation in agriculture. Kumar and Parikh (1998a,b) have showed that even with adaptation by farmers of their cropping patterns and inputs, in response to climate change, the losses would remain significant. The loss in farm-level net revenue is estimated to range between 9% and 25% for a temperature rise of 2°C–3.5°C.

There is need to be identify district or agroclimatic regions vulnerable to climate change and identify suitable adaptation practices to be followed in order to sustain the productivity of these regions to some extent. This adaptation strategies may include altered crops and cropping systems to maintain soil fertility in sustainable manner and improved management practices. Modern technologies in agriculture could also be beneficial with or without climate change; government should encourage farmers to shift towards newer technologies. The government should also encourage research on developing crop varieties that can withstand in the climate.

While the impact assessment of the future climate change is quite important, most crops in India, even in irrigated environments are quite sensitive to climatic variability. We had a record harvest of 75.5 Mt of wheat in 1999–2000, an increase of 5 Mt over 1998–99. This change was largely due to very cool weather during January to March 2000, which was favorable to grain formation and filling. The gluts and shortage of onions and potatoes in recent times besides being caused by policy and management are also manifestation of the effects of climate variability. Such variation in food production would be much larger in rice, pulses and oilseeds where larger portion of the crop area is rainfed. Any changes in weather during smaller periods would have much larger effect on short-season crops such as vegetables that have less time available to adjust and adopt relative to longer duration crops. Thus it is very likely that at least in the short run the effects of climatic variability are much larger than the projected impact of global climatic change. Therefore, it appears that if we can evolve strategies for managing climatic variability in agricultural production, adaptation required for climatic change would presumably be automatically taken care of (Aggarwal, 2003).

7. Limitation of the Studies

The findings reported in the different studies depend on the many assumptions built into the crop simulation models. For example, most of the relationships relating the effect of temperature and CO_2 on the plant processes are derived from experiments in which the crop's environment was changed for only part of the season; acclimation of the crop to changes in its environment is not taken account of in the model. Studies have shown that in some crops growing under enhanced CO_2 condition, there is initially a large response, but over time, this response declines and approaches that of crops growing under current CO_2 levels. The impact of the weeds, diseases and insect pests on crop growth, development and final yield formation assume to be controlled. Which need to be incorporated in the future studies for better assessment of final yield.

As regards the climate change scenarios inferred from GCMs, uncertainties are associated with imperfect knowledge and/or representation of physical processes, limitations due to the numerical approximation of the model's equations, simplifications and assumptions in the models and/or approaches, internal model variability, and inter-model or inter-method differences in the simulation of climate response to given forcing. Reducing the wide range of uncertainty inherent in projections of global and regional climate change will require major advances in our scientific understanding on the subject in the years to come. Projections about the probability, frequency, and severity of extreme weather events should be carefully evaluated. Current GCMs have only limited ability to predict changes in the interannual and intraseasonal variability of the weather or the frequency of the catastrophic events such as hurricanes, floods, or even the intensity of monsoons, all of which can be just as, or more, important in determining crop yields as the average climatic data. Nevertheless, despite these limitations, these studies mark significant progress in our understanding of how future climates may affect food grain production in India.

The impact assessment studies reviewed in this paper, however do not consider, due to uncertainties in climate change projection what type technological changes and adaptation measures will take place in future. Future long term projected scenarios of climate change may show the impact after more than 50 years whereas in the mean time several changes in Indian agriculture such as new heat tolerance crop varieties, farm level adaptation, change in demand, market and changes in agricultural technologies is expected to transform agricultural production in India significantly. Whole Indian agricultural system may become changed in coming decades due to the fast technological change, which is expected. These lacking in the present studies need to be incorporated in future studies for better-integrated assessment of impact of climate change on Indian agriculture for sustainable development, mitigation and other policy planning's. Also, there is need to be paying more attention on the impact of future climate extreme events and pest incidence and virulence on agriculture in future research.

8. Discussion and Conclusion

The current simulation results from GCM's are still considered uncertain. Present GCM's ability in predicting the impact of climate change on rainfall is still not promising. In addition, the uncertainty involved in predicting extreme flood and drought events by the models are large. There is, considerable uncertainties in the projected magnitude of change in temperature and rainfall for India (Table II). While climate models predict a change in precipitation by −24 to 15% over India by the end of century (Lal et al., 2001), the regional change may be different (Rupakumar et al., 2003). Studies on inter-annual and long-term variability of monsoon and annual rainfall have found that the variation in rainfall for the subcontinent is within statistical limit (Thapliyal and Kulshrestha, 1991; Srivastava et al., 1992). However, analysis of past weather data indeed indicates a warming trend at many places in India and changes in rainfall (statistically not significant) pattern in different parts of the country (Table I). Therefore, it is very difficult, at this juncture, to convince the planner and development agencies to incorporate the impact of climate change into their projects and agricultural system. However, 60% of the total cropped area is still rainfed in India and dependent on uncertainties of monsoon. The country's food grains production during 2002–03 had slumped to 174.19 Mt, due to widespread drought, from the record level of 212.02 Mt in 2001–02. Which shows the dependency of Indian agriculture on climate in spite of recent technological development. Therefore, given the potential adverse impacts on agriculture that could bring about by climate change, it is worthwhile to conduct more in-depth studies and analyses to gauge the extent of problems that the country may face in future. We must focus on how the possible climate change will affect the intensity, spatial and temporal variability of the rainfall, surface and groundwater availability for irrigation, evaporation rates and temperature in different agro-climatic regions. For this more studies are needed on direct or indirect effect of climate change on crop growth, uncertainties of onset of rainfall, spatial and temporal rainfall variability, duration and frequency of drought and floods, availability of irrigation, changes in groundwater level, soil transformations, crop-pest interaction and submergence of coastal land due to sea level rise.

Rupakumar et al. (1994) showed that there was an asymmetry in the temperature trends in terms of day and night temperature over India; the observed warming was predominantly due to an increase in maximum temperatures while minimum temperatures remained practically constant during the past century. Rupakumar et al. (2003) also projected that there is likely to be substantial increase in extreme maximum and minimum temperatures all over the country due to increase in greenhouse gas concentrations. This is very important finding for agriculture point of view as the *mid-day high temperature* increases the saturation deficit of the plants. It accelerates photosynthesis and ripening of fruits (Papadakis, 1970). The maximum production of dry matter occurs when the temperature ranges between 20 to 30°C, provided moisture is not limiting factor. When high temperature occurs in combination with high humidity, it favours the development of many plant diseases. High temperature also affects plant metabolism. However, h*igh night temperature* increases respiration. It favours the growth of the shoot and leaves at the cost of roots, stolons, cambium and fruits. It governs the distribution of photosynthesis among the different organs of the plants, favouring those, which are generally not useful. Therefore asymmetry in the temperature trends in terms of day and night temperature may be incorporated in future studies for better assessment of crop production due to global warming. Extreme climatic events, abnormal temperatures in a specific development stage, caution us to identify suitable management options with 'no regret' to face the situation. The crop-pest-weather interaction and socio-economic components are relatively weaker, and need to be strengthened.

Generally the studies reviewed in this paper used dynamic crop simulation models to simulate yield impacts. With the development of science and technology, dynamic crop simulation models have been developed, tested and have become the main method of analyzing the potential impacts of climate change on agriculture. As a tool to assess the vulnerability and adaptation of agriculture to climate change, it is more accurate. Generally, climate change scenarios for the selected regions of the Indian subcontinent were developed using the outputs of GCMs, such as GFDL, UKMO and GISS with climate variability (changing temperature from $-1 to + 5°C$ and rainfall from -20 to $+30\%$) considered.

Increase in food grain production during last three decades made India self sufficient and contributed tremendously to their food security. The later, however, is now at risk due to increased demand of continuously increasing population. Also the situation is grim as decline in soil fertility, decline in groundwater level, rising salinity, resistance to many pesticides, degradation of irrigation water quality and genetic diversity of the popular varieties in the farmers field has been rapidly decreasing. It is however of paramount importance to sustain the natural resource. Enhancing the organic matter content of soils will ensure better soil fertility, irrigation pricing in the western Indo-Gangetic plains will ensure the efforts to increase the efficiency of water use and improve other associated environmental impact. However, since this adversely affects income from the rice-wheat system, there is considerable socio-political resistance to its implementation. In recent years, the prospect of climate changes has stimulated considerable research interest in attempting to predict how production of crops will be effected. The purpose of this review was to provide overview of the likely effect of the climate change on food production in India.

Several studies projected increase or decrease in yields of cereal crops (rice, wheat, maize and sorghum), Oilseed and pulses crops (soybean, groundnut, chickpea, brassica (mustard) and pigeon pea) depending on interaction of temperature and CO_2 changes, production environment, season and location in India (Table VI). Still the climate change impact studies have not conducted on several important crops in India such as sugarcane, cotton, jute, sunflower, potato and onion etc., which may be done in future for better assessment of vulnerability of Indian agriculture due to climate change. However, these studies have indicated that the direct impacts of climate changes would be small on 'kharif' crops but overall '*kharif*' agriculture will become vulnerable due to increased incidence of weather extremes such as onset of monsoon, duration and frequency of drought and floods, and pest incidence and virulence. Production of '*rabi'* crop is relatively more risky due to projection of larger increase in temperature and higher uncertainties in rainfall. Unless considerable adaptation takes place, this would result in decreased winter or '*rabi'* production. An index of sustainability that included economic (agricultural production, income, and risk) and environmental (ground water level, land degradation and biodiversity) indicators clearly shows that the agricultural production is under threat and needs immediate attention (Joshi et al., 2003) Although, the effect of climate change on crop productivity could be biased depending upon the uncertainties in crop models used for impact assessment, climate change scenarios, region of study, technological changes and the agronomic management, the integrated assessment of climate change impact on different sectors of Indian economy is very important to determine future strategies for sustainable development, adaptation and other policy decisions. It is worthwhile to note that Kumar and Parikh (2001) projected that with 2°C increase in temperature and 7% increase in the precipitation the net-revenue of India will be decline by 8.4%. It is also important that losses expected from the climate change on Indian agriculture will be more. This should be due to the warmer temperature that the Indian farmers face under the present climatic conditions and also the relatively low level of management because small and marginal farmers with less land holding are more than 60% of the total farmers. Such an assessment on agriculture and therefore policy response to manage climate change impacts will not be complete unless the biophysical, environmental and socioeconomic sectors of agro-ecosystems are studied together. Global integrated impact assessment models though provide such a framework, but are inadequate for regional policy planning because these are not validated at that scale and due to their inherent inter-and intra-sectoral conflicts. We need to urgently develop our own integrated assessment simulation models in which cropping systems; water use and socioeconomic parameters need to be brought together for assessing the impact of environmental change in diverse regions of the country. It may be developed in collaboration with several stakeholders including policy makers, agricultural and environmental scientist, climatologist, economist, administrators, industry and farmers organization.

In future studies, only when the uncertainties and limitations discussed above have been considered in the crop simulation modeling and climate change scenarios, the assessment of climate change on Indian agriculture can be more precise and provide sound basis for regional policy planning (Figure 9). However, it is expected that the fast improvement of climate and crop model across the global and regional level in the last decades to be sustained. It is not too distant future; these models should yielding reliable results on regional scale for the nature of climate change in response to various factors.

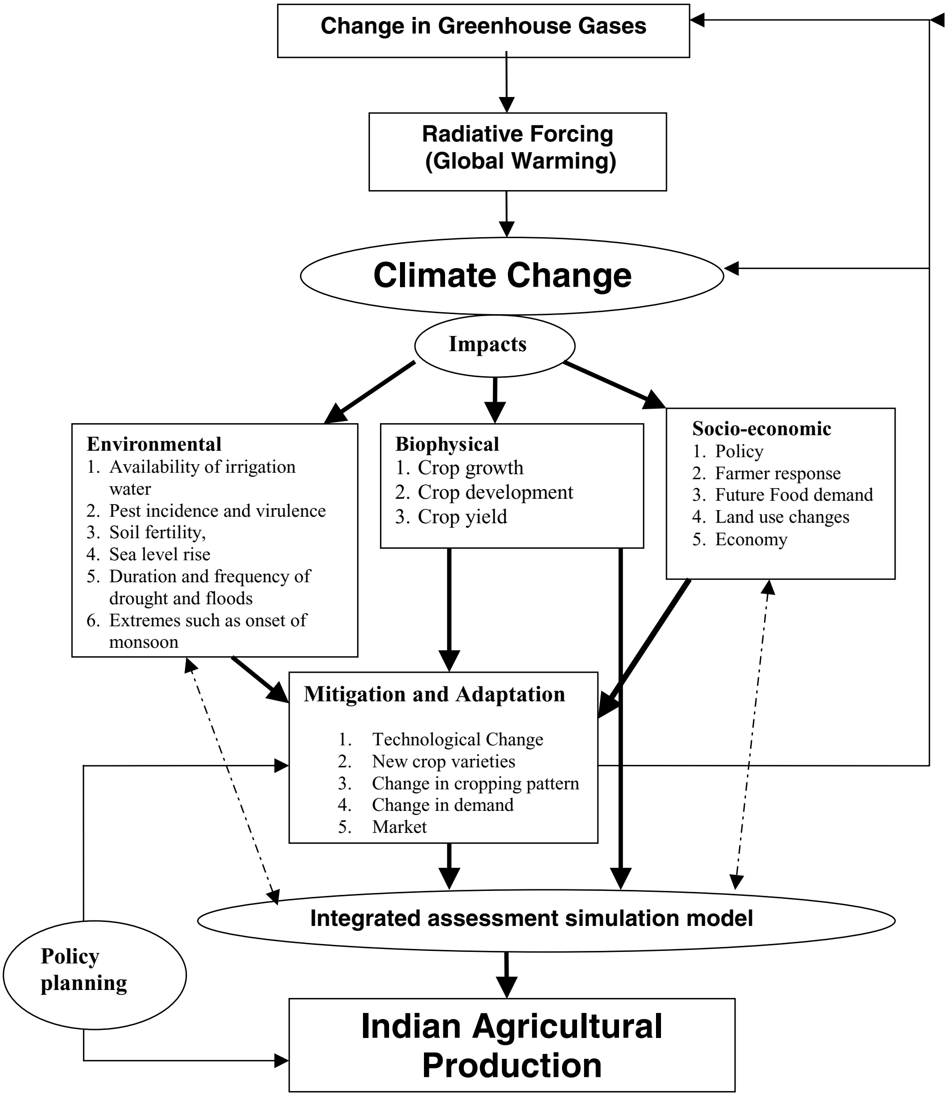

Figure 9. Driving forces of assessment of the vulnerability of Indian agriculture production to climate change.

At this juncture, based on the different reports it can be concluded that the agricultural impacts of climate change in India are uncertain. The total average impact may be positive or negative depending on the climate scenarios (temperature rising in 2°C, 3°C, 4°C, increase in CO_2 and interaction of increase in temperature and CO_2). Impacts also vary both quantitatively and qualitatively by crop, level of agronomic management, region and season. As to the seasonal impacts, the ‘*rabi*’ agriculture (winter season) in central and southern India will be more risky. But most scenarios show that climate change will have an overall positive impact or not affect significantly on India's agriculture until 2050. By the year 2080 when temperature increase are very large, the Indian agriculture will suffer the most. In other word it can be say that food production is not threatened up to 2050 and does not need to import food, but by the year 2080 food production is threatened.

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