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Simulating the impacts of climate change on cotton production in India

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Abstract General circulation models (GCMs) project increases in the earth's surface air temperatures and other climate changes by the mid or late 21st century, and therefore crops such as cotton (*Gossypium* spp L.) will be grown in a much different environment than today. To understand the implications of climate change on cotton production in India, cotton production to the different scenarios (A2, B2 and A1B) of future climate was simulated using the simulation model Infocrop-cotton. The GCM projections showed a nearly 3.95, 3.20 and 1.85 °C rise in mean temperature of cotton growing regions of India for the A2, B2 and A1B scenarios, respectively. Simulation results using the Infocrop-cotton model indicated that seed cotton yield declined by 477 $kg ha^{-1}$ for the A2 scenario and by 268 $kg ha^{-1}$ for the B2 scenario; while it was non-significant for the A1B scenario. However, it became non-significant under elevated [CO_2] levels across all the scenarios. The yield decline was higher in the northern zone over the southern zone. The impact of climate change on rainfed cotton which covers more than 60 % of the country's total cotton production area (mostly in the central zone) and is dependent on the monsoons is likely to

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be minimum, possibly on account of marginal increase in rainfall levels. Results of this assessment suggest that productivity in northern India may marginally decline; while in central and southern India, productivity may either remain the same or increase. At the national level, therefore, cotton production is unlikely to change with climate change. Adaptive measures such as changes in planting time and more responsive cultivars may further boost cotton production in India.

1 Introduction

Cotton, the fifth most economically important crop in the world, was grown on more than 12.0 Mha in India and on over 30.0 Mha worldwide in 2011–2012 (www.cotton.org). Most of the world's cotton is produced in arid and semi-arid climates. Cotton, being indeterminate in growth habit, responds fairly well to changes in environment and management (Reddy et al. 1997; Gerik et al. 1998). The most recent future scenarios of atmospheric greenhouse gases indicate that [CO_2] could increase from current levels of 380 ppm to between 500 and 970 ppm by the end of the twenty-first century (IPCC 2007). If the predicted increase in greenhouse gas concentrations is then translated into temperature changes, a global temperature increase of between 1 and 5.5 °C is predicted for 2100.

The plant processes directly affected by changes in atmospheric [CO_2] are mainly photosynthesis, photorespiration, dark respiration and transpiration (Fitter and Hay 1987). Elevated [CO_2] generally enhances leaf and canopy photosynthesis because of increased concentrations of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) and suppression of photorespiration in C3 plants such as cotton (Reddy et al. 2000). Kimball (1983), in his analysis of plant responses to elevated [CO_2], found that on an average, doubling of atmospheric [CO_2] would cause a 33 % increase in yield in C3 crops. Although cotton growth rates are sensitive to elevated [CO_2] levels, the duration of major phenological phases, the emergence to reproductive initiation, the square period, and the boll maturation period are not affected by [CO_2] (Reddy et al. 1997).

Crop responses to the environment, however, vary from region to region based on soil type, plant type and regional weather; and hence crop simulation models are used to simulate the growth and yield of crops in different regions. Simulation models in combination with GCMs or other climate scenarios have been used for predicting future crop production (Rosenzweig and Iglesias 1998; Reilly and Schimmelpfennig 1999). Temperature is the most important weather variable forecast to change due to anthropogenic causes. Precipitation and the interaction of weather and soils are also important determinants of agricultural productivity. Several models have earlier projected an increase in both temperature and precipitation in India under future climate (Kumar et al. 2006; O'Brien et al. 2004); hence, the objective of this study was to assess the impact of temperature and precipitation of future climate and elevated [CO_2] levels on cotton production in India.

2 Materials and methods

2.1 The cotton simulation model Infocrop

To simulate cotton production under future climate, the Infocrop-cotton model, which has been calibrated and validated earlier, was utilized (Hebbar et al. 2008) in this study. Infocrop is a generic model that has been extensively used to simulate the growth and yield of various crops in the Indian region, viz., wheat and rice (Aggarwal et al. 2004), maize (Byjesh et al. 2010), sorghum (Srivastava 2010), cotton (Hebbar et al. 2008), coconut (Naresh Kumar et al. 2008), potato (Singh et al. 2005) and mustard (Boomiraj et al. 2010).

2.1.1 Model description

The Infocrop model is written in FORTRAN SIMULATION TRANSLATOR (FST) language (Van Kraalingen 1995). The time step of the model is 1 day. The general structure and details of the Infocrop series of models are described by Aggarwal et al. (2004, 2006). Cotton is also a part of a wider group of field crops simulated by this generic model, and the reader is referred to Hebbar et al. (2008; and also see the electronic supplementary material, ESM) for a more complete description of the approach.

In brief, the Infocrop cotton model considers different crop development and growth processes influencing the simulation of yield. The total crop growth period in the model is divided into three phases—viz., sowing to seedling emergence, seedling emergence to anthesis, and boll development phases. The model requires various varietal coefficients such as thermal time for phenological stages, potential boll weight, specific leaf area, maximum relative growth rate, and maximum radiation use efficiency. Crop-management inputs used in this model include the time of planting, seed rate, sowing depth and the application schedule of fertilizer and irrigation, while soil input data includes soil pH, soil texture, thickness, bulk density, saturated hydraulic conductivity, soil organic carbon, slope, soil-water holding capacity and permanent wilting point. Daily weather data—such as solar radiation, maximum and minimum temperatures, rainfall, wind speed, and vapour pressure—are also required for simulating crop performance (Hebbar et al. 2008; Venugopalan et al. 2007) with this model.

Infocrop accounts for the change in temperature, [CO_2] levels and rainfall in different ways. The total development of a crop is calculated by integrating the temperature-driven development rates of the phases from sowing to seedling emergence, seedling emergence to anthesis, and boll development phases. Dry matter production is a function of radiation use efficiency (RUE), photosynthetically active radiation, total leaf area index (LAI), and a crop/cultivar specific light interception coefficient. RUE is further governed by a crop specific response of photosynthesis to temperature, water, N availability, [CO_2], etc. (ESM).

The net dry matter available each day for crop growth is partitioned as a crop specific function of the development stage, which as mentioned earlier, is affected by temperature. Adverse temperatures during the meiosis stage significantly increases sterility; and a part of the storage organ may become sterile if either the maximum or minimum temperature of the day deviates from their optimum values during a short period between the anthesis phase and a few days after anthesis period. This reduces the number of storage organs available subsequently for accumulating boll weight. As far as the influence of rainfall is concerned, it is simulated in the model through soil–water balance.

The model has been calibrated and validated to simulate the growth and production of cotton using field experiment data collected during 2000–2005 from a network project, 'Technology Mission on Cotton', funded by the Government of India (Hebbar et al. 2008; Venugopalan et al. 2007). The parameters and relationships needed to build the functions of the Infocrop cotton model are described in the electronic supplementary material (ESM).

2.2 Study areas and cultivars selected

India is a large country (326 Mha) and cotton is grown in three distinct agro-climatic zones as listed in Table 1.

Table 1 List of cotton growing locations and their details used for model simulations of future climate

Sl No.	Location	Lat/Long	Agro- eco region (AER)	Area in AER as percentage of all India cotton area	Zone	Bt hybrid	Duration to maturity (days)	Temperature range °C		Solar radiation (MJ $m^{-2}day^{-1}$)	Rain-fall (mm)	Sowing in Julian days	
								Max	Min			Rainfed	Irrigated
1	Coimbatore	11° 00′ N 77° 00′ E	Hot semiarid AER with mixed red and black soil.	1.0	South	Mallika	190	26.5–34.7	14.0–25.0	22.1–28.8	500–700	–	221
2	Dharwad	15° 27′ N 75° 05′ E	Hot semiarid AER with deep and medium deep black soils	38	South	RCH 2	160	22.8–31.9	10.9–21.5	8.2–22.1	400–600	180	–
3	Nagpur	21° 09′ N 79° 09′ E	Hot dry sub-humid AER with deep black soil	2.3	Central	RCH 2	150	23.8–40.5	12.2–28.4	6.4–19.0	700–900	180	–
4	Surat	21° 12′ N 72° 52′ E	Hot semiarid AER with deep black soils	19.8	Central	RCH 2	160	24.7–39.0	12.5–28.0	9.5–26.5	700–900	180	180
5	Hisar	29° 10′ N 75° 46′ E	Hot arid AER with deep to very deep sandy to sandy loam soils	23.1	North	MECH 184	140	25.4–45.5	11.9–32.5	10.0–28.0	300–400		125

2.2.1 Northern zone

This zone includes the states of Punjab, Haryana and Rajasthan. Cotton cultivation in this region is mostly irrigated and grown on alluvial soil. Since the crop is usually sown in the month of May and harvested in November, the crop is grown under high temperature conditions. Short duration hybrids are generally preferred for cultivation in this zone, because wheat is sown immediately after the harvest of cotton.

2.2.2 Central zone

This region includes the states of Maharashtra, Madhya Pradesh and Gujarat. This is a rainfed region where cotton is planted on black soil. Maharashtra alone accounts for more than 30 % of the total cotton cultivated area of the country, of which 90 % is rainfed. In this region, sowing generally commences with the arrival of the monsoon in the month of June. Late sowing because of the late arrival of the monsoon leads to a significant yield loss due to terminal moisture stress as well as low temperature effect in the months of December and January (Hebbar et al. 2003).

2.2.3 Southern zone

The states of Andhra Pradesh, Karnataka and Tamil Nadu comprise this zone. Cotton cultivation in this region is partly irrigated and partly rainfed. In Karnataka and Andhra Pradesh, for instance, cotton is sown in the month of July with the commencement of the southwest monsoon; while in Tamil Nadu it is sown in the months of August–September with the commencement of the northeast monsoon. In comparison to the north and central zones, cotton in this region is grown in relatively lower temperatures.

For the purposes of this study, five districts from the above zones—viz. Coimbatore and Dharwad from the southern zone, Nagpur and Surat from the central zone, and Hissar from the north—were selected to simulate cotton production under future climatic conditions. The sites selected for cultivation typically captured the bioclimatic variability of cotton growing conditions in India (Table 1). The locations of Nagpur and Hissar represented extreme climatic conditions with their dry sub-humid and hot arid bio-climates, beyond which cotton is not grown in India. The bulk of India's cotton cultivation areas experience a semi-arid bio-climate, where cotton is grown with water from the southwest monsoon. Coimbatore, in particular, is a unique bio-climatic region, where cotton is grown in winter because of the northeast monsoon. The agro-ecological regions (AERs) where these five sites were selected, together account for nearly 84 % of the total cotton acreage in India. These districts, moreover, were also part of a network project (the Cotton Technology Mission) and therefore the genetic coefficients of popular local hybrids, the soil characteristics of the region and weather data, which were required to run the model, were all easily available.

2.2.4 Cultivars

Almost the entire cotton production area in India is under Bt cotton hybrids, replacing other existing varieties and conventional hybrids. Since it was difficult to generate the genetic coefficients of all the commercially cultivated Bt hybrids (> 2,000 hybrids), they were broadly classified into short (125–145), medium (145–165), and long (170–190) duration hybrids. The hybrids, and their duration, used in this study, have been listed in Table 1; and the experimental approach has been described in Hebbar et al. (2008).

2.3 Weather data collection and climate change scenarios

This study selected three different scenarios—A2, B2 and A1B—to estimate how future precipitation and temperature was going to affect change in India's cotton growing regions. As per IPCC (2007), scenario A2 assumes rapid population growth, self-reliance in terms of resources, and less emphasis on economic, social, and cultural interactions between regions. Economic growth in this scenario is uneven, and the income gap between the now-industrialized and developing parts of the world does not lessen. The B2 scenario, on the other hand, is one of increased concern for environmental and social sustainability in comparison to the A2 storyline. It assumes government policies and business strategies at the national and local levels are being increasingly influenced by environmentally aware citizens, with a trend towards local self-reliance and stronger communities. For the purposes of this study, the A1B scenario is considered to be the most appropriate as it represents high technological development infused with renewable energy technologies, following a sustainable growth trajectory.

The climate change scenarios of A2, B2 and A1B were derived from PRECIS RCM, which has HADCM3 as its GCM. The PRECIS is an atmospheric and land surface model with a 50×50 km horizontal resolution over the South Asian domain, and is run by the Indian Institute of Tropical Meteorology (IITM), Pune. Daily gridded data 0.44°×0.44° was processed using the MS-Excel macro, and was arranged grid-wise. This data was then converted to the Infocrop weather file format using a custom-made software. The historical weather data from 1969 to 1990 was taken as the current climate scenario, while the weather data generated from the 2071 to 2100 projections for the A2 and B2 scenarios, and that of 2031–2060 for the A1B scenario, were used as the future climate data.

2.4 Simulations

Using the Infocrop cotton model, various simulations were run to understand the effects of climate change on cotton production at Dharwad and Coimbatore in the southern zone, Nagpur and Surat in the central zone, and Hissar in the northern (Table 1). These simulations made use of past weather data from 1961 to 1990 as the baseline data. Several earlier models had projected an increase in both temperature and precipitation in India under future climatic conditions (Kumar et al. 2006; O'Brien et al. 2004); and hence, the maximum temperature (TMAX), the minimum temperature (TMIN), and precipitation in the baseline data were substituted from the A2, B2 and A1B scenarios to represent future climate in India. The current atmospheric [CO_2] concentration for the study is fixed at 383 ppm. The response of cotton to the enrichment of atmospheric [CO_2] was simulated for present and future atmospheric [CO_2] levels (460 and 700 ppm). As an adaptation measure under future climate, the model was run with a delayed date of sowing of 15 days. Management practices were assumed to be optimal, with no effects of weeds, insects or disease pests for all the simulations. The results have been presented as the mean of 30-year simulations.

3 Results

3.1 Projected climatic scenarios

The change projected for future climate, in the different agro-climatic regions of India selected for this study, showed significantly higher maximum temperature (TMAX) and minimum temperature (TMIN), while precipitation did not show any significant change (Fig. 1). Amongst the different scenarios considered for the study, temperature increase was observed to be highest in A2, followed by B2, and the least in A1B. An increase in TMAX across the cotton growing regions stood at 3.6 °C for scenario A2, at 3.2 °C for scenario B2, and at 1.9 °C for scenario A1B. The corresponding increase in minimum temperature was noted to be at 4.3 °C for scenario A2, at 3.2 °C for scenario B2, and at 1.8 °C for scenario A1B. The total precipitation, on the other hand, increased from the current level of 760 mm to 890 mm in the A2 and 790 mm in the B2 scenarios, whereas for the A1B scenario it had actually reduced to 736 mm.

Amongst the cotton growing regions selected for the study, the northern and central zones (Hissar, Surat and Nagpur) were noted to be more likely to encounter higher temperature increases over the southern zone (Coimbatore and Dharwad; Fig. 2). In the north, Hissar is likely to experience high TMAX and TMIN of 41 °C and 28.5 °C for A2, and 40 °C and 26.5 °C for B2, respectively. The corresponding TMAX and TMIN values for Dharwad in the south are likely to stand at 32 °C and 22 °C for A2, and at 31 °C and 21 °C for B2. On the contrary, precipitation did not show any significant differences across the regions; a decreasing trend, however, has been noted for Hissar in the north.

3.2 Impact of projected climatic scenarios on cotton

The simulated impact of increased temperatures and altered patterns of precipitation indicated a statistically significant decline in seed cotton yield (Table 2 and Fig. 3). The mean seed cotton declined by 477 kg ha^{-1} in the A2 scenario, and by 268 kg ha^{-1} in the B2; whereas for the A1B scenario, the decline was not noted to be significant. Yield reduction was observed to be more in the irrigated northern zone (Hissar), compared to the irrigated south (Coimbatore). In fact, the

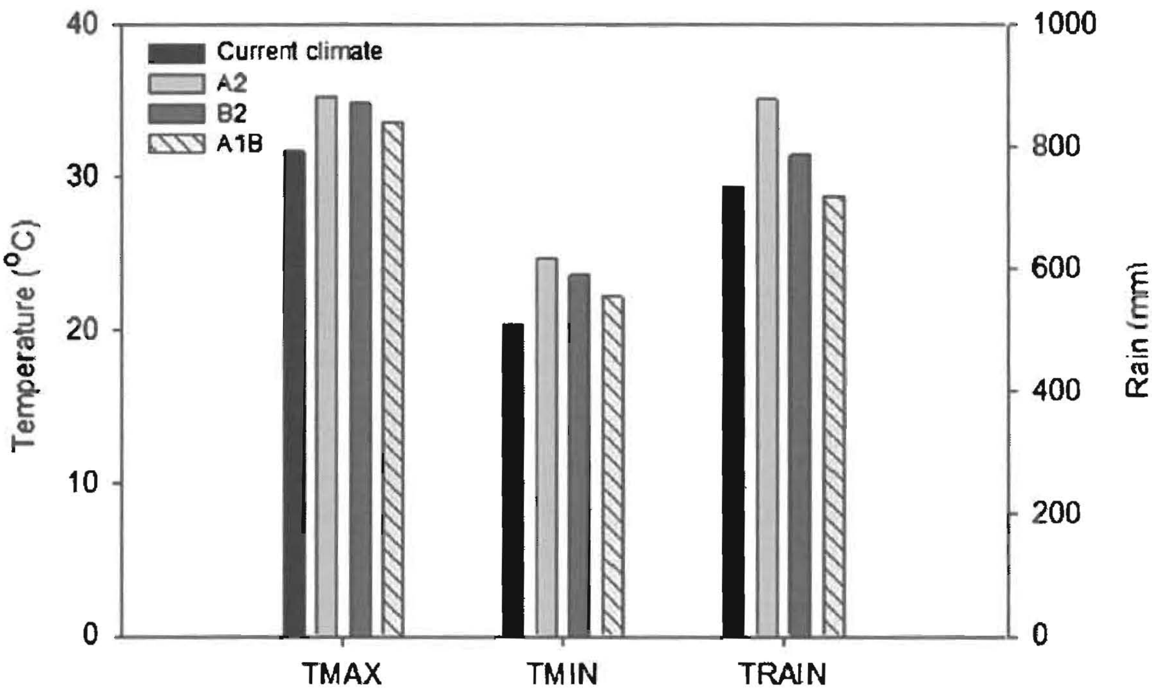

Fig. 1 Shows the average maximum temperature (*TMAX*), minimum temperature (*TMIN*) and precipitation (*TRAIN*) for the current climate and the future scenarios of *A2*, *B2* and *A1B*. Each value is a mean of the cropping season climate of 5 years of five cotton growing locations (Coimbatore, Dharwad, Nagpur, Surat and Hissar) of India. CD values for TMAX=0.37; TMIN=0.88; TRAIN=NS)

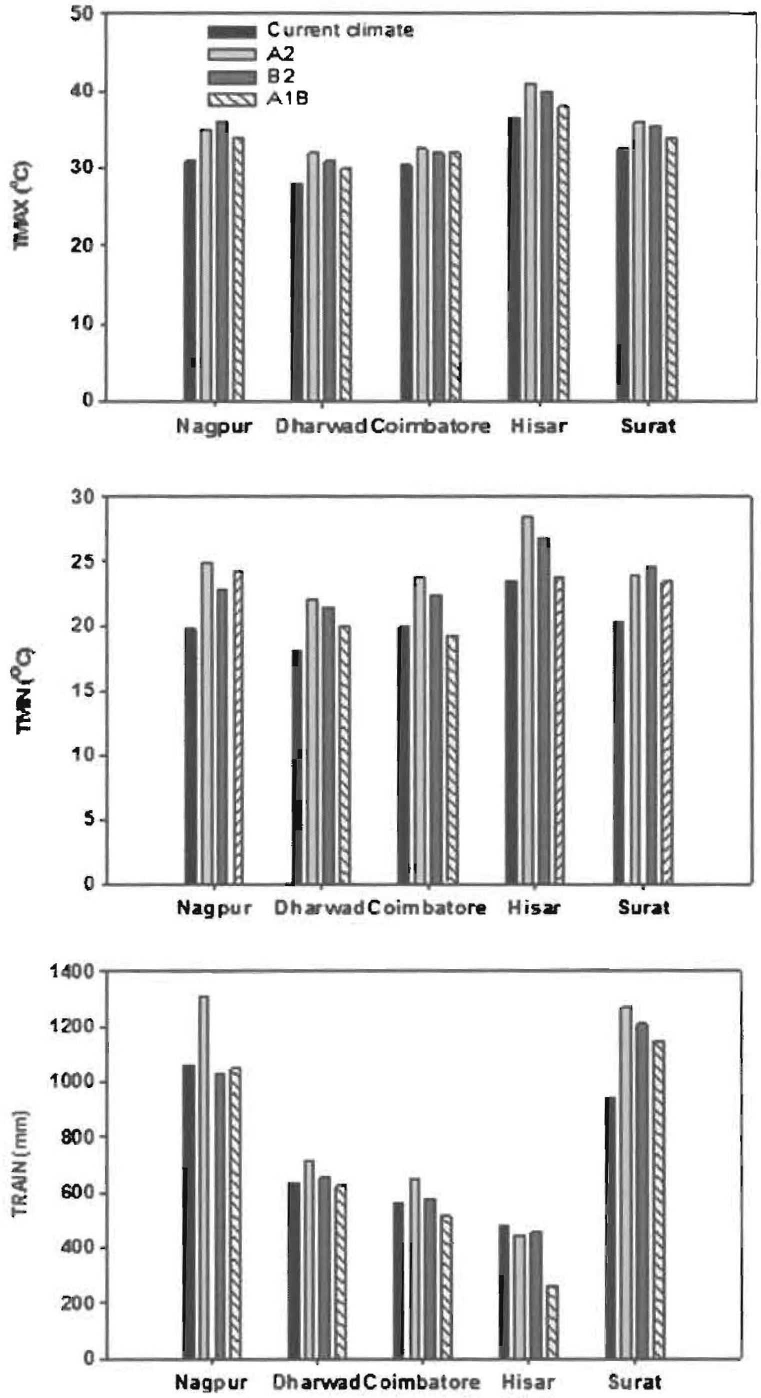

Fig. 2 Shows the mean *TMAX*, *TMIN* and *TRAIN* for the current climate and the future scenarios of *A2*, *B2* and *A1B* for the different cotton growing regions of India. Each value is a mean of cropping season climate of 5 years

yield was observed to have increased by 200 kg ha^{-1} on the average in Coimbatore. Under rainfed regions (Nagpur and Dharwad), however, yield reduction was observed to be relatively less (approximately 200 kg ha^{-1}) for the A2 and B2 scenarios, in comparison to the irrigated regions (Hisar and Surat) (Fig. 4a).

3.3 Adaptation to climate change

When the model was run with elevated [CO_2] levels, the significant yield decline—including changes in temperature and precipitation—was not observed to be significant across all the

Table 2 Average simulated seed yield in kg per ha of rainfed (Nagpur and Dharwad) and irrigated (Coimbatore, Surat and Hisar) cotton crops under present and changed climate conditions (TMAX, TMIN and precipitation change)

Location	Current climate	A2	B2	A1B	Mean
Nagpur	1,877	1,686	1,540	1,880	1,746
Dharwad	2,472	2,209	2,253	2,043	2,244
Coimbatore	3,093	3,375	3,408	3,466	3,335
Hisar	3,226	2,319	2,549	2,916	2,752
Surat	3,381	2,077	2,961	3,338	2,939
Mean	2,810	2,333	2,542	2,728	
CD at 5 %					
Location	255				
Scenario	226				
L × S	506				

three scenarios (Table 3). Across all locations, on the other hand, a significant difference was noted. Hissar's yield, for instance, was noted to be significantly low in all the three scenarios (Fig. 4b).

Another major reason for cotton yield loss under Indian conditions is the late planting season due to delays in monsoon arrival. The higher temperature and higher rainfall patterns could offset the yield loss due to late planting under the A2, B2 and A1B scenarios (Figs. 3 and 4c). It may be noted that in Nagpur, Coimbatore and Dharwad, the yield increased significantly for all the scenarios from the present climate. Contrarily, Hissar's yield declined for all the scenarios, while in Surat the yield declined for scenario A2 alone.

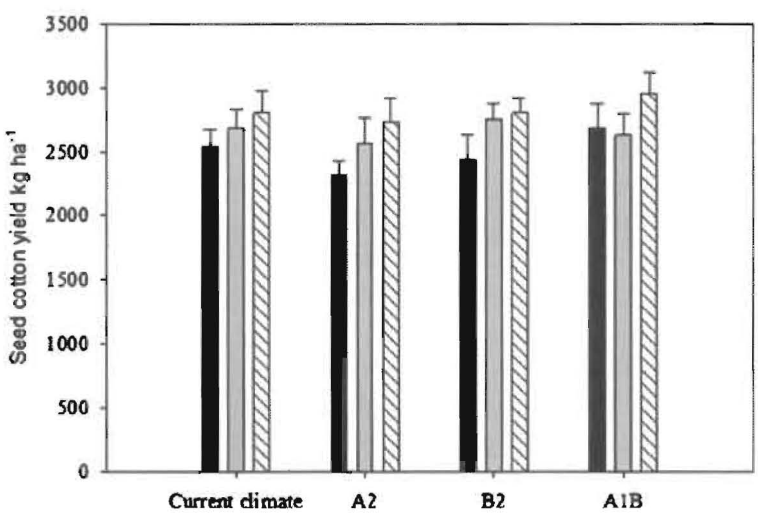

Fig. 3 Shows model simulations of overall changes in cotton production across the regions for the present and the three scenarios of future climate. (▬) includes the changes in climate only (TMAX, TMIN and precipitation change); (▭) includes the changes in climate and the effect of increasing [CO_2] (A1B year 2030: TMAX, TMIN and precipitation change and [CO_2] at 460 μmol mol^{-1}; A2 and B2, year 2080: TMAX, TMIN and precipitation change and [CO_2] at 700 μmol mol^{-1}); (▨) included an adaptation measure, i.e., change in planting date (delayed date of sowing by 15 days)

Fig. 4 Shows model simulations of average changes in cotton yields at five locations. The yield changes are given as percentages and represent the differences between current yields and those projected for three scenarios. **a** Includes the changes in climate only (TMAX, TMIN and TRAIN change); **b** includes the changes in climate and the effect of increasing [CO_2] (A1B year 2030: TMAX, TMIN and precipitation change and [CO_2] at 460 μmol mol^{-1}; A2 and B2year 2080: TMAX, TMIN and precipitation change and [CO_2] at 700 μmol mol^{-1}); **c** included an adaptation measure in part **b**, which included a change in the planting date (delayed date of sowing by15days)

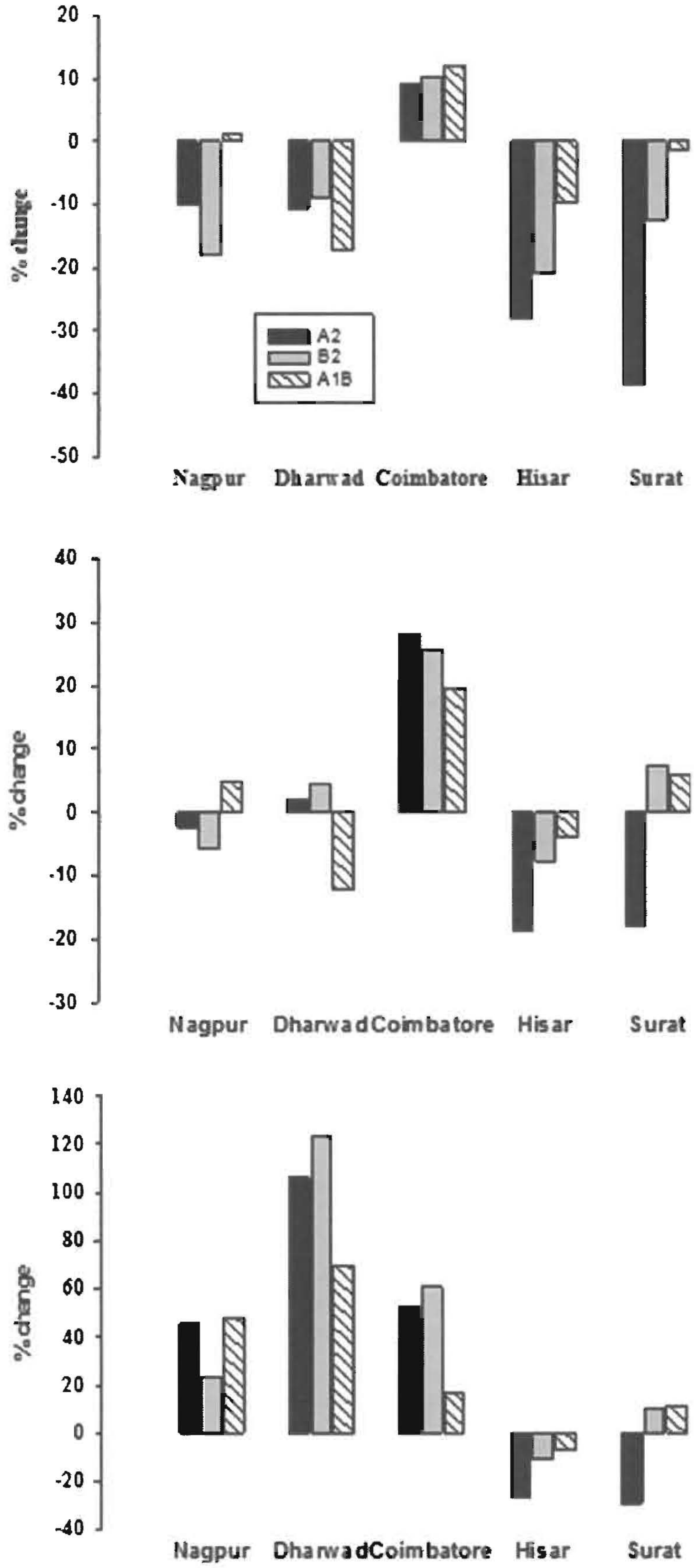

Table 3 Average simulated seed yield in kg per ha of rainfed (Nagpur and Dharwad) and irrigated (Coimbatore, Surat and Hisar) cotton crops under present and changed climate conditions (A1B year 2030: TMAX, TMIN and precipitation change and [CO_2] at 460 μmol mol^{-1}; A2 and B2year 2080: TMAX, TMIN and precipitation change and [CO_2] at 700 μmol mol^{-1})

Location	Current climate	A2	B2	A1B	Mean
Nagpur	1,877	1,833	1,769	1,966	1,861
Dharwad	2,472	2,518	2,583	2,172	2,436
Coimbatore	3,093	3,967	3,886	3,694	3,660
Hisar	3,226	2,631	2,976	3,098	2,983
Surat	3,381	2,773	3,630	3,579	3,341
Mean	2,810	2,744	2,969	2,902	
CD at 5 %					
Location	282				
Scenario	NS				
L × S	568				

4 Discussion

There has been a paradigm shift in India's cotton cultivation since the introduction of Bt cotton hybrids in 2002. Almost the entire cotton cultivation area of the country has been sowing Bt cotton hybrids, replacing other traditional varieties and conventional hybrids. At present, there happens to be more than 200 Bt cotton hybrids under cultivation. Bt cotton hybrids are similar to non-Bt hybrids up to squaring. At early boll development, Bt hybrids exhibit faster growth and higher photosynthesis over non-Bt hybrids because of a high demand for assimilates due to more synchronized boll development (Hebbar et al. 2007a, b). Similarly, the early maturity of Bt hybrids observed over conventional hybrids (Singh et al. 2006) was adjusted in the model by changing the thermal time requirement from their anthesis to maturity phases; in Bt hybrids this was 1,500–1,700° days (unpublished data) as opposed to 1,600–1,900 for non-Bt hybrids. The incorporation of the aforementioned genetic coefficients to the earlier validated Infocrop-cotton model (Hebbar et al. 2008) simulated the yield of Bt hybrids reasonably well, with an accuracy of 85 % between observed and simulated seed cotton yield (Unpublished data).

In this study, the Infocrop-cotton model was used to simulate cotton yield under future climate. Results of simulations using this model indicated that increased temperature and reduced precipitation might decrease cotton yield in northern India to a greater extent, over that of southern India. The elevated levels of [CO_2] during climate change, however, could compensate for the yield loss caused by high temperatures to a certain extent. All cotton regions of India are not likely to be affected to the same degree by the projected climate scenarios studied in this assessment. In general, this study finds that climate change favors southern and central India's cotton producing areas. Coimbatore and, to certain extent, Dharwad exhibited yield gains across all the three climate scenarios in the 2030 and 2090 time frames. In the southern zone, where cotton is grown in a relatively cooler season, increased temperature and a minor increase in rainfall increased yield. On the other hand, in the northern zone, where cotton is grown under relatively high temperatures, climate-induced high temperatures reduced yield. Similar observations were reported earlier by Rosenzweig and Hillel (1998), who found that higher temperatures favored colder parts of the world because of a longer growing season, while in the warmer regions, it hastened development and reduced yields, particularly during the critical crop growth periods in summer.

The rainfed region of central India, where temperature rise is relatively less, may benefit from the slight increase in rainfall; and hence, its yield might not get adversely affected. Moreover, in these regions the cotton crop is exposed to low winter temperatures during the later part of its reproductive phase (Hebbar et al. 2003). A slight increase in minimum and maximum temperatures would offset this condition and have a positive effect on boll growth. Thus, in all likelihood, climate change as defined by different scenarios examined in this assessment may not hamper cotton production in India. The results of this assessment suggest that in northern India, cotton productivity may marginally decline, while in central and southern India, it may either remain the same or increase. At the national level, therefore, cotton production is unlikely to change with projected climate change. Moreover, technological advancements, mitigation strategies and the evolution of adaptive measures such as changes in planting times, could enhance yield levels to keep pace with future requirements of cotton.

5 Conclusion

The results of the study indicated that projected high temperature and reduced precipitation might decrease cotton yield in northern India to a great extent over that of southern India. The impact of climate change on rainfed cotton (central India)—which covers more than 60 % of the country's total cotton area and is dependent on the monsoons—is likely to be minimum on account of marginal increase in rainfall events. Moreover, increased photosynthesis due to higher [CO_2] levels could compensate for the likely reductions in cotton yield due to high temperature and reduced precipitation. As a result, in northern India (29° 10′ N 75° 46′ E), productivity may marginally decline, while in central (21° 09′ N 79° 09′ E) and southern (11° 00′ N 77° 00′ E) India it may either remain the same or increase. At the national level, therefore, cotton production is unlikely to change with climate change. Adaptive measures such as changes in planting time, may further boost cotton production in the country.

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