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Mitigating climate change impact on soybean productivity in India: a simulation study

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Abstract

Field experiments with soybean were conducted over a period of 1990–1998 in diverse Indian locations ranging in latitude, longitude, and elevation. These locations provided a wide range of environments for testing and validation of the crop growth (CROPGRO) model considered in this study with observed changes in soils, rainfall and other weather parameters. Model predicted satisfactorily the trends of days to flowering, maturity and grain yields. The deviations of simulated results were within ±15% of the measurements.

Validated CROPGRO model has been used to simulate the impact of climate change on soybean production in India. The projected scenarios for the Indian subcontinent as inferred from three state-of-the-art global climate models (GCMs) have been used in the present study. There was a decrease (ranging between about 10 and 20%) in soybean yield in all the three future scenarios when the effect of rise in surface air temperature at the time of the doubling of CO_2 concentration was considered. The results obtained 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.

Keywords: Global climate models; Impact mitigation; Climate change; Soybean; Sowing dates; Crop simulation model

1. Introduction

Crop growth 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 externally applied inputs and food production is seriously impaired. The increasing CO_2 concentration in the atmosphere and the anticipated climate change due to global warming are also likely to affect future global agricultural production through changes in rate of plant growth (Lemon, 1983; Cure and Acock, 1986) and transpiration rate (Morison, 1987; McNaughton and Jarvis, 1991; Jacobs and DeBruin, 1992).

Soybean [*Glycine max* (L.) *Merrill*] ranks first among the oilseeds in the world and has now found

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a prominent place in India. It has seen phenomenal growth in area and production in India in the past decade (Paroda, 1999). Area under soybean cultivation has steadily increased over the years from the level of 0.50 million ha (Mha) in 1979–1980 to 5.86 Mha in 1997–1998. The growth in production and productivity has been from 0.28 million tonnes in 1979–1980 to 6.72 million tonnes in 1997–1998 and 570 kg/ha in 1979–1980 to 1150 kg/ha in 1997–1998, respectively (SOPA, 1999). This increasing trend of fast adaptation of the crop by the farmers in India points out that soybean is going to be the future leading commercial venture in the country. Its cultivation has also brought about positive socio-economic changes in the life of farmers in some parts of India (Tiwari et al., 1999). There is still substantial scope to increase both area and productivity of soybean in India. The current estimated growth in area coverage is 10 Mha and, by 2010 A.D., productivity enhancement will be about 1500 kg/ha such that production of 15 million tonnes by 2010 can be expected in India (Holt et al., 1997). Soybean has a good potential to get involved in the intercropping (Jat et al., 1998) as well as crop sequences, as it is a short duration (85–125 days) leguminous crop.

Future climatic change is likely to have substantial impact on soybean production depending upon the magnitude of variation in CO_2 and temperature. Increased temperature significantly reduces the grain yield due to accelerated development and decreased time to accumulate grain weight (Seddigh and Joliff, 1984a,b; Baker et al., 1989). There have been a few studies in India and elsewhere aimed at understanding the nature and magnitude of gains/losses in yields of soybean crop at different sites under elevated atmospheric CO_2 conditions and associated climate change (Adams et al., 1990; Sinclair and Rawlins, 1993; Haskett et al., 1997; Lal et al., 1999).

In this study, an attempt has been made: (*i*) to evaluate the performance of CROPGRO model under different seasons, weather, locations, management, and sowing dates; (*ii*) to know the yield potential of soybean; and (*iii*) to explore the possibilities of employing different mitigating options to alleviate the climate change impacts on soybean production under different climate change scenarios inferred from

Fig. 1. Locations of the selected sites in India considered in the study.

the state-of-the-art global climate models (GCMs) in the major soybean growing area in India using CROPGRO-soybean simulation model. The long-term observed daily weather data on rainfall, maximum and minimum temperatures and solar radiation at the selected stations in India, namely Coimbatore, Dharwad, Ludhiana, Hissar, Pantnagar, Delhi, Pune, Hyderabad, Ranchi, Indore, Raipur, Jabalpur and Gwalior have been used in this study. The geographical location of these stations is shown in Fig. 1.

2. Data and methodology

2.1. The CROPGRO-soybean model

Crop growth simulation models which share a common input and output data format have been developed and embedded in a software package called the Decision Support System for Agrotechnology Transfer (DSSAT) (Tsuji et al., 1994; Jones et al., 1994; Hoogenboom et al., 1994). The models under DSSAT umbrella include CROPGRO for soybean. Its major components are vegetative and reproductive development, carbon balance, water balance and nitrogen balance. A detailed description of the modified version of CROPGRO-soybean model is provided in Boote et al. (1996). The model uses empirical functions to compute daily canopy gross photosynthesis in response to CO_2 concentration, air temperature and daily canopy evapotranspiration. Canopy photosynthesis is computed at hourly time steps using leaf-level photosynthesis parameters and hedgerow light interception calculations (Boote and Pickering, 1994). Photosynthesis and evapotranspiration algorithms also take into account the changes in daily canopy photosynthesis under elevated CO_2 concentration and temperature conditions (Curry et al., 1990a,b). The model simulates the potential, water and nutrient limited yields of soybean.

2.2. Input data

The model requires input data on soil, crop and weather for its calibration and validation in different environments. Weather (solar radiation, maximum and minimum temperatures and rainfall) and soil (albedo, first stage evaporation, drainage, USDA Soil Conservation Service Curve Number for runoff and layer-wise information and saturation, field capacity, wilting point, texture and hydraulic conductivity) and crop management data (dates of sowing, plant and row spacing, irrigation, fertilizer, etc.) were collected for each of the locations under study. The details on weather data used in this study are given in Table 1.

2.3. Evaluation of the crop model

2.3.1. Genetic coefficients

To simulate a crop variety, the crop model requires 15 genetic coefficients. The genetic coefficients of the ‘Bragg’ variety of soybean for the model were estimated by repeated iterations in the model calculations until a close match between simulated and observed phenology, growth and yield was obtained. All calibration data required to derive genetic coefficients were obtained from field experiment conducted at Indore during 1995 and 1996 using random block design. In this field experiment, the soybean crop was sown at row spacing of 35 cm and the seed depth was maintained as 5 cm. A net 20 kg of urea was applied as basal dose at the time of sowing. Plant population was kept as 25 plants/m^2. The genetic coefficients determined in the model using the identical conditions as in the field experiment for ‘Bragg’ variety of soybean are presented in Table 2. These coefficients were used in the subsequent validation and application.

2.3.2. The model validation

A large number of field experiments have been conducted in India where the effect of different agro-ecological factors such as season, weather, sowing dates and variety has been studied on growth and yield of soybean crop in different locations. This database included all relevant information (including the different management practices adapted and the location specific weather conditions) obtained from field experiments conducted between 1980 and 1998 in major soybean producing states of India and had representations varying from Hissar in north India to Coimbatore in South India (Table 1).

2.4. The climate change scenarios

Climate change is no longer a distant scientific prognosis but is becoming a reality. The anthropogenic

Table 1
Mean simulated potential yields of variety Bragg and their coefficients of variation (CV%), period of weather data used and average seasonal temperature for current climatic conditions at selected locations in India

Location	Period	Latitude (°N)	Longitude (°E)	Yield (kg/ha)	CV %	Seasonal average temperature, max/min (°C)
Ludhiana (LUDH)	1974–1998	30.9	75.8	4200	5.3	33.8/24.6
Hissar (HISR)	1969–1996	29.1	75.5	4400	4.3	33.4/24.1
Pantnagar (PANT)	1970–1997	29.0	79.3	3900	4.6	32.2/24.4
Delhi (DELH)	1969–1998	28.3	77.1	4300	9.4	33.2/23.4
Gwalior (GWLR)	1965–1988	26.1	78.1	3300	11.9	33.5/23.6
Ranchi (RANC)	1986–1995	23.3	85.2	4000	5.9	29.2/22.3
Jabalpur (JBLP)	1969–1997	23.1	79.9	4050	5.2	30.8/22.9
Indore (INDR)	1985–1995	22.7	71.8	3550	9.4	32.1/23.5
Raipur (RAIP)	1971–1997	21.2	81.6	3800	7.1	31.6/22.5
Pune (PUNE)	1985–1997	18.3	73.5	4200	5.2	29.1/20.8
Hyderabad (HYDE)	1975–1997	17.4	78.4	4000	4.9	29.9/22.2
Dharwad (DHAR)	1990–1998	15.3	75.6	4000	8.1	30.8/21.2
Coimbatore (COIM)	1964–1994	11.0	77.0	3800	5.9	31.2/22.1

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. Over land regions of the Indian subcontinent, the projected area-averaged annual mean surface temperature rise by the end of 21st century has been estimated to range between 3.5 and 5.5 °C depending upon the future trajectory of anthropogenic radiative forcing (Lal et al., 2001). The projected temperature increase has a large seasonal and spatial dependency over India. During the monsoon

Table 2
Genetic coefficients of cultivar 'Bragg' obtained in calibration experiment

Description	Genetic coefficients
Development aspects	
Critical short day length (h)	11.81
Slope of relative response of development to photoperiod (h)	0.32
Time between plant emergence and flower appearance (photothermal days)	19.5
Time between first flower and first pod (photothermal days)	10.0
Time between first flower and first seed (photothermal days)	15.0
Time between first seed and physiological maturity (photothermal days)	30.5
Time between first flower and end of leaf expansion (photothermal days)	17.0
Seed filling duration for pod cohort at standard growth conditions (photothermal days)	24.9
Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	10.9
Growth aspects	
Maximum leaf photosynthesis rate at 30 °C and high light (mg CO_2/m^2s)	1.0
Specific leaf area of cultivar under standard growth conditions (cm^2/g)	350.0
Maximum size of full leaf (three leaflets) (cm^2)	170.0
Maximum fraction of daily growth that is partitioned to seed + shell	1.0
Maximum weight per seed (g)	0.16
Average seed per pod under standard growing conditions	2.1

season, the temperature rise over south India is projected to be less than 1.5 °C by 2050s while the increase in surface temperature is more pronounced over north, central and east India (∼2 °C).

Globally averaged precipitation is projected to increase based on an ensemble of simulations performed with the state-of-the-art GCMs, but at the regional scale both increases and decreases have been projected. Over the Indian subcontinent, a marginal increase of about 7–10% in area-averaged annual mean precipitation has been projected by the end of this century (Lal, 2001). During the monsoon season, an increase in area-averaged precipitation of only about 3–5% over the land regions has been projected by 2050s. 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.

Other 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 here.

Climate change scenarios for the selected regions of the Indian subcontinent were developed using three widely known 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 regionalization techniques suggested by IPCC (Carter et al., 1999; Mearns 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.

3. Results and discussion

3.1. *The model validation*

The correct estimation of crop phenology is very crucial for the successful validation of crop growth simulation models at a specific site. Observed duration to flowering of soybean crop at selected sites in India varies from 30 days (in Pune) to 60 days (in Hissar), whereas simulated duration in our model validation exercises ranged from 30 days (in Jabalpur) to 59 days (in Hissar). Similarly, the observed duration to maturity of soybean crop at selected sites varies from 89 days (in Coimbatore) to 134 days (in Ludhiana). The simulated duration to maturity ranged from 84 days (in Jabalpur) to 131 days (in Hissar). The analysis further suggested that the root mean square error (RMSE) and the mean bias error (MBE) in the model simulated duration to flowering were significantly small (RMSE = 2.9, MBE = −0.6). The RMSE and MBE for the model simulated duration to maturity of crop were also negligible (RMSE = 4.3, MBE = 0.5). RMSE provides information on the performance of a model by allowing a term by term comparison of the actual difference between the simulated and observed values. MBE provides information on the performance of a model by over-estimation or under-estimation; a positive value gives the average amount of over-estimation in the estimated values and vice versa. The simulated durations to flowering as well as maturity were within 15% error line. This exercise confirmed that the selected crop growth model was able to simulate the observed flowering and maturity periods reasonably well for most treatments and at all sites selected in this study (Fig. 2a and b).

Fig. 2c depicts a close correspondence between simulated and observed grain yields across all treatments. Observed grain yields ranged from 235 kg/ha (Delhi) to 3788 kg/ha (Pune) depending upon the location whereas simulated grain yields ranged from 367 kg/ha (Delhi) to 3588 kg/ha (Pune). It is evident from Fig. 2c that model predicted grain yields within ±15% of the measured yields (RMSE = 154, MBE = 3.2). In general, the predicted yields were relatively higher than the observed yields in the years with low yields indicating the model's inability to simulate crop growth when there is extreme stress. Considering that the field measurements too generally have ±10–15% error and that the treatments covered widely varied weather conditions it is assumed that the model is adequate to simulate the effects of climate change on soybean yields in diverse agro-environments of India.

3.2. Predicted potential yield under present-day climate

The model simulates the potential yield of soybean, mainly driven by solar radiation and temperature and on varietal characteristics. In predicting the potential yields, it is assumed that the crop has no water and nitrogen stress and is free from any insect, pest and disease effects. Dates of sowing for each location were chosen based on the local practice. The potential soybean yields for the selected 13 sites under current climatic conditions along with their coefficients of variation (CV%) are shown in Table 1. The seasonal average daily temperature during the soybean growing period is also included in this table. Simulated potential yields ranged from 3300 kg/ha (at Gwalior) to 4400 kg/ha (at Hissar).

3.3. Performance of soybean under climate change scenarios

We performed a set of simulations to examine the sensitivity of soybean productivity to the enhanced surface air temperature at the selected sites using the CROPGRO model wherein daily maximum and minimum surface air temperature changes as obtained in the GFDL, GISS and UKMO climate model projections for South Asia region for the present-day conditions and also at the time of doubling of CO_2 have been considered. These temperature changes were superimposed on the observed daily maximum and minimum temperature data series for all the years considered in our simulations. The results of simulation for three GCM scenarios are presented in Table 3. The UKMO and GISS models simulate somewhat higher surface air temperatures than the observed weather records for the present-day atmosphere (equivalent CO_2 concentration ∼350 ppm by volume) and as a consequence the simulated grain yields show a decline in crop yield for different GCM-generated climate (it ranged from 13% in GFDL simulated present-day atmosphere to 21% in UKMO simulated present-day atmosphere. The yields in soybean are found to decline almost identically for the climate change scenarios as inferred from all the three GCMs for the case when a doubling of CO_2 with respect to the present-day atmosphere occurs. The simulated decline in crop yield was from 12% (GFDL model climate) to 21% (UKMO model climate) under the doubled CO_2 climate change scenario. The total above ground biomass was most affected under the UKMO model-generated climate scenario under both the levels of CO_2. The maturity day of the crop also extended by 2 to 5 days in duration for both the CO_2 levels in our crop model simulations (Table 3).

All the GCM projected climate change scenarios (at the time of doubling of CO_2 concentrations) predicted decreased yields (Table 4) for almost all locations. Mean decline in yields across different scenarios ranged from 14% in Pune (west India) to 23% in Gwalior (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. In view of this, the assessment of the options to mitigate the negative impact of the climatic change will be dealt in the next section with special reference to the UKMO model-generated climate change scenarios.

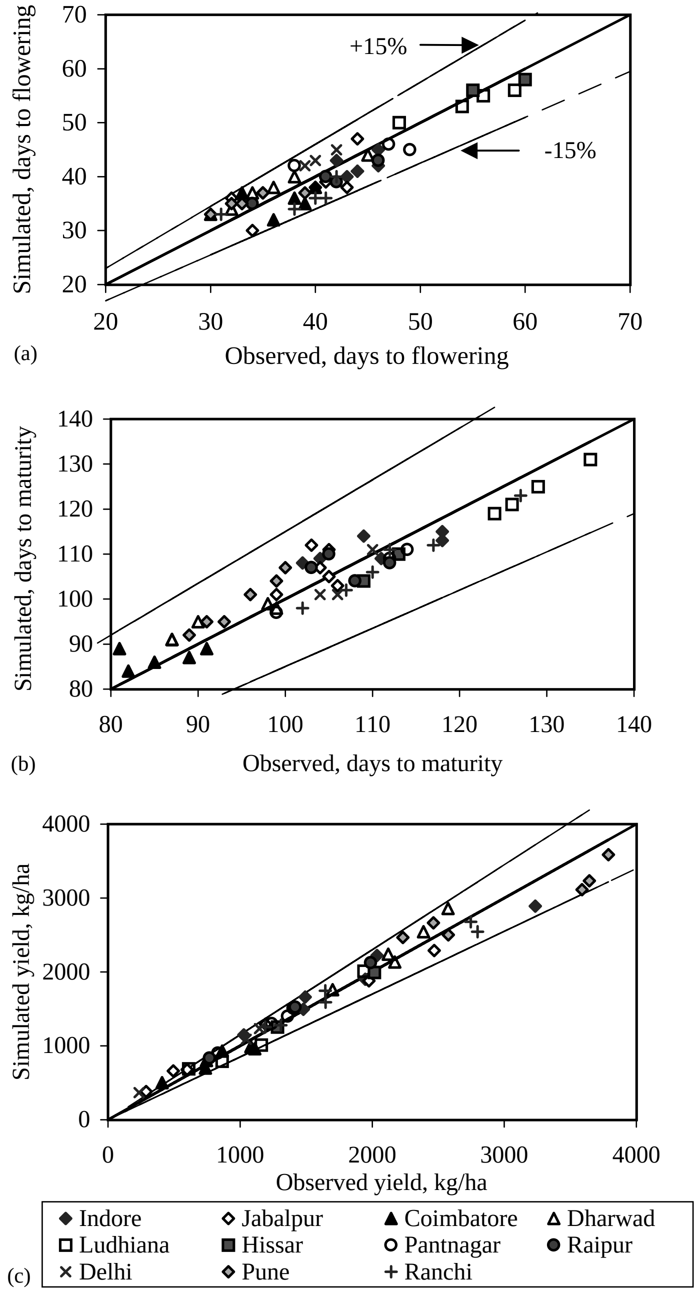

Fig. 2. Comparison of simulated and measured (a) duration to flowering, (b) duration to maturity and (c) yields across data sets varying in seasons, weather, locations, nitrogen and water management, and sowing dates. Also shown are 1:1 line (solid) and error lines of ±15% (dashed).

Table 3
Some crop growth parameters of the soybean variety 'Bragg' as simulated by crop simulation model for two CO_2 levels and temperature increase projected in selected GCMs (values represent average of 13 selected locations in India)

CO_2 level	Crop growth parameters	T_{obs}	GFDL	GISS	UKMO
Present	Yield (kg/ha)	3950	3450	3200	3100
	Change in yield	0%	−13%	−19%	−21%
	Total above ground biomass (kg/ha)	7300	6900	6750	6650
	Change in above ground biomass	0%	−5%	−7%	−8%
	Maturity duration (days)	109	111	113	114
	Change in maturity duration	0%	1%	3%	4%
Doubled	Yield (kg/ha)	5400	4750	4450	4250
	Change in yield	0%	−12%	−18%	−21%
	Total above ground biomass (kg/ha)	10000	9450	9200	9100
	Change in above ground biomass	0%	−5%	−7%	−8%
	Maturity duration (days)	109	111	113	114
	Change in maturity duration	0%	1%	3%	4%

3.4. Mitigation strategies

While agriculture may benefit from carbon dioxide fertilisation and an increased water efficiency of some plants at higher atmospheric CO_2 concentrations, these positive effects are likely to be negated due to thermal and water stress conditions associated with climate change. Thermal stress significantly affects the agricultural productivity when it occurs in critical life stages of the crop (Rounsevell et al., 1999). Increase the temperature reduces the total duration of crop by inducing early flowering and shortening grain fill period (Iglesias et al., 1996). The shorter the crop duration, the lower is the yield per unit area; a rise in temperature should therefore lead to a fall in agricultural production in a warmer atmosphere. Reports of heat-stressed crops have become common in the recent years in India. Even irrigated crops suffer from high evaporation losses and heat stress. Under these conditions, photosynthesis declines and the plant switches from a growth path to a survival mode thus reducing yields. A clear understanding of the relationship between climatic variability, crop management and agricultural productivity is critical in assessing

Table 4
Changes in potential soybean yields (kg/ha) for three GCM scenarios in selected locations in India

Site	2 × CO_2[a]	GFDL yield	Percent change	GISS yield	Percent change	UKMO yield	Percent change	Mean
Ludhiana	5600	5000	−11	4700	−16	4600	−18	−15
Hissar	5850	5000	−15	4650	−20	4350	−26	−20
Pantnagar	5720	5100	−11	4850	−15	4750	−17	−14
Delhi	5800	5000	−13	4650	−20	4500	−22	−18
Gwalior	4450	3700	−17	3400	−24	3250	−27	−23
Ranchi	4950	4250	−14	3850	−22	3700	−25	−20
Jabalpur	5600	4900	−12	4600	−17	4450	−20	−17
Indore	4950	4250	−14	3850	−22	3700	−25	−20
Raipur	5300	4550	−13	4250	−20	4050	−23	−19
Hyderabad	5700	5000	−11	4750	−16	4650	−18	−15
Pune	5950	5350	−10	5100	−15	4950	−17	−14
Dharwad	5050	4400	−12	4100	−17	3950	−20	−16
Coimbatore	5650	5000	−11	4750	−16	4550	−19	−15
Mean	5400	4750	−12	4450	−18	4250	−21	−18

[a] In this column, the temperature effect is not included and the yields are for the 2 × CO_2 alone.

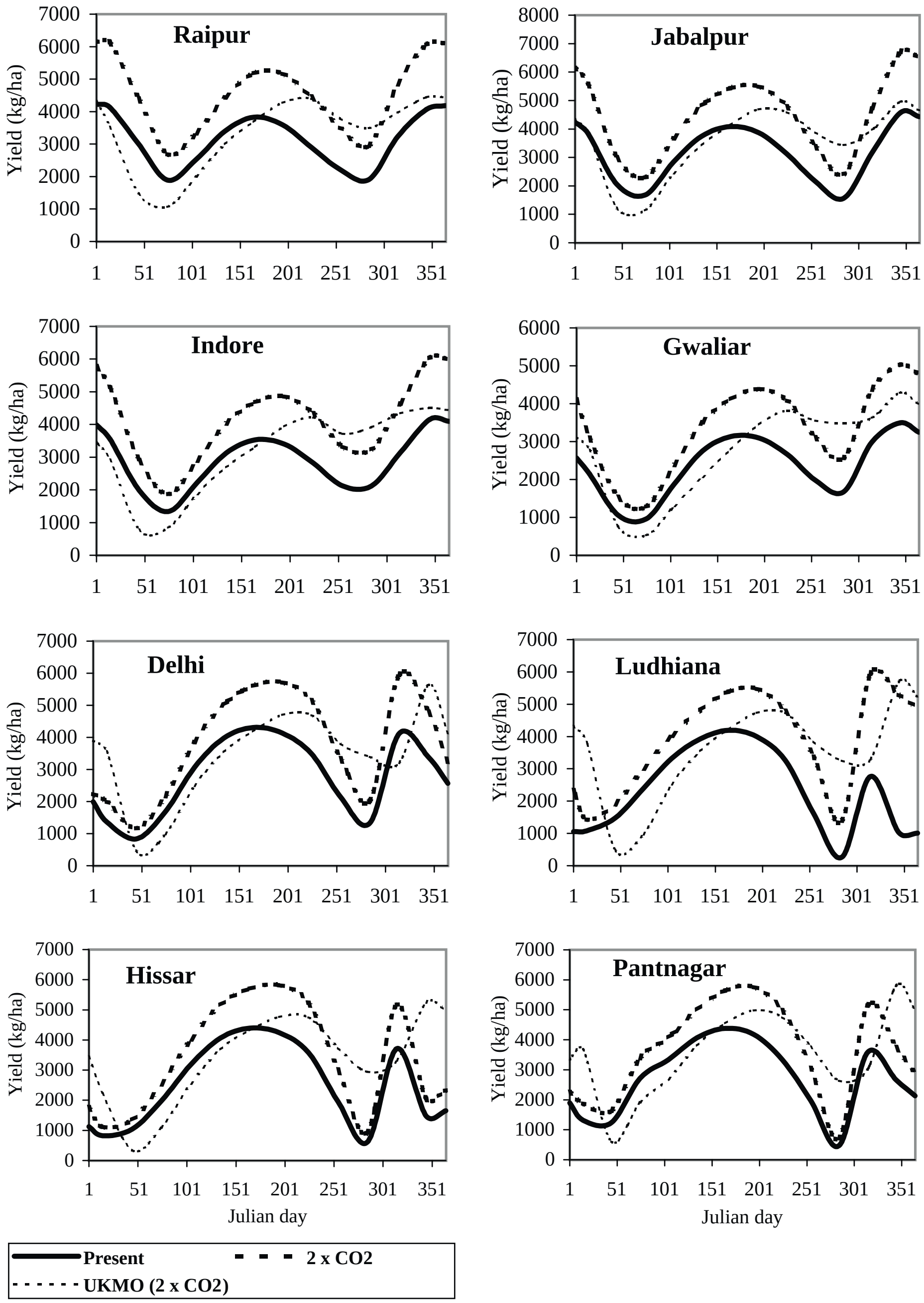

Fig. 3. Effect of varying planting dates on soybean yields [under present-day CO_2 and thermal conditions (solid line), under doubled CO_2 conditions (dashed line) and under changed thermal conditions as projected in UKMO Model with doubled CO_2 conditions (dotted line)] at selected locations in India.

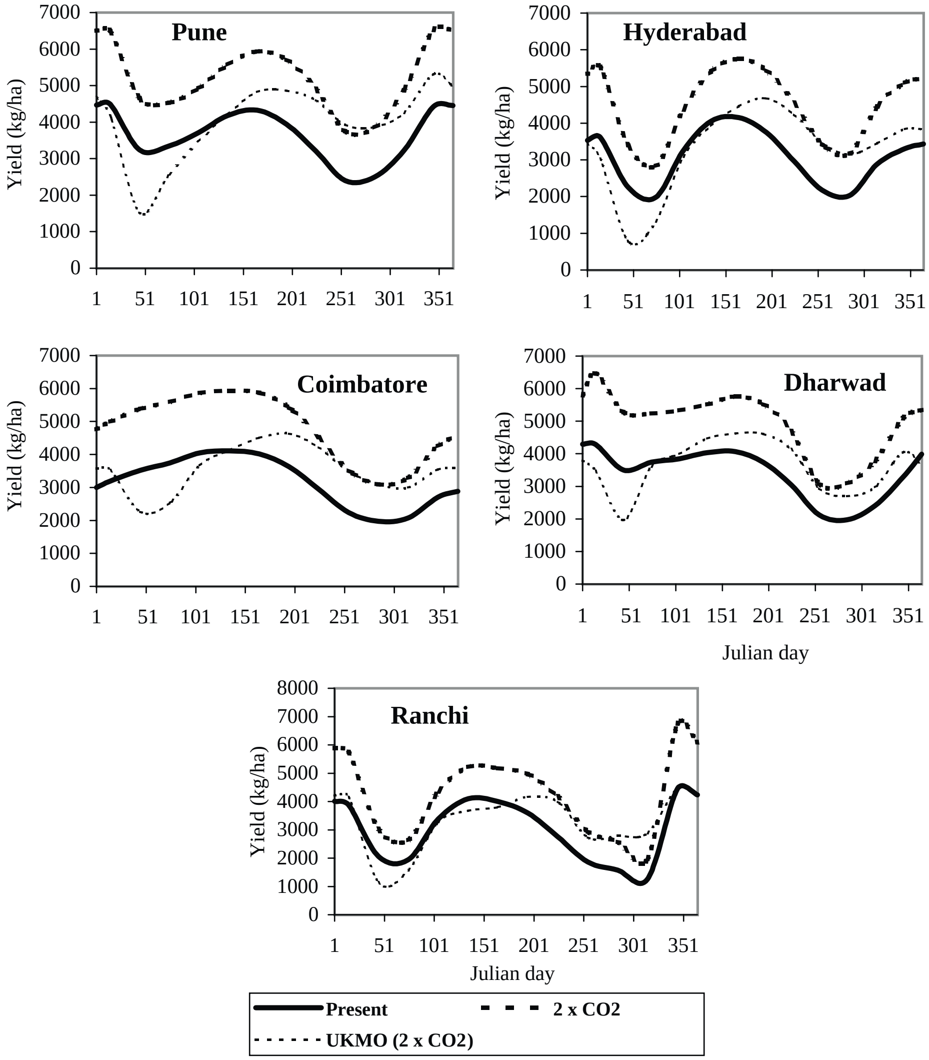

Fig. 3. (*Continued*)

the impacts of climatic variability and change on crop production, the identification of adaptation strategies and appropriate management practices, and the formulation of mitigating measures to minimize the negative effects of climatic variability including extreme events on agricultural productivity (Reilly, 1995). Considering the importance of soybean as a major cash crop in India, the key focus in this study is to identify measures in order to reduce the potential negative effects of climate change on soybean productivity.

3.4.1. Crop variety tolerance to temperature

Studies have shown that responses to climate change are strongly variety specific (Wang et al., 1992). A study by Easterling et al. (1993) explored how hypothetical new varieties would respond to climate change. The present simulation analysis, however, considers the variety characteristics to be almost the same in the future as at present. In reality, it is likely that the plant breeding research will develop newer high yielding varieties under the projected climatic conditions, thus alleviating the climate change impact to some extent.

3.4.2. Sowing date and seasonal changes

Planting date is one of the important management practices influencing soybean yield. Fig. 3 illustrates the changes in simulated potential yield at selected locations in India under varying sowing dates in a calendar year for the present-day climatic conditions and current level of CO_2 in the atmosphere (solid line), under doubled CO_2 atmosphere (dashed line) and for thermal stress conditions as projected in UKMO Global Climate Model in a doubled CO_2 atmosphere (dotted line). It is clearly evident that the present choices of sowing dates (Julian days 152–183 corresponding to June–July months) of soybean are most appropriate in terms of maximum crop yield in different parts in India. Proper sowing date adjustments will, however, be necessary for efficient utilisation of natural resources under the climate change scenarios. The simulation results suggest that for central Indian stations (Raipur, Jabalpur, Indore and Gwalior), the sowing of soybean crop may have to be delayed from June and first week of July to first fortnight of August, such that the adverse impacts of thermal stress due to projected climate change could be avoided during reproductive growth of the crop. Results also suggest that seasonal shift in sowing of soybean crop to December will be beneficial in terms of higher yields particularly in north India (Delhi, Ludhiana, Hissar and Pantnagar).

In view of findings reported above, potential adaptation options for sustained soybean productivity in India include adjustment in cropping calendar and crop rotation, development and promotion of use of high yielding varieties and sustainable technological applications. Delayed sowing date for soybean crop at all locations in India should be most effective in mitigating the thermal effects of climate change. Since soybean is a short duration leguminous crop, it has a good potential to get involved in the intercropping as well as crop sequences. However, under the circumstances, it might not be feasible to grow second crop in the subsequent season at some locations, thus resulting in overall reduction in the food productivity at these locations. Therefore, delay in the planting dates for soybean crop must be decided on the basis of the temporal rainfall distribution pattern at any particular region. It may be noted here that increasing number of recent studies have also recommended the effectiveness of agronomic adaptation strategies including adjustments in planting dates in coping with climate-induced yield losses in different regions of the globe (see Rosenzweig and Iglesias, 1998; Yates and Strzepek, 1998; Parry et al., 1999; Winters et al., 1999; Darwin and Kennedy, 2000).

4. Limitation of the analysis

The findings reported here 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.

As regards the climate change scenarios inferred from global climate models, 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, this study marks significant progress in our understanding of how future climates may affect soybean production in India.

5. Conclusions

The crop simulation model used in this study has been able to simulate the trends in grain yield and phenology as measured in field experiments. The observed variance in the results could be due to inadequate initialisation of the model and the lack of information on the possible yield losses due to pests. The simulation experiments were performed for recommended irrigation schedules and following the nitrogen requirements for optimum yield. It is possible that some degree of water or nitrogen stresses over different years influenced the field experiments in some cases. The precision with which field measurements used in this analysis were taken was not quantitatively known but is expected to be usually between ± 10 and $\pm 15\%$. Considering this and also that the treatments in this study widely varied in terms of prevailing weather conditions at selected locations, particularly in terms of surface air temperatures and the management practices, it can be concluded that the crop simulation model was adequate to simulate the likely effects of climate change on soybean yields.

In general, the simulation results indicate that increasing temperature levels could pose a serious threat in decreasing the growth of soybean crop and hence the yield. The thermal stress on the soybean crop at selected sites in India due to projected regional climate change as inferred from three GCMs namely the GFDL, GISS and UKMO could reduce the yield of soybean crop by about 12, 18 and 21% respectively compared to no temperature change under doubled CO_2 concentration.

Our findings suggest that delaying the sowing dates of soybean crop should be able to mitigate the detrimental effect of thermal stress due to climate change. Also, soybean sowing in the second season, i.e. in the month of December could be favorable for higher yields particularly at north Indian stations. 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.

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