

Model-based Approach to Study the Response of Bt-cotton Towards Elevated Temperature and Carbon Dioxide in the Semi-arid Region of Hisar

A. Shikha¹, K.K. Singh², A.P. Dimri^{1*}, R. Niwas³ and P. Maharana⁴

¹School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India

²India Meteorological Department, Ministry of Earth Sciences, New Delhi, India

³Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana, India

⁴Delhi College of Arts and Commerce, University of Delhi, New Delhi, India

✉ apdimri@hotmail.com

Received April 4, 2019; revised and accepted June 28, 2019

Abstract: Cotton is one of the principal commercial fibercrop. India is highest in terms of agricultural land involved in cotton production but second highest in production. Decadal yield data reveals that its productivity is 243 kg/ha lesser than the global average. Weather aberrations is one of the paramount reasons for the productivity loss. The present study aims at estimating the implications of increasing temperature and CO₂ concentrations on cotton yield using a crop model DSSAT. Three different Bt-cotton varieties Pancham-541, RCH-791 and SP-7007 are considered for the study with three sowing dates 10th May, 21st May and 6th June. For Pancham-541 variety, rise in 1°C of temperature with 50 ppm CO₂ is beneficial, but further rise is harmful. Whereas for RCH-791 and SP-7007, productivity decreases gradually with increasing temperature and CO₂. Generally, yield decreases with increase in temperature (by 1°C), but no significant effect observed with increasing CO₂ (50 ppm) cumulatively. The adverse effects of rising temperature is moderated due to increase of CO₂ with the increase in photosynthesis when considered together. The leaf area index as well as evapotranspiration rate increase with increasing temperature and CO₂ for all varieties in all sowing dates. Whereas, the harvest index and maturity dates decrease in general. Therefore, increasing temperature at the present rate will be harmful for the productivity of cotton with the changing climate. Although this effect is abated with simultaneously rising CO₂ but yet the adversity due to global rise in temperature is partially mitigated.

Keywords: Cotton; Temperature; CO₂; Climate change.

Introduction

The global crop productivity is under threat due to the climate change. It is one of the potent challenges in the 21st century. Chemical composition of the atmosphere has been changing enormously with the beginning of industrial revolution due to anthropogenic activities. Burning of fossil fuel, vehicular emissions, and rapid deforestation resulted in an increase of atmospheric

CO₂ levels. The gradual increase in the concentrations of greenhouse gases hence leads to global temperature rise. Understanding its severity and its impact on various ecosystems, there are international climate treaties to control the global temperature. The Earth Summit and now Paris agreement addressing the problem of climate change, aim at keeping the global temperature rise below 2°C and further try to limit it within 1.5°C.

*Corresponding Author

Climate variability is one of the major factors, which influences the crop production even in high yielding and advanced technology regions (Kang et al., 2009). The impact of climate change on crop productivity has become a major area of scientific concern. Various studies are being conducted to assess the impact of climate change on crop productivity such as maize, wheat and rice (Howden et al., 1997; Hoogenboom, 2000; Gbetibouo et al., 2005; Aggarwal et al., 2006a; Aggarwal et al., 2006b; Dhungana et al., 2006; Challinor et al., 2008), forests (Lexer et al., 2002), industry (Harle et al., 2007) and native landscape (Dockerty et al., 2005; Dockerty et al., 2006). Crop and climate models are widely used by the research community to study the crop productivity and soil water balance in the changing climate (Kang et al., 2009).

Response of plant towards the climatic factor such as temperature on yield varies amongst species based upon crop's cardinal temperature requirements. The increasing global temperature will affect the plant physiology, growth cycle, and development along with yield (Kang et al., 2009). Crop yield is reported to be sensitive to both temperature and precipitation (Krause et al., 1997; Popova et al., 2005). The increase in the yield under future warming scenario is attributed to the elevated CO₂ concentration due to enhanced photosynthesis which is termed as the 'fertilisation effect' that moderates the negative impacts of rising temperature as reported on rice yield in Kerala (Saseendran et al., 2000). It has also been found that with climate change, growing period will be reduced i.e. crop can mature earlier; therefore planting dates have to be advanced to improve the crop yield apart from introducing new resistant varieties (Cuculeanu et al., 2002). Temperature above the normal optimum levels are termed as 'heat stress'. It interferes with the normal homeostasis, growth retardation and even causes apoptosis (Mathur et al., 2014). Studies conducted to characterize energy use of cotton showed that latent heat flux was the major energy utilizing process which determines yield variation (Singh et al., 2008). Bt cotton cultivars in the semi-arid region of Punjab showed negative correlation of seed yield with temperature in reproductive phase (Sahoo et al., 2000, Singh, 2008; Liyong et al., 2007). As sessile organism, plants are exposed to various abiotic and biotic factors, such as temperature, CO₂ and precipitation which ultimately affect the yield.

Cotton is grown across 80 countries all over the world with an average productivity of 765 kg/ha. India ranks first in total area of land under cotton production

with an average productivity of 522 kg/ha i.e. 23 percent of the world average. Whereas China ranks first in average production of cotton with an average productivity of 1352 kg/ha (Status Paper of Indian Cotton report by Directorate of Cotton Development Government of India, Jan 2017). The reasons for this gap of 243 kg/ha in the productivity can be attributed as weather aberrations. This includes temperature extremes, inadequate or excess rain with uneven distribution, incidence of pest attack, especially sucking pest. Optimum temperature required for cotton growth and development of boll and its retention is around 28 °C (Reddy et al., 1991) but can continue to better yield till temperatures up to 32 °C, which is a critical threshold temperature for its yield (Schlenker et al., 2009).

Increase in temperature above optimum i.e. the tolerable limit of the plant is found to negatively impact the yield of cotton due to increased boll abscission during flowering and smaller boll at maturity. Daily evaporative demand and crop water utilization are largely a function of the leaf area index and therefore yield of the crop. It is strongly influenced by the genetics and growing conditions (Reddy et al., 1997). Whereas increasing CO₂ above the present level will improve crop productivity due to improved carbon exchange rates (Reddy et al., 2005). These findings are also documented in a report by National Cotton Council of America as Cotton Physiology Today (1999). CO₂ which helps to boost photosynthesis and therefore production also could not ameliorate the adverse effects of high temperature on some phenological phases like reproductive growth, boll formation and maturity that affects the quality of fibre. It is reported that in future climates, the yield and quality of fibre will decrease if increasing CO₂ is associated with increase in temperatures particularly in fields where present temperature are near to optimum for the crop (Reddy et al., 2005). Studies on the cotton crop of Stoneville region with future GCM projected data indicates, under rainfed conditions yield declined for all the RCP scenarios but under irrigated conditions yield declined only during extreme conditions. Yield partially increased with an increase in rainfall or supplementing the crop with water. As an adaptability measure, planting crop earlier also somewhat compensated for yield losses (Anapalliet al., 2016).

Models such as Decision Support System for Agrotechnology Transfer (DSSAT) uses detailed location-specific data for physiological crop information, climate data, soil characteristics data etc. (Islam et al.,

2016). It generally assesses under plausible future climate change scenarios taking other factors such as management practice and crop variety constant (Islam et al., 2016). Latest DSSAT Version 4.6.1 (Jones et al., 2003) is developed to simulate the growth and yield on 31 crops. It is an assemblage of various crop models in Crop Environment Resource Synthesis such as CERES CROPGRO etc., where CROPGRO assesses fibre crop cotton (Thorp et al., 2014; Hoogenboom et al., 2015).

Biophysical and socioeconomic factors are also studied with the combination of climate, crop, and economic models. It allows to estimate the difference in yields and other parameters with the changing climate. Historical data are utilized to analyze the climate of that location and field level experimental data are being used to calibrate and then validate the models for this structural framework. The set up can also be translated forward into looking at simulations for future scenarios. The Ministry of Agriculture uses these modelling assessments in their FASAL and GKMS projects to improvise and assess the package and practices for the crop management and the crop production forecast. This is to help researchers, farmers and policy-makers to make strategies adapting climate change. The present study is based upon impact climate change on cotton crop using a DSSAT crop model. Specifically, it aims at finding the implications of increasing temperature and CO₂ individually and then combined to analyze the effect of climate change.

Climatic Condition of the Study Area

The study area considered for the present study is Hisar, Haryana, situated between 74°24' to 76°18'E longitude and 28°54' to 29°59'N latitude at an elevation of 215.2 amsl. The district lies in alluvial plains of the Yamuna, which is a sub-basin of Ganga River. Soil texture is gradually changing from light sandy (bhur) to firm loamy (rausli), thus light and highly permeable. Semi-arid climate of Hisar owes to its continental location and on the margin of south-west monsoon. It can be further classified as tropical steppe type of climate (Singh et al., 2014). Annual temperature ranges from 3.5 to 48°C, which specifies that it has hot dry summer and chilling cold winter. Most of its precipitation (77%) occurs through the south-west monsoon during JJAS. Else from October to April weather remains dry, except with the wake of western disturbances. Occasional hailstorms also occur from February to April. Fog occurs during December and January. This region sometimes experiences thunderstorms during summer and post-monsoon (Singh et al., 2014).

Cotton is a kharif crop sown in the month of May-June and harvested in Sep-Oct. The climatological analysis of temperature (1970 – 2008) over the study region illustrates that mean monthly daily range of temperature during the sowing period of cotton are 31.5°C (May) and 26.0°C (June). Maximum and minimum temperatures during the cropping period are 40.2°C and 22.8°C, 39.8°C and 26.0°C, 36.2°C and 26.3°C, 34.8°C and 25.4°C, 34.8°C and 25.4°C, and 34.8°C and 22.6°C, 33.5°C and 16.1°C in the months of May, June, July, August, September and October, respectively. Similarly, the cumulative rainfall during May, June, July, August, September, and October are 30.5, 56.1, 128.0, 109.1, 59.4 and 10.1 (mm) respectively. The bright sun shine hours during May, June, July, August, September, and October are 8.4, 6.7, 6.1, 7.1, 8.5 and 8.8 (hrs) respectively (Singh et al., 2014).

Methodology

Method for Raising Crop

For the present investigation on “impact of increasing temperature and CO₂ on the cotton crop” agronomic practices were carried out in experimental field of Chaudhary Charan Singh Haryana Agricultural University (CCSHAU), Haryana during the year 2013-14. Certified and delinted Bt-Cotton seeds for recommended varieties of Pancham-541, RCH-791 and SP-7007 were sown during the Kharif season. Sowing was done by hand ploughing method, by keeping a distance of 60 cm between the rows. All the management and agronomic practices were followed as per the recommended package of practices by the Haryana Agricultural University for growing the crop under irrigated conditions. The size and design of the experimental plot was 5.4 m × 5.0 m and split plot respectively.

Model Description

Crop models are used to imitate or simulate the behaviour of real crop grown on the field. DSSAT-CSM Version 4.6.1 model has been employed for the present study. Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM) suite includes the CROPGRO-cotton model for the simulation cropping systems based on cotton crop (Jones et al., 2003; Boote et al., 1998a). This model is utilized globally for about 40 crops (Jones et al., 2003). The DSSAT-CSM is a crop simulating model which contains the following components (Jones et al., 2003):

- **Weather module:** To read and generate daily weather data using WGEN or SIMMETEO.
- **Soil module:** Designed to read the soil properties as an input for the experiment.
- **Soil/plant/atmosphere module:** To compute daily soil evaporation, transpiration and finally compute ET based on Penman-FAO method (Doorenbos and Pruitt, 1977), LAI etc.
- **Template crop module (CROPGRO):** To predict growth of different crop such as cotton, soybean, chickpea etc. from a common source code (Boote et al., 1998a).
- **Individual crop module interface (plant module):** Similar to CROPGRO, it links plants growth dynamics with other DSSAT-CSM modules.
- **Management module:** Includes input variables such as planting, applying nutrients, irrigating etc. specified as standard 'experiment' in input file (Hunt et al., 2001). It is then analysed with different years to see the impact of changing crop for different weather/year.
- **Pest module:** As an input in field observations to analyse insect populations or disease severity for specified pest and diseases infesting development and yield of the crop.

In this experiment, the seasonal management practices and soil modules are kept the same for the entire simulation, while the changes in the weather module is considered during the period of entire model integration.

Data for the Analysis

Daily agrometeorological observations are taken from the Agrometeorological Observatory under India Meteorological Department (IMD) situated about 0.5 km away from the experimental plot. Weather data utilized for this study includes daily maximum and minimum temperature, bright sunshine hours and rainfall. Three sowing (planting) dates are considered in the study, such as 10th May, 21st May, and 6th June which are widely practiced. The genetic coefficient of the cotton crop is employed in the model, which has been adopted from Swami et al. (2016). The model has been calibrated and validated for these cultivars with the actual production for simulating cotton production under Hisar region (Shikha et al., 2018).

Experimental Design

The climatology of thirty-five years daily weather data from IMD has been taken for Hisar station starting from 1981 to 2015. Seasonal simulation has been carried out

for that duration to assess the climatological impact of 35 years of data. The final output for yield, LAI, ET, MD are all 35 years mean for this duration. The experiment has been replicated thrice for minimizing errors. To examine the impact of increasing temperature under changing climate, four different simulations are carried out taking normal climatology, further by adding 1°C, 2°C and 3°C to the climatological temperature value in the simulations. Similarly, another set of four simulations are made by increasing the CO₂ by 50 ppm, 100 ppm and 150 ppm respectively to estimate the impact of increasing CO₂ on yield. Further, four new simulations are designed by changing the CO₂ concentration and temperature together in order to examine impacts on the productivity. It is important to mention that the increment of temperature and CO₂ are done on the climatological data of the 35 years in the model to observe changes w.r.t. the present mean behaviour. Observed climatology has been taken as normal in the study, depicted as N. The climate change simulations for temperature are denoted as N+1 °C, N+2 °C and N+3 °C. The experiments with change in CO₂ concentration are represented as N for normal CO₂, N+50 ppm, N+100 ppm and N+150 ppm. Model simulates various phenological and physiological parameters such as anthesis date, harvest index, dry matter, maturity date etc. (Jones et al., 2011). From these simulated output, four different physiological parameters are examined to assess the impact of the possible climate change. These parameters considered for this study are:

1. Evapotranspiration (ET; mm) (It is the sum of crop transpiration and transpiration from crop adjacent soil and water surface) (Shih et al., 1993)
2. Leaf Area Index (LAI; Maximum) (It is generally defined as leaf area of one side per unit ground area for broadleaf canopies) (Myneni et al., 1997).
3. Maturity date (MD) (Days of physiological maturity of the crop from the planting date) (Corbeels et al., 2016)
4. Harvest index (HI) (Harvest index is defined as ratio of the reproductive yield with respect to total plant biomass) (Gur et al., 2010)

Results and Discussion

This section deals with the sensitivity in the yield and four different physiological characters (ET, LAI, MD and HI) of the three different cotton varieties in response towards the change in temperature, CO₂ concentration and combined at three different sowing dates.

Sensitivity of Yield Towards Change in Temperature

The model simulation shows that Pancham-541 sown on 6th June is most sensitive to changes in temperature (Figure 1a), as the decrease in yield is maximum for 3 °C rise in temperature. However, it has a high optimum range of temperature for tolerance, which is evident from the rise in yield with a temperature rise of 1°C. Further rise in temperature reduces the crop yield for all sowing dates. Interestingly, the decline in production is more for the crop sown in June as compared to the one sown during May. The varieties like Pancham-541 and RCH-791 also show a gradual reduction in yield with temperature rise (Figure 1b). RCH-791 also shows higher sensitivity (decreasing yield) towards increasing temperature for crop sown on 6th June as compared to the other sowing dates considered in the study. This indicates that the present day temperature is the critical temperature for the crop and it could not withstand any further increase in temperature. This is the reason for decrease in crop yield beyond the present climatological temperature value. The sensitivity of SP-7007 towards the rise in temperature is least as compared to the other two varieties (Figure 1c). Interestingly, the decrease in crop yield is least for N+3 °C for the crop sown on 6th June than the earlier sowing dates. Therefore, the results indicate that the early sowing (during May) relatively reduces the impact of rising temperature as compared to the varieties sown late (during June) in the agricultural practices. Higher the temperature rise, more is the severity and its impact on the crop yield.

The earlier studies indicate that the temperature significantly affected the crop phenology, leaf expansion, biomass production, internode elongation, and distribution of the assimilates to the different parts of the plant (Reddy et al., 1991; Reddy et al., 1996; Reddy et al., 1999). Similar decline in yield with rise of temperature is reported (Jalotaa et al., 2009). They examined yield of Bt-cotton under semi-arid conditions and illustrated that the cotton seed yield declines from 4700 kg/ha to 2300 kg/ha with an increase in temperature from 28 °C to 32 °C and the reduction is high during sowing to flowering stage (Jalotaa et al., 2009). Similarly, the findings from this study show that the simulated yield for Pancham-541 sown on 10th May compared to normal climate has reduced to 2737.54 kg/ha from 2598.31 kg/ha. The negative impact associated with rising temperature could be potentially due to reduction in vegetative growth period, increased fruit shedding due to enhanced temperature stress and loss of reproductive capacity because of reduced boll

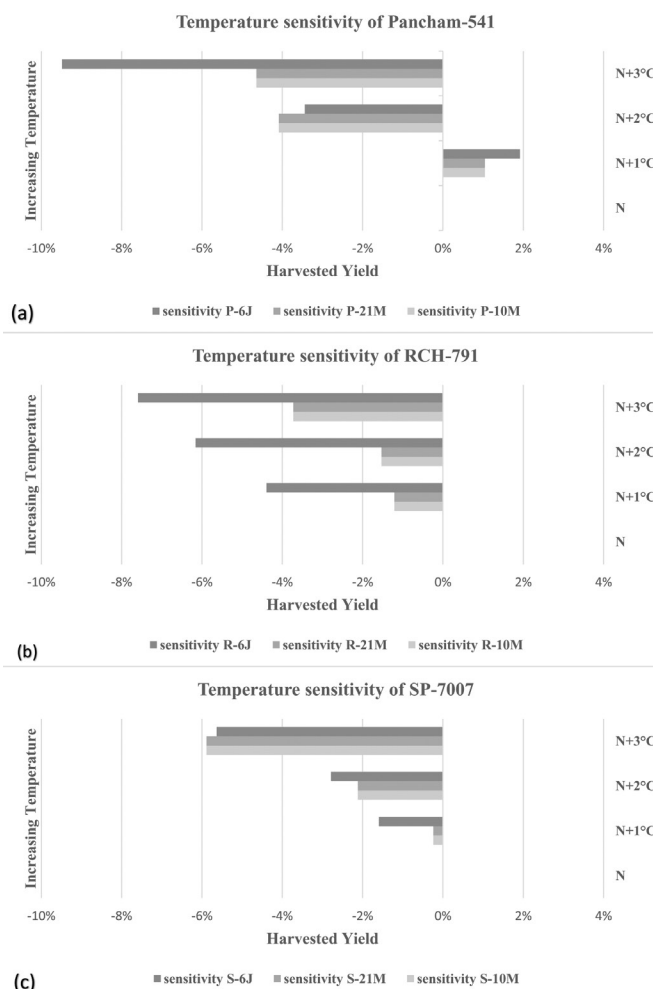


Figure 1: Temperature sensitivity of cotton cultivars for three different sowing dates 10th May, 21st May and 6th June for (a) Pancham-541, (b) RCH-791 and (c) SP-7007.

filling (Luo et al., 2014). Similar studies based on field experiments showed strong positive correlation of temperature with cotton seed, cotton lint, boll opening and negative correlation with leaf area index (Tripathi, 2005; Pouresia and Nabipour, 2007; Singh et al., 2008).

Maximum temperature, minimum temperature and vapour pressure deficit showed a strong positive correlation with cotton seed, cotton lint and bolls per plant during boll opening stage, whereas morning and evening relative humidity showed negative correlation with seed cotton, cotton seed, cotton lint and bolls per plant during vegetative, flowering and boll opening stages. A negative correlation was observed between air temperature, sunshine hours and leaf area index during seed development phase (Tripathi, 2005; Pouresia and Nabipour, 2007). Negative correlations between temperatures during two later phenophases and seed yield were due to higher temperatures during

reproductive phase. Such results were also reported by various researchers (Sahoo et al., 2000; Singh, 2005; Pouresia and Nabipour, 2007; Liyong et al., 2007).

Sensitivity of Yield Towards Change in CO₂

It is interesting here to observe that Pancham-541 sown in May is positively impacted by an increase in CO₂ concentration in the atmosphere, while the opposite is found for cases with sowing date during June (Figure 2a). Surprisingly, the RCH-791 variety shows exactly opposite behaviour as compared to Pancham-541 (Figure 2b), where the increasing CO₂ has declined the yield except for variety sown in June. The sensitivity of SP-7007 is reported to be least as compared to other two varieties considered in the study (Figure 2c). However, the yield increase (decrease) for the variety shown in June (May) with increase in CO₂ concentration. The present analysis found that Pancham-541 (SP-7007) variety is most (least) sensitive to increase in CO₂. However, for RCH-791 and SP-7007 varieties, the

increase in CO₂ has negatively impacted to crop sown in May than the variety sown in June.

In cotton an increase in boll size is also evident due to elevated CO₂ (Ruiz-Vera et al., 2018). Sowing dates also play greater role for the plan to increase productivity; the improvement in cotton yield for early-sown crop is around 10% higher in comparison to late sown crop. This may be due to the lower cutout/abortion rate of the fruit that results in holding greater number of bolls for the plant (Pettigrew et al., 2002). Further, the positive influence on the crop due to sowing dates can also be attributed to early emergence and therefore increase in reproductive period which results in earlier onset of first square and delayed last square (Bange et al., 2004).

Sensitivity of Yield Towards Change in Combined Temperature and CO₂

As discussed earlier, the Pancham-541 has a high optimum range of temperature tolerance with respect to present temperature climatology, which is reflected from the rise in yield with 1 °C rise but subsequently yield decreases with temperature rise of 2 °C and 3 °C. Similar finding are also observed from the combined rise of temperature and CO₂ (Figure 3a). The pattern is very close to the change in temperature but with a moderated effect. Similar declining yield is also observed for RCH-791 variety (Figure 3b). For SP-7007 variety, the crop sown during May shows a positive effect in terms of yield with an increase in 50 ppm and 1 °C rise in temperature, which further decreases with increase in the concentration of both (Figure 3c). The yield decreases with increasing temperature, which is partially but not totally moderated by increasing CO₂. The crop still imitates the same behaviour as increasing temperature but with lesser intensity. This moderation can be because of increasing CO₂ concentrations called the fertilization effect and reported in other crops as well (Saseendran et al., 2000). In general, rise in temperature and CO₂ negatively impacted the yield for all the planting dates.

Similar studies conducted for cotton crop, based upon field trials, showed that the vegetative growth is increased by increasing temperature and CO₂ together (Reddy et al., 2005). This could be because of the pretext that vegetative growth may require lesser time to support more fruit loads (Jalotaa et al., 2009). Therefore, reduced vegetative growth 'cutout' may occur forthwith and consequently reduce potential of crop yield (Lawlor et al., 2014; Pettigrew et al., 2002). Further curtailment in time for 'cutout' can advance maturity, therefore decrease the yield (Bange et al., 2004b). It

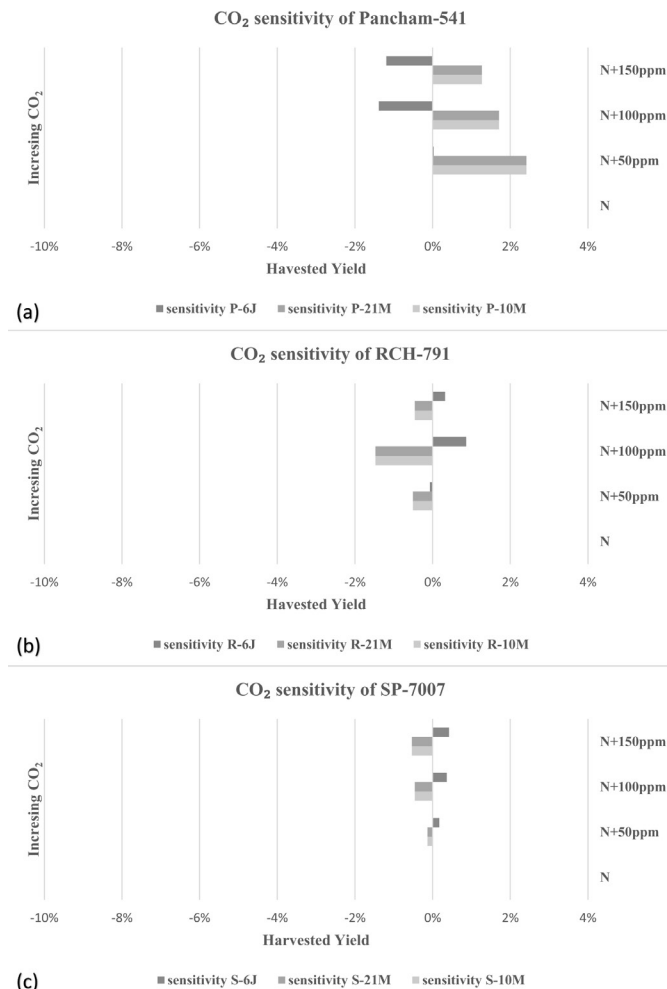


Figure 2: Same as Figure 1, but for carbon dioxide.

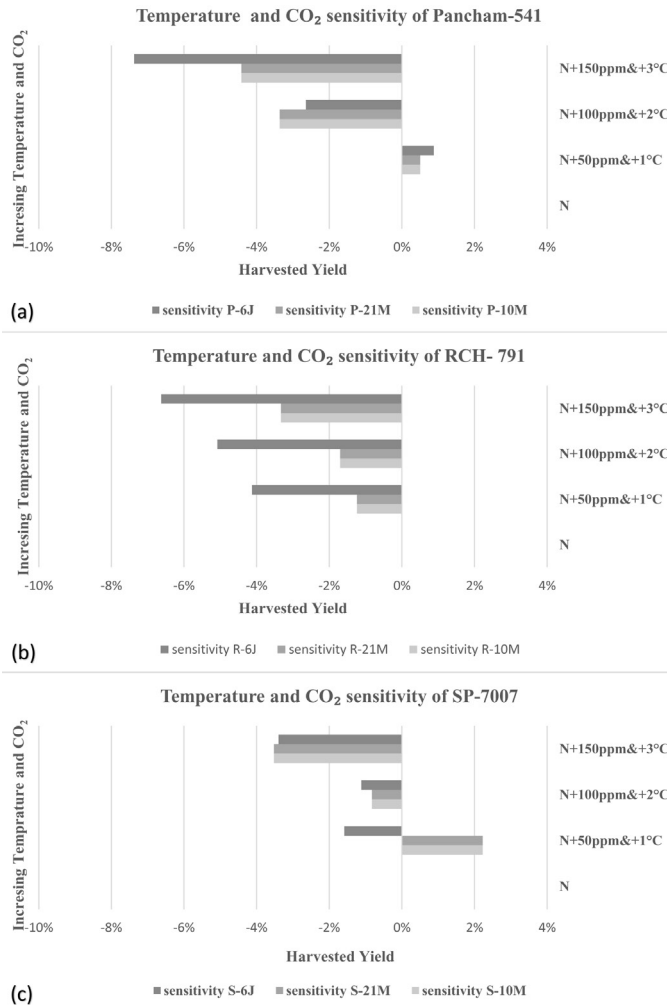


Figure 3: Same as Figure 1, but for temperature and carbon dioxide combined.

is also reported that higher vegetative growth is good to support yield of transgenic cotton with additional and early fruiting bodies (Constable et al., 2006). The effect of elevated CO₂ masked the apparent high temperature injury that limited the growth of all plant organs, especially reproductive system (Reddy et al., 1991; Reddy et al., 1996; Reddy et al., 1999). Studies also indicate that bolling periods will be shorter under warming climate (Reddy et al., 1999; Luo et al., 2014). Therefore, the fibre quality is compromised and boll size are reduced despite potentially increased fruiting periods and more fruit. This reduction in yield may be due to cutout in vegetative phase or reduction in boll size in reproductive phase (Lawlor et al., 1991).

Sensitivity of Yield Towards Phenological Characters

In this section, the mean of the four major phenological parameters for the crop such as Evapotranspiration (ET),

Leaf Area Index (maximum) (LAI), Harvest Index (HI) and Maturity Date (MD) are analyzed. As discussed earlier, ET has positive correlation with LAI and HI with MD; they are plotted together (Ruiz-Vera et al., 2018; Reddy et al., 2005; Anapalli et al., 2016; Reddy et al., 2005).

A gradual increase in ET and LAI with increase in temperature is observed for Pancham-541 (Figure 4a) but interestingly, no significant change is observed under experiments with gradual increase of CO₂ (Figure 4b). However, the ET and LAI both increase gradually with the rise of both temperature and CO₂ from 1 °C and 50 ppm cumulatively to further higher values (Figure 4c). The simulation shows higher ET and LAI for the crop sown during June than that sown in May, with an increase in 1 °C temperature and 50 ppm CO₂ concentrations cumulatively. For Pancham-541, the HI is higher for 1 °C rise as compared to the present climatology for all sowing dates (Figure 4d). The MD decreases slightly with increase in temperature and highest for the crop sown during June (Figure 4a). It also decreases slightly for combined increase of temperature and CO₂ concentrations. Similar studies indicate that low temperatures and prolonged growing period are advantageous for cotton productivity (Reddy et al., 1999).

It is observed that the HI is approximately same for all the sowing dates for Pancham-541 variety for present temperature climatology and N+1 °C. However, it decreases with further rise of temperature. Interestingly, the sowing dates also play a major role in deciding the productivity. For example, June (May) shows higher productivity for temperature rise of 2 °C (3 °C). Moreover, the HI as well as MD do not show any significant change for 50 ppm increase in CO₂ w.r.t. the climatological value. HI decreases faintly with further rise in CO₂ concentration mostly for crop sown in June (Figure 4e). The crop under combined rise of temperature and CO₂ concentrations mimics similar behaviour as with rising temperature but with less intensity for N+2 °C and N+3 °C along with 100 ppm and 150 ppm CO₂ concentrations (Figure 4f). However, for 2 °C (3 °C) temperature rise with 100 ppm (150 ppm) CO₂, June (May) is showing better yield.

For the cultivar RCH-791, ET and LAI show similar response as Pancham-541. The increasing temperature leads to gradual increase in both ET and LAI (Figure 5a). But with increasing CO₂ concentrations, there is no significant impact observed upon them (Figure 5b). The fertilization effect dominates under combined increase of temperature and CO₂ leading to lesser impact (Figure

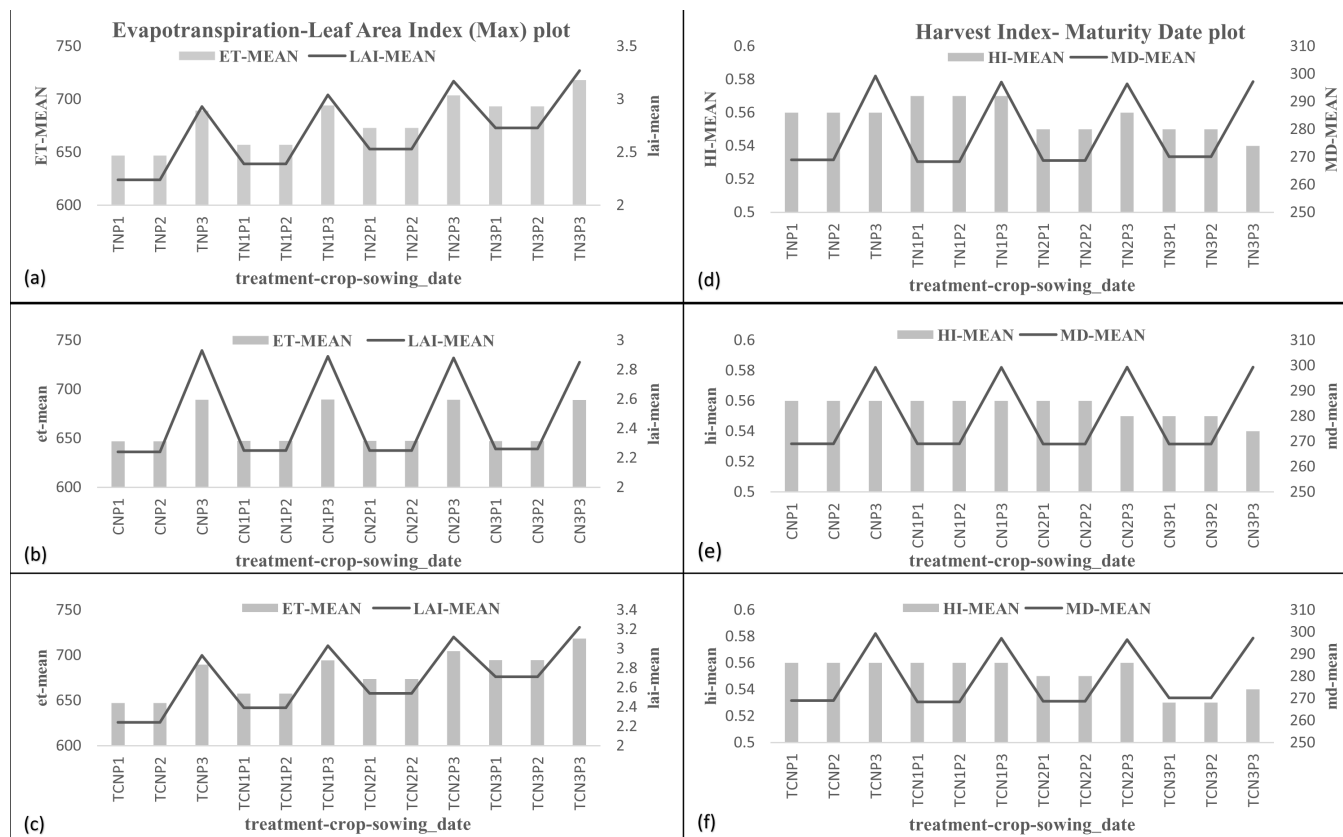


Figure 4: Cotton variety Pancham-541, physiological parameters taken combined for three sowing dates 10th May, 21st May and 06th June: (a) Evapotranspiration and Leaf Area Index (Maximum) with increasing temperature, (b) Same as (a), but for increasing CO₂, (c) Same as (a) but for temperature and CO₂, (d) Harvest Index and Maturity date with increasing temperature, (e) Same as (d), but for increasing CO₂ and (f) Same as (d), but for temperature and CO₂.

Abbreviations used in Figure 4

TNP1	Evaluating temperature sensitivity with respect to (w.r.t) normal climate for Pancham-541 with sowing date(SD) 10 th May
TNP2	Evaluating temperature sensitivity w.r.t normal climate for Pancham-541 with SD 21 st May
TNP3	Evaluating temperature sensitivity w.r.t. normal climate for Pancham-541 with SD 06 th June
TN1P1	Evaluating temperature sensitivity for 1 °C increase in Temperature w.r.t. to normal climate for Pancham-541 with SD 10 th May
TN1P2	Evaluating temperature sensitivity for 1 °C increase in Temperature w.r.t. to normal climate for Pancham-541 with SD 21 st May
TN1P3	Evaluating temperature sensitivity for 1 °C increase in Temperature w.r.t. to normal climate for Pancham-541 with SD 06 th June
TN2P1	Evaluating temperature sensitivity for 2 °C increase in Temperature w.r.t. to normal climate for Pancham-541 with SD 10 th May
TN2P2	Evaluating temperature sensitivity for 2 °C increase in Temperature w.r.t. to normal climate for Pancham-541 with SD 21 st May
TN2P3	Evaluating temperature sensitivity for 2 °C increase in Temperature w.r.t. to normal climate for Pancham-541 with SD 06 th June
TN3P1	Evaluating temperature sensitivity for 3 °C increase in Temperature w.r.t. to normal climate for Pancham-541 with SD 10 th May
TN3P2	Evaluating temperature sensitivity for 3 °C increase in Temperature w.r.t. to normal climate for Pancham-541 with SD 21 st May
TN3P3	Evaluating temperature sensitivity for 3 °C increase in Temperature w.r.t. to normal climate for Pancham-541 with SD 06 th June
CNP1	Evaluating CO ₂ sensitivity w.r.t. normal climate for Pancham-541 with SD 10 th May
CNP2	Evaluating CO ₂ sensitivity w.r.t normal climate for Pancham-541 with SD 21 st May
CNP3	Evaluating CO ₂ sensitivity w.r.t. normal climate for Pancham-541 with SD 06 th June
CN1P1	Evaluating CO ₂ sensitivity for 50 ppm increase in CO ₂ w.r.t. normal climate for Pancham-541 with SD 10 th May
CN1P2	Evaluating CO ₂ sensitivity for 50 ppm increase in CO ₂ w.r.t. normal climate for Pancham-541 with SD 21 st May
CN1P3	Evaluating CO ₂ sensitivity for 50 ppm increase in CO ₂ w.r.t. normal climate for Pancham-541 with SD 06 th June

CN2P1	Evaluating CO ₂ sensitivity for 100 ppm increase in CO ₂ w.r.t. normal climate for Pancham-541 with SD 10 th May
CN2P2	Evaluating CO ₂ sensitivity for 100 ppm increase in CO ₂ w.r.t. normal climate for Pancham-541 with SD 21 st May
CN2P3	Evaluating CO ₂ sensitivity for 100 ppm increase in CO ₂ w.r.t. normal climate for Pancham-541 with SD 06 th June
CN3P1	Evaluating CO ₂ sensitivity for 150 ppm increase in CO ₂ w.r.t. normal climate for Pancham-541 with SD 10 th May
CN3P2	Evaluating CO ₂ sensitivity for 150 ppm increase in CO ₂ w.r.t. normal climate for Pancham-541 with SD 21 st May
CN3P3	Evaluating CO ₂ sensitivity for 150 ppm increase in CO ₂ w.r.t. normal climate for Pancham-541 with SD 06 th June
TCNP1	Evaluating temperature and CO ₂ sensitivity w.r.t. normal climate for Pancham-541 with SD 10 th May
TCNP2	Evaluating temperature and CO ₂ sensitivity w.r.t. normal climate for Pancham-541 with SD 21 st May
TCNP3	Evaluating temperature and CO ₂ sensitivity w.r.t. normal climate for Pancham-541 with SD 06 th June
TCN1P1	Evaluating temperature and CO ₂ sensitivity for 1 °C+50 ppm increase w.r.t. normal climate for Pancham-541 with SD 10 th May
TCN1P2	Evaluating temperature and CO ₂ sensitivity for 1 °C+50 ppm increase w.r.t. normal climate for Pancham-541 with SD 21 st May
TCN1P3	Evaluating temperature and CO ₂ sensitivity for 1 °C+50 ppm increase w.r.t. normal climate for Pancham-541 with SD 06 th June
TCN2P1	Evaluating temperature and CO ₂ sensitivity for 2 °C+100 ppm increase w.r.t. normal climate for Pancham-541 with SD 10 th May
TCN2P2	Evaluating temperature and CO ₂ sensitivity for 2 °C+100 ppm increase w.r.t. normal climate for Pancham-541 with SD 21 st May
TCN2P3	Evaluating temperature and CO ₂ sensitivity for 2 °C+100 ppm increase w.r.t. normal climate for Pancham-541 with SD 06 th June
TCN3P1	Evaluating temperature and CO ₂ sensitivity for 3 °C+150 ppm increase w.r.t. normal climate for Pancham-541 with SD 10 th May
TCN3P2	Evaluating temperature and CO ₂ sensitivity for 3 °C+150 ppm increase w.r.t. normal climate for Pancham-541 with SD 21 st May
TCN3P3	Evaluating temperature and CO ₂ sensitivity for 3 °C+150 ppm increase w.r.t. normal climate for Pancham-541 with SD 06 th June

5c). However, the HI and MD slightly increase with 1 °C rise of temperature for crops sown in May; which further reduces under N+2 °C and N+3 °C. The crop sown in June shows gradual reduction in its yield with gradual temperature rise from 1 °C to 3 °C (Figure 5d). HI and MD are almost insensitive (show no change) towards 50 ppm increase of the CO₂ concentrations; but there is a slight reduction in HI with further rise of CO₂ w.r.t climatological value for the crop sown in May (Figure 5e). Again, the fertilization effect dominates for increasing CO₂ together with temperature rise leading to a small change in the mean values (Figure 5f). The change of temperature, CO₂ and combined has a little effect on MD which reduces by 1-2 days; while the change is maximum for the crop sown during June (Figure 5d-e-f). HI (0.37 to 0.34) and MD (1-2 days) are also least affected by these changes for this particular variety. This cultivar is found to be least affected and better performing in terms of yield with the changing climate. Similar studies indicated that early sowing increases the MD up to 1–2 days while late sown crop reduces it by 0–3 days, which is comparable with the present finding (Luo et al., 2014).

The ET and LAI means, for the cultivar SP-7007, are gradually increasing with the cumulative increase

in temperature by 1 °C (Figure 6a). For all experiments, the crop sown on 6th June has the highest ET and LAI mean values among all the sowing dates. Like other two varieties, the increasing CO₂ does not bring any significant change in the ET and LAI means (Figure 6b). Partial moderation in the increase in ET and LAI is observed for combined increase in temperature and CO₂ concentration (Figure 6c). The HI is almost insensitive to almost 1 °C temperature rise and further decline slightly under N+2 °C and the lowest is observed for late sown crop of 6th June (Figure 6d). This indicates that this crop sown in May (early) provides better performance than sown in June (late) under future warming climate. Under 3 °C rise in temperature, the yield has significantly reduced for the crops sown in May while the production is relatively higher for late sown crop on 6th June. Similar pattern is also observed for increase in CO₂ concentration (Figure 6e). But the maturity date is not much impacted with increasing temperature and CO₂ and both combined (Figure 6d-e-f). The HI mean slightly decreases with increase in CO₂ with lowest values for the crop sown on 6th June. Again, the increase in temperature and CO₂ combined mimic the similar behaviour as with rise in temperature but the effect has been partially moderated (Figure 6f).

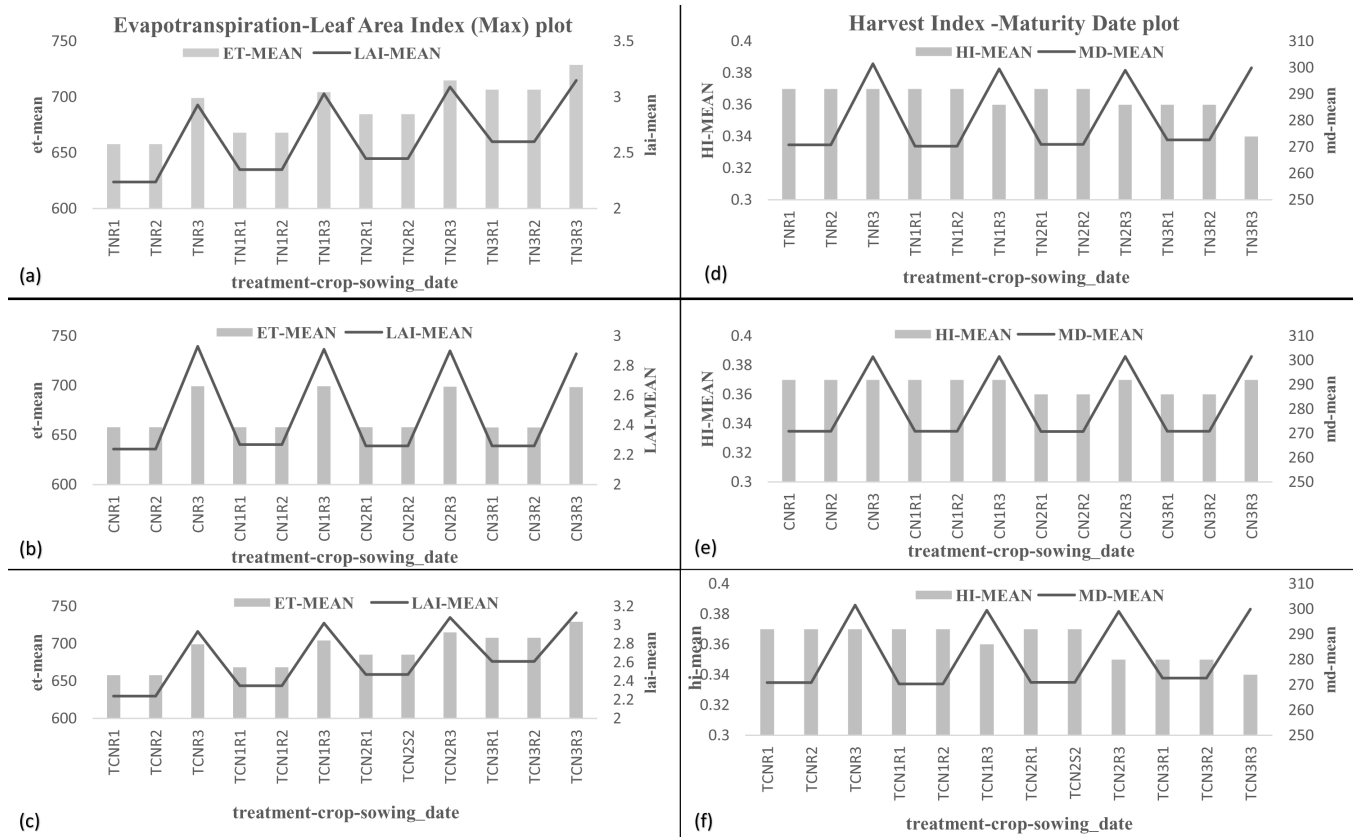


Figure 5: Same as Figure 4 but for cotton variety RCH-791.

Abbreviations used in Figure 5

TNR1	Evaluating temperature sensitivity with respect to (w.r.t) normal climate for RCH-791 with sowing date (SD) 10 th May
TNR2	Evaluating temperature sensitivity w.r.t normal climate for RCH-791 with SD 21 st May
TNR3	Evaluating temperature sensitivity w.r.t. normal climate for RCH-791 with SD 06 th June
TN1R1	Evaluating temperature sensitivity for 1 °C increase in Temperature w.r.t. to normal climate for RCH-791 with SD 10 th May
TN1R2	Evaluating temperature sensitivity for 1 °C increase in Temperature w.r.t. to normal climate for RCH-791 with SD 21 st May
TN1R3	Evaluating temperature sensitivity for 1 °C increase in Temperature w.r.t. to normal climate for RCH-791 with SD 06 th June
TN2R1	Evaluating temperature sensitivity for 2 °C increase in Temperature w.r.t. to normal climate for RCH-791 with SD 10 th May
TN2R2	Evaluating temperature sensitivity for 2 °C increase in Temperature w.r.t. to normal climate for RCH-791 with SD 21 st May
TN2R3	Evaluating temperature sensitivity for 2 °C increase in Temperature w.r.t. to normal climate for RCH-791 with SD 06 th June
TN3R1	Evaluating temperature sensitivity for 3 °C increase in Temperature w.r.t. to normal climate for RCH-791 with SD 10 th May
TN3R2	Evaluating temperature sensitivity for 3 °C increase in Temperature w.r.t. to normal climate for RCH-791 with SD 21 st May
TN3R3	Evaluating temperature sensitivity for 3 °C increase in Temperature w.r.t. to normal climate for RCH-791 with SD 06 th June
TNR1	Evaluating CO ₂ sensitivity w.r.t. normal climate for RCH-791 with SD 10 th May
TNR2	Evaluating CO ₂ sensitivity w.r.t normal climate for RCH-791 with SD 21 st May
TNR3	Evaluating CO ₂ sensitivity w.r.t. normal climate for RCH-791 with SD 06 th June
CN1R1	Evaluating CO ₂ sensitivity for 50 ppm increase in CO ₂ w.r.t. normal climate for RCH-791 with SD 10 th May
CN1R2	Evaluating CO ₂ sensitivity for 50 ppm increase in CO ₂ w.r.t. normal climate for RCH-791 with SD 21 st May
CN1R3	Evaluating CO ₂ sensitivity for 50 ppm increase in CO ₂ w.r.t. normal climate for RCH-791 with SD 06 th June
CN2R1	Evaluating CO ₂ sensitivity for 100 ppm increase in CO ₂ w.r.t. normal climate for RCH-791 with SD 10 th May
CN2R2	Evaluating CO ₂ sensitivity for 100 ppm increase in CO ₂ w.r.t. normal climate for RCH-791 with SD 21 st May
CN2R3	Evaluating CO ₂ sensitivity for 100 ppm increase in CO ₂ w.r.t. normal climate for RCH-791 with SD 06 th June

CN3R1	Evaluating CO ₂ sensitivity for 150 ppm increase in CO ₂ w.r.t. normal climate for RCH-791 with SD 10 th May
CN3R2	Evaluating CO ₂ sensitivity for 150 ppm increase in CO ₂ w.r.t. normal climate for RCH-791 with SD 21 st May
CN3R3	Evaluating CO ₂ sensitivity for 150 ppm increase in CO ₂ w.r.t. normal climate for RCH-791 with SD 06 th June
TCNR1	Evaluating temperature and CO ₂ sensitivity w.r.t. normal climate for RCH-791 with SD 10 th May
TCNR2	Evaluating temperature and CO ₂ sensitivity w.r.t. normal climate for RCH-791 with SD 21 st May
TCNR3	Evaluating temperature and CO ₂ sensitivity w.r.t. normal climate for RCH-791 with SD 06 th June
TCN1R1	Evaluating temperature and CO ₂ sensitivity for 1 °C+50 ppm increase w.r.t. normal climate for RCH-791 with SD 10 th May
TCN1R2	Evaluating temperature and CO ₂ sensitivity for 1 °C+50 ppm increase w.r.t. normal climate for RCH-791 with SD 21 st May
TCN1R3	Evaluating temperature and CO ₂ sensitivity for 1 °C+50 ppm increase w.r.t. normal climate for RCH-791 with SD 06 th June
TCN2R1	Evaluating temperature and CO ₂ sensitivity for 2 °C+100 ppm increase w.r.t. normal climate for RCH-791 with SD 10 th May
TCN2R2	Evaluating temperature and CO ₂ sensitivity for 2 °C+100 ppm increase w.r.t. normal climate for RCH-791 with SD 21 st May
TCN2R3	Evaluating temperature and CO ₂ sensitivity for 2 °C+100 ppm increase w.r.t. normal climate for RCH-791 with SD 06 th June
TCN3R1	Evaluating temperature and CO ₂ sensitivity for 3 °C+150 ppm increase w.r.t. normal climate for RCH-791 with SD 10 th May
TCN3R2	Evaluating temperature and CO ₂ sensitivity for 3 °C+150 ppm increase w.r.t. normal climate for RCH-791 with SD 21 st May
TCN3R3	Evaluating temperature and CO ₂ sensitivity for 3 °C+150 ppm increase w.r.t. normal climate for RCH-791 with SD 06 th June

It is observed from the present analysis that the increasing temperature has more impact on the ET and LAI as compared to the increasing CO₂ in general. Pancham-541 variety is found to be most tolerant towards increasing temperature till 1 °C temperature rise. The mean values are higher for ET and LAI for varieties sown late (6th June) for all the conditions. Combining the effect of temperature and CO₂, the higher impact of the increasing temperature is moderated by increasing CO₂ for all the cultivar with all sowing dates in the experiment. The cotton being a C₃ plant is impacted by an increase in CO₂, which influences the photosynthesis, yield and dry matter production substantially (Lawlor et al., 1991). In some crops such as maize, vegetative and reproductive growth can be accelerated by rising temperature whereas increasing CO₂ concentrations has no apparent effect (Ruiz-Vera et al., 2018). Further, another study advocates an increase in productivity with doubling CO₂ concentration which is related to the higher leaf area (Reddy et al., 2005). With increased incidences of heat stress, there is a rapid crop development and maturity if the management strategies are not adjusted (Luo et al., 2014).

In general, higher Maturity Date (MD) are observed in crop sown on 6th June. This signifies that the crop sown late takes more time to mature. As observed, crops sown in May are performing better under warming climate, which is also supported by earlier studies. Therefore, early planting is one good remedy to maintain a good yield for the future climate (Anapalli et al., 2016; Reddy et al., 2005). With increase of temperature, CO₂ and both, the harvested yield and maturity period decreases. ET and LAI are found

directly (indirectly) proportional to HI (MD) for all three varieties considered for the study. Crop sown during May seems to be better performing in terms of HI with increasing temperature and CO₂ for Pancham-541 and RCH-791. But, the SP-7007 variety has least HI for the crop sown during June. The positive impacts of early sowing in productivity and development are related to early emergence and increase in reproductive period which results into earlier First Square and delayed last Effective Square (Anapalli et al., 2016; Reddy et al., 2005). Some degree of loss of fruiting bodies (decrease in yield) due to rise of temperature can be compensated by greater resources like irrigation and nutrition (Constable et al., 2006).

Conclusions

Climate change has been a daunting challenge in the present era. This poses a serious question on the sustainability of the mother earth and the viability of food thus posing risks to future generations. Along with experimental field studies, crop and climate are also widely used for research purposes to study the crop productivity and soil water balance with the changing climate. Modelling studies nowadays are essential for the effect of elevated CO₂, increasing temperature, both together water balance and nutrition with the crop simulation models as they give good overview about the crop development which is further designed for the tests and the predictions (Schlenker et al., 2009). It helps in assimilating field experiment based knowledge for computation. It benefits scientific communities for interdisciplinary research to solve problems at

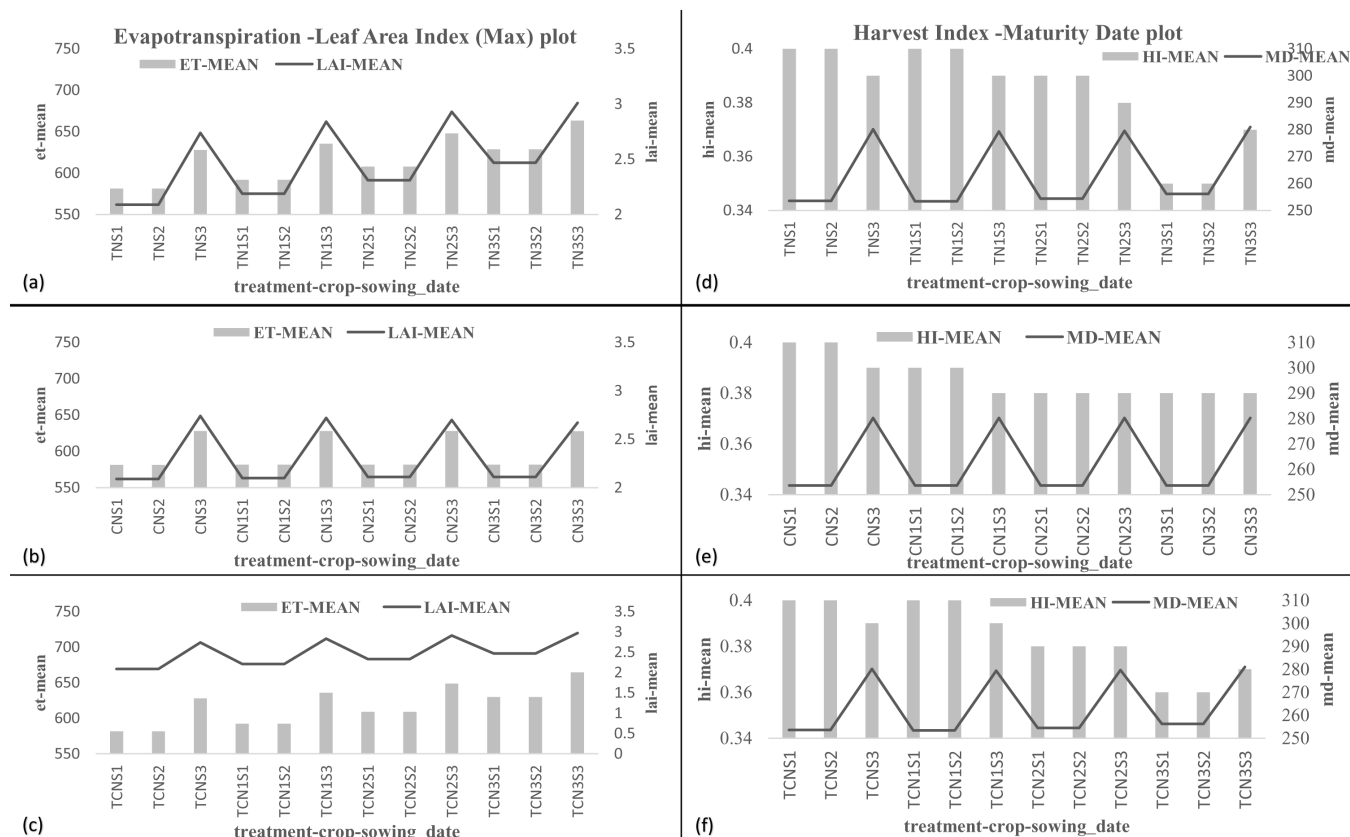


Figure 6: Same as Figure 4 but for cotton variety SP-7007.

Abbreviations used in Figure 6

TNS1	Evaluating temperature sensitivity with respect to (w.r.t) normal climate for SP-7007 with sowing date (SD) 10 th May
TNS2	Evaluating temperature sensitivity w.r.t normal climate for SP-7007 with SD 21 st May
TNS3	Evaluating temperature sensitivity w.r.t. normal climate for SP-7007 with SD 06 th June
TN1S1	Evaluating temperature sensitivity for 1 °C increase in Temperature w.r.t. to normal climate for SP-7007 with SD 10 th May
TN1S2	Evaluating temperature sensitivity for 1 °C increase in Temperature w.r.t. to normal climate for SP-7007 with SD 21 st May
TN1S3	Evaluating temperature sensitivity for 1 °C increase in Temperature w.r.t. to normal climate for SP-7007 with SD 06 th June
TN2S1	Evaluating temperature sensitivity for 2 °C increase in Temperature w.r.t. to normal climate for SP-7007 with SD 10 th May
TN2S2	Evaluating temperature sensitivity for 2 °C increase in Temperature w.r.t. to normal climate for SP-7007 with SD 21 st May
TN2S3	Evaluating temperature sensitivity for 2 °C increase in Temperature w.r.t. to normal climate for SP-7007 with SD 06 th June
TN3S1	Evaluating temperature sensitivity for 3 °C increase in Temperature w.r.t. to normal climate for SP-7007 with SD 10 th May
TN3S2	Evaluating temperature sensitivity for 3 °C increase in Temperature w.r.t. to normal climate for SP-7007 with SD 21 st May
TN3S3	Evaluating temperature sensitivity for 3 °C increase in Temperature w.r.t. to normal climate for SP-7007 with SD 06 th June
TNS1	Evaluating CO ₂ sensitivity w.r.t. normal climate for SP-7007 with SD 10 th May
TNS2	Evaluating CO ₂ sensitivity w.r.t normal climate for SP-7007 with SD 21 st May
TNS3	Evaluating CO ₂ sensitivity w.r.t. normal climate for SP-7007 with SD 06 th June
CN1S1	Evaluating CO ₂ sensitivity for 50 ppm increase in CO ₂ w.r.t. normal climate for SP-7007 with SD 10 th May
CN1S2	Evaluating CO ₂ sensitivity for 50 ppm increase in CO ₂ w.r.t. normal climate for SP-7007 with SD 21 st May
CN1S3	Evaluating CO ₂ sensitivity for 50 ppm increase in CO ₂ w.r.t. normal climate for SP-7007 with SD 06 th June
CN2S1	Evaluating CO ₂ sensitivity for 100 ppm increase in CO ₂ w.r.t. normal climate for SP-7007 with SD 10 th May
CN2S2	Evaluating CO ₂ sensitivity for 100 ppm increase in CO ₂ w.r.t. normal climate for SP-7007 with SD 21 st May
CN2S3	Evaluating CO ₂ sensitivity for 100 ppm increase in CO ₂ w.r.t. normal climate for SP-7007 with SD 06 th June

CN3S1	Evaluating CO ₂ sensitivity for 150 ppm increase in CO ₂ w.r.t. normal climate for SP-7007 with SD 10 th May
CN3S2	Evaluating CO ₂ sensitivity for 150 ppm increase in CO ₂ w.r.t. normal climate for SP-7007 with SD 21 st May
CN3S3	Evaluating CO ₂ sensitivity for 150 ppm increase in CO ₂ w.r.t. normal climate for SP-7007 with SD 06 th June
TCNS1	Evaluating temperature and CO ₂ sensitivity w.r.t. normal climate for SP-7007 with SD 10 th May
TCNS2	Evaluating temperature and CO ₂ sensitivity w.r.t. normal climate for SP-7007 with SD 21 st May
TCNS3	Evaluating temperature and CO ₂ sensitivity w.r.t. normal climate for SP-7007 with SD 06 th June
TCN1S1	Evaluating temperature and CO ₂ sensitivity for 1 °C+50 ppm increase w.r.t. normal climate for SP-7007 with SD 10 th May
TCN1S2	Evaluating temperature and CO ₂ sensitivity for 1 °C+50 ppm increase w.r.t. normal climate for SP-7007 with SD 21 st May
TCN1S3	Evaluating temperature and CO ₂ sensitivity for 1 °C+50 ppm increase w.r.t. normal climate for SP-7007 with SD 06 th June
TCN2S1	Evaluating temperature and CO ₂ sensitivity for 2 °C+100 ppm increase w.r.t. normal climate for SP-7007 with SD 10 th May
TCN2S2	Evaluating temperature and CO ₂ sensitivity for 2 °C+100 ppm increase w.r.t. normal climate for SP-7007 with SD 21 st May
TCN2S3	Evaluating temperature and CO ₂ sensitivity for 2 °C+100 ppm increase w.r.t. normal climate for SP-7007 with SD 06 th June
TCN3S1	Evaluating temperature and CO ₂ sensitivity for 3 °C+150 ppm increase w.r.t. normal climate for SP-7007 with SD 10 th May
TCN3S2	Evaluating temperature and CO ₂ sensitivity for 3 °C+150 ppm increase w.r.t. normal climate for SP-7007 with SD 21 st May
TCN3S3	Evaluating temperature and CO ₂ sensitivity for 3 °C+150 ppm increase w.r.t. normal climate for SP-7007 with SD 06 th June

the farm level. It gives us cost-benefit approach for experimentation of different management strategies (Jones et al., 2003; Hoogenboom et al., 2015). But still they have some limitations as with the DSSAT model; it cannot accurately project natural processes. It is limited only to quantify the input data and could not properly assess the nutrient like potassium and biotic stress such as pest (Jones et al., 2003).

Each species has its specific tolerance limit for cardinal temperatures represented as maximum, minimum and optimum. Therefore, plant being a sessile organism is dependent on the surrounding environment. Thus, under climate changes, it is evident to see its effects upon the productivity, yield and growth cycle. Although the responses of cotton being an indeterminate C₃ plant are complex, but several generalizations are evident from this study. The modelling output suggests that increasing temperature and CO₂ have a major role to play in the cotton productivity. Increase in temperature negatively impacted the crop productivity in general, but this effect was moderated by increasing CO₂. For Pancham-541 increasing 1 °C of temperature and 50 ppm CO₂ was beneficial but further 2 °C and 3 °C is harmful, which was not the case with RCH and SP varieties. For SP-7007, increase in temperature without an increase in CO₂ is harmful but when increasing 1 °C combined with 50 ppm and 2 °C with 100 ppm are beneficial but further 3 °C with 150 ppm are harmful. The ET rate and LAI have been increasing with increasing temperature and CO₂ for all the varieties for all the sowing dates. Whereas, Harvest Index and maturity period were decreasing in general for all temperatures above optimum. This reduces the number

of retained bolls, boll-cellulose filling during maturation period and its rate of filling thus affecting the size of the boll under ambient and elevated CO₂. Elevated CO₂ helps to increase the total biomass chiefly due to increased photosynthesis simulated and increased boll weights because of increased branching, leaf area and increased fruiting sites every branch. It is observed from the study that with 1 °C rise in temperature and corresponding CO₂, the yield of Pancham-541 and SP-7007 has increased, when sown in May. Therefore, early planting of these two crop varieties can be recommended in near future. Further SP-7007 variety is found to be least sensitive to the increase in temperature by 2 °C. Thus, it is concluded that the increasing temperature at the present rate will be harmful for the productivity of cotton under changing climate, particularly over a semi-arid region like Hisar for all three varieties. Therefore, productivity of cotton will reduce in future where the temperature is near optimum for the existing variety. The present study suggests necessary management practices such as using heat tolerant cultivars and changing the sowing time (early) will be needed in future to overcome the climatic constraints.

These modelling studies can also be applied to analyse the influence of weather on crop performance. The model takes care of the interaction of crop in a complex way for soil and management interactions to assess its vulnerability and adaptability. Thus, the study helps in understanding the uncertainty in crop production with the changing climate and associated economic risks. Presently, attempts are made by the government for providing farmers with management strategies through extension services using the crop

models. Further our objective is to integrate the study with future climate data from the climate models to analyse the impact and its mitigation measures, which will be a move towards sustainable agriculture by the means of Climate-Smart-Agriculture (CSA).

References

- Aggarwal, P.K., Kalra, N., Chander, S. et al., 2006a. InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I: Model description. *Agricultural Systems*, **89**: 1–25.
- Aggarwal, P.K., Banerjee, B., Daryaei, M.G. et al., 2006b. InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. II: Performance of the model. *Agricultural Systems*, **89**: 47–67.
- Anapalli, S.S., Fisher, D.K., Reddy, K.N., Pettigrew, W.T., Sui, R. and Ahuja, L.R., 2016. Vulnerabilities and adapting irrigated and rainfed cotton to climate change in the lower Mississippi Delta region. *Climate*, **4**(4): 55.
- Bange, M.P. and Milroy, S.P., 2004. Growth and dry matter partitioning of diverse cotton genotypes. *Field Crops Research*, **87**: 73–87.
- Boote, K.J., Jones, J.W. and Hoogenboom, G., 1998a. Simulation of crop growth: CROPGRO model. In: Peart, R.M. and Curry, R.B. (Eds.), *Agricultural Systems Modeling and Simulation* (Chapter 18). Marcel Dekker, Inc, New York.
- Challinor, A.J. and Wheeler, T.R., 2008. Crop yield reduction in the tropics under climate change: Processes and uncertainties. *Agricultural and Forest Meteorology*, **148**: 343–356.
- Constable, G. and Bange, M., 2006. What is cotton's sustainable yield potential. *Australian Cotton Grower*, **26**(7): 6–10.
- Corbeels, M., Chirat, G., Messad, S. and Thierfelder, C., 2016. Performance and sensitivity of the DSSAT crop growth model in simulating maize yield under conservation agriculture. *European Journal of Agronomy*, **76**: 41–53.
- Cuculeanu, V., Tuinea, P. and Balteanu, D., 2002. Climate change impacts in Romania: Vulnerability and adaptation options. *Geol J*, **57**: 203–209.
- Dhungana, P., Eskridge, K.M., Weiss, A. et al., 2006. Designing crop technology for a future climate: An example using response surface methodology and the CERES-Wheat model. *Agricultural Systems*, **87**: 63–79.
- Directorate of Cotton Development (GOI), 2017. Status Paper of Indian Cotton, January 2017, Ministry of Agriculture and Farmers Welfare, Department of Agriculture, Cooperation and Farmers Welfare (DAC & FW), Government of India, 1999 (Report Number 1. Retrieved on Mar 2019 from <https://www.nfsm.gov.in/StatusPaper/Cotton2016.pdf>
- Dockerty, T., Lovett, A., Appleton, K. et al., 2006. Developing scenarios and visualisations to illustrate potential policy and climatic influences on future agricultural landscapes. *Agriculture, Ecosystems & Environment*, **114**: 103–120.
- Dockerty, T., Lovett, A. and Sunnenberg, G., 2005. Visualising the potential impacts of climate change on rural landscapes. *Computers, Environment and Urban Systems*, **29**: 297–320.
- Doorenbos, J. and Pruitt, W.D., 1977. Guidelines for predicting crop water requirements. Food and Agriculture Organization of the United Nations, Rome. Irrigation and Drainage Paper No. 24.
- Gbetibouo, G. and Hassan, R., 2005. Economic impact of climate change on major South African field crops: A Ricardian approach. *Global and Planetary Change*, **47**: 143–152.
- Gur, A., Osorio, S., Fridman, E., Fernie, A.R. and Zamir, D., 2010. hi2-1, A QTL which improves harvest index, earliness and alters metabolite accumulation of processing tomatoes. *Theoretical and Applied Genetics*, **121**(8): 1587–1599.
- Harle, K.J., Howden, S.M. and Hunt, L.P., 2007. The potential impact of climate change on the Australian wool industry by 2030. *Agricultural Systems*, **93**: 61–89.
- Hatfield, J.L. and Prueger, J.H., 2015. Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, **10**: 4–10.
- Hoogenboom, G., 2000. Contribution of agrometeorology to the simulation of crop production and its applications. *Agricultural and Forest Meteorology*, **3**: 137–157.
- Hoogenboom, G., Jones, J.W., Wilkens, P.W., Porter, C.H., Boote, K.J., Hunt, L.A., Singh, U., Lizaso, J.L., White, J.W., Uryasev, O., Ogoshi, R., Koo, J., Shelia, V. and Tsuji, G.Y., 2015. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.6.1. (www.DSSAT.net) DSSAT Foundation, Prosser, Washington, USA.
- Howden, S.M. and O'Leary, G.J., 1997. Evaluating options to reduce greenhouse gas emissions from an Australian temperate wheat cropping system. *Environ Modell Software*, **12**: 169–176.
- Islam, S., Cenacchi, N., Sulser, T.B., Gbegbelegbe, S., Hareau, G., Kleinwechter, U. and Wiebe, K., 2016. Structural approaches to modeling the impact of climate change and adaptation technologies on crop yields and food security. *Global Food Security*, **10**: 63–70.
- Jalotaa, S.K., Sood, C.A., Butterb, G.S., Sidhua, S. and Sharmac, P.K. (2009). Simulating the effect of temperature on growth and yield of Bt cotton under semi-arid conditions of Punjab, India. ISPRS Archives XXXVIII-8/W3 Workshop Proceedings: Impact of Climate Change on Agriculture.
- Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh,

- U., Gijsman, A.J. and Ritchie, J.T., 2003. The DSSAT cropping system model. *Eur. J. Agron.*, **18**: 235–265.
- Jones, J.W., He, J., Boote, K.J., Wilkens, P., Porter, C.H. and Hu, Z., 2011. Estimating DSSAT cropping system cultivar-specific parameters using Bayesian techniques. Methods of introducing system models into agricultural research. ACSESS DL Pub., 365–394. ISBN: 978-0-89118-196-5
- Kang, Y., Khan, S. and Ma, X., 2009. Climate change impacts on crop yield, crop water productivity and food security – A review. *Progress in Natural Science*, **19(12)**: 1665–1674.
- Krause, P.F. and Flood, K.L., 1997. Weather and Climate Extremes (No. TEC-0099). Army Topographic Engineering Center Alexandria Va.
- Lal, R., 2005. Climate change, soil carbon dynamics, and global food security. In: Lal, R., Stewart, B., Uphoff, N. et al. (eds), *Climate Change and Global Food Security*. Boca Raton (FL): CRC Press.
- Lawlor, D.W. and Mitchell, R.A.C., 1991. The effects of increasing CO₂ on crop photosynthesis and productivity: A review of field studies. *Plant, Cell & Environment*, **14(8)**: 807–818.
- Lexer, M.J., Honninger, K. and Scheifinger, H., 2002. The sensitivity of Austrian forests to scenarios of climatic change: A large-scale risk assessment based on a modified gap model and forest inventory data. *For Ecol Manage*, **162**: 53–72.
- Liyong, Hu, Zhiquang, Lu and Tinglong, Fu, 2007. The effects of sowing date on fatty acid synthesis of rapeseed (*B. napus*. L). In: Proceedings of 12th International Rapeseed Congress. Wuhan, China. March 26–30.
- Luo, Q., Bange, M. and Clancy, L., 2014. Cotton crop phenology in a new temperature regime. *Ecological Modelling*, **285**: 22–29.
- Mathur, S., Agrawal, D. and Jajoo, A., 2014. Photosynthesis: Response to high temperature stress. *Journal of Photochemistry and Photobiology B: Biology*, **137**: 116–126.
- Myneni, R.B., Ramakrishna, R., Nemani, R. and Running, S.W., 1997. Estimation of global leaf area index and absorbed PAR using radiative transfer models. *IEEE Transactions on Geoscience and Remote Sensing*, **35(6)**: 1380–1393.
- National Cotton Council of America (US), 1999. Cotton Physiology Today. United States, <https://www.cotton.org/tech/physiology/cpt/plantphysiology/upload/CPT-v10No2-99-REPOP.pdf>
- Pettigrew, W.T., 2002. Improved yield potential with an early planting cotton production system. *Agronomy Journal*, **94(5)**: 997–1003.
- Popova, Z. and Kercheva, M., 2005. CERES model application for increasing preparedness to climate variability in agricultural planning-risk analyses. *Phys Chem Earth*, **30**: 117–124.
- Pouresia, M. and Nabipour, M. 2007. Effect of planting date on canola phenology, yield and yield components. In: Proceedings of 12th International Rapeseed Congress. Wuhan, China. March 26–30.
- Rauff, K.O. and Bello, R., 2015. A review of crop growth simulation models as tools for agricultural meteorology. *Agricultural Sciences*, **6(9)**: 1098.
- Reddy, K.R., Hodges, H.F. and McKinion, J.M., 1997. Crop modeling and applications: A cotton example. *Advances in Agronomy*, **59**: 226–290.
- Reddy, K.R., Hodges, H.F., McCarty, W.H. and McKinion, J.M., 1996. Weather and cotton growth: Present and future. Vol. 1061. MSU-MAFE.
- Reddy, K.R., Vara Prasad, P.V. and Kakani, V.G., 2005. Crop responses to elevated carbon dioxide and interactions with temperature: Cotton. *Journal of Crop Improvement*, **13(1-2)**: 157–191.
- Reddy, K.R., Davidonis, G.H., Johnson, A.S. and Vinyard, B.T., 1999. Temperature regime and carbon dioxide enrichment alter cotton boll development and fibre properties. *Agron. J.*, **91**: 851–858.
- Reddy, V.R., Baker, D.N. and Hodges, H.F., 1991. Temperature effect on cotton canopy growth, photosynthesis and respiration. *Agron. J.*, **83**: 699–704.
- Ruiz-Vera, U.M., Siebers, M.H., Jaiswal, D., Ort, D.R. and Bernacchi, C.J., 2018. Canopy warming accelerates development in soybean and maize, offsetting the delay in soybean reproductive development by elevated CO₂ concentrations. *Plant, Cell & Environment*, **41(12)**.
- Saseendran, S.A., Singh, K.K., Rathore, L.S., Singh, S.V. and Sinha, S.K., 2000. Effects of climate change on rice production in the tropical humid climate of Kerala, India. *Climatic Change*, **44(4)**: 495–514.
- Schlenker, W. and Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to yields under climate change. *Proc. Natl. Acad. Sci. USA*, **106**: 15594–15598.
- Shih, C.C., Chang, T.B. and Chiang, S.S., 1993. Study on Evapotranspiration Coefficient of Corn. Effects of Agriculture and Agriculture on the Pacific Ocean and the Pacific Region (1993.05).
- Shikha, A., Maharana, P., Singh. K.K., Dimri, A.P. and Niwas, R., 2018. A modeling case study of cotton crop in changing climate. *Current Science*, **115(5)**, 10 September 2018.
- Shikha, A., Dimri, A.P., Singh, K.K., Singh, P.K., Rana, M. and Gohain, G.B., 2018. A model based case study of impact of weather on different cultivars of Bt Cotton and sowing dates. *Vista International Journal on Energy, Environment & Engineering*, **4**: 20–28.
- Singh, R., Shekhar, C., Singh, D. and Rao, V.U.M., 2008. Characterization of energy use by cotton and wheat crops. *Journal of Agrometeorology*, (**Special issue–Part 1**): 127–130.
- Singh, S., Butter, G.S. and Singh, S., 2007. Heat use efficiency of Bt cotton cultivars in the semi-arid region of Punjab. *Journal of Agrometeorology*, **9(1)**: 122–124.
- Singh, S., Singh, P., Buttar, G.S. and Bains, G.S., 2008.

- Evaluation of cotton genotypes for their performance during spring summer season. *Journal of Agrometeorology*, **10**: 82–85.
- Singh, D., Singh, M., Singh, R. and Singh, S., 2014. Climatic variability and its periodicity at Hisar, Haryana. Technical Bulletin #19.
- Swami, P., Maharshi, A. and Niwas, R., 2016. Effect of Weather Variability on Phenological Stages and Growth Indices in Bt-cotton under CLCuD Incidence. *Journal of Pure and Applied Microbiology*, **10**(2).
- Thorp, K., Ale, S., Bange, M., Barnes, E., Hoogenboom, G., Lascano, R. and Rajan, N., 2014. Development and application of process-based simulation models for cotton production: A review of past, present, and future directions agronomy and soils. *J. Cotton Sci.*, **18**: 10–47.
- Tripathi, M.K., 2005. Quantification of micrometeorological variations in Indian mustard under different growing environments. Ph.D. Thesis., CCS HAU, Hisar.