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Yield and water productivity of *Bt* cotton (*Gossypium hirsutum*) as influenced by temperature under semi-arid conditions of north-western India: field and simulation study

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ABSTRACT

Cotton cultivation in semi-arid region of Indian Punjab is considered as most risky crop as its yield is very sensitive to weather parameters like rain and temperature. In future due to global warming increase in the temperature is expected, which is most likely to influence the growth and yield of this fiber crop like other cereal crops. Studies on the effect of temperature on the growth and seed yield of *Bt* cotton in this region are lacking. The present 2-year field and 15-year simulation studies concern to simulate the effect of temperature on duration of pheno-phases and seed yield of *Bt* cotton hybrid RCH 134 and also on crop water productivity. Simulations were run for 15 years (1991–2005) using the already customized CropSyst model. The simulated results indicated that with increase in temperature from 28 to 32°C, cotton seed yield was reduced to half (from 4 700 to 2 300 kg/ha) following a linear relation with high coefficient of determination (0.97), and the reduction was more with increased temperature during sowing to flowering stage than other pheno-phases. Total evapo-transpiration (ET) during crop period and crop water productivity was also decreased with increased temperature. Relationship of cotton seed yield was linear with ET and quadratic with total water supply (rain +irrigation). Real crop water productivity (yield/ET) and apparent crop water productivity (yield/irrigation water) were 0.362$\pm$0.129 and 0.485$\pm$0.120 kg/m^3, respectively.

Key words: *Bt* cotton, Evapotranspiration (ET), Pheno-phases, Seed cotton yield, Temperature, Water productivity

Cotton (*Gossypium hirsutum* L.), the king of fibres, is one of the most important commercial cash crops of semi-arid region of Indian Punjab. Its cultivation on 5.31 lakh ha during 2010 in this region provides the full potential to offer livelihood security to millions of farmers. Area wise, India ranks first in global scenario (about 20 % of the world cotton area) but with regard to production, it is ranked second, next to china. Temporally, cotton production in India has increased from a meager 2.79 million bales (170 kg lint/bale) in 1947–48 to as high as 3.15 million bales during 2007–08 (AICCIP 2008). This record production was expected due to the favourable weather condition (with mean minimum and maximum temperatures, rainfall and solar radiation of 22°C, 35°C, 486 mm and 4403 MJ/m^2, respectively) and introduction of *Bt* cotton hybrids. More yield of *Bt* cotton than traditional varieties has been reported by Alse and Jadhav (2010). It is considered as most risky crop as its yield is sensitive to temperature (Reddy *et al*. 1999). In a review, Sankaranaryanan *et al*. (2010) reported that at high temperature cotton plants loose their reproductive capacity to a greater extent than their ability to produce biomass and face problems of cotton sterility and boll retention. However, the effect of high temperature on quality of cotton crop is controversial (Pettigrew 2007, Hodges *et al*. 1993, Reddy *et al*. 1999). In future, due to global warming temperature is likely to be increased. According IPCC 4th Assessment Report (2007), average global air warming of 1.8°C can occur in the low scenario (B_1) and 4°C in the high scenario (A_1F_1) by the end of the 21st century. Increased temperature may influence the plant growth, seed cotton yield, evapo-transpiration and crop water productivity. At present, no study is available that shows the quantitative effect of increased temperature on pheno-phases and yield of the *Bt* cotton in this region. Generation of such information through field experimentation

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is possible only under controlled environmental conditions, which are very expensive. Alternately simulation models are the most powerful tool for such studies to have the conclusive results (Jalota *et al*. 2006). Therefore, the present simulation study using CropSyst model was undertaken with the objectives to quantify: (i) duration of pheno-phases in relation to temperature, (ii) yield in relation to duration of pheno-phases and (iii) evapo-transpiration (ET) and crop water productivity. The cotton crop in Punjab is sown under irrigated condition. The optimum temperature for cotton crop during germination, vegetative growth and fruiting stages is 16, 21–27 and 27–32 ºC. It can tolerate temperature of 43ºC and less than 21ºC is undesirable (Lenka 1998). In south western region of Punjab (at Bhatinda) during the last 20 years (from 1986 to 2006), temperature remained higher by 0–1.4^{0}C in 9 years than that of average (28.7ºC); and rainfall was less by 76–314 mm than the average (486 mm) in eight years. As per HadCm3 model in 2020, 2050 and 2080 the projected increase in maximum temperature will be by 0.4, 1.5 and 3.2ºC respectively. The corresponding increase in minimum temperature will be 1.5, 3.1 and 5.0ºC respectively.

MATERIALS AND METHODS

Field experiments were conducted during rainy *(kharif)* season of 2004 and 2005 on Entisols, low in organic carbon (0.21%) and nitrogen (41 kg/ha), medium in available phosphorus (13.9 kg/ha) and high in potassium (431 kg/ha) at PAU Regional Station, Bathinda (30º58''latitude, 74º18'' longitude and 211 m above mean sea level). Soil physical (texture, bulk density and hydraulic conductivity) and chemical (pH, EC, OC, ammonical-nitrogen and nitrate-nitrogen) properties of experimental field were determined up to 1.8 m with 0.15 m soil depth interval following the standard procedures. The sand, silt and clay contents were determined with Pipette method (Gee and Bauder 1986), bulk density with core method (Blake and Hartage 1986), hydraulic conductivity with constant head method (Jalota *et al.*1998). EC was measured with solu bridge method and pH with potentiometric method (Jackson 1973), OC by wet digestion method (Walkley and Black 1934). Ammonical and nitrate nitrogen were determined by Kjeldahal method (Keeney 1982). The ground water at the experimental site was more than 10 m deep. Daily weather data on maximum and minimum temperature, maximum and minimum relative humidity, wind speed and rainfall during the crop growth period were recorded at meteorological observatory, situated at the experimental site.

A pre-sowing irrigation of 100 mm was applied on 16 April and 18 April during 2004 and 2005, respectively. When water content in surface soil dried to field capacity field was prepared with two disking,followed by two planking and plots of size 29.1m^2 (7.2m × 4m) were made. Earthen dikes of 30 cm height surrounding all plots were made to check run off /gain by irrigation or rainwater. *Bt* cotton hybrids RCH 134, RCH 317, MRC 6301,Ankur 651, Ankur 2534 were sown on 22 and 23 April during 2004 and 2005 respectively. The crop was sown at a spacing of 67.5 cm × 90 cm distance. Nitrogen @ 150 kg/ha and P_2O_5 @ 30 kg /ha were applied to the crop. Entire phosphorus was applied at the time of sowing of the crop, whereas half the nitrogen was applied at the time of first irrigation (4 June) and remaining half at flowering stage of the crop (9 September) in both the years. Weeds were controlled with pre-emergence application of Stomp 30 EC (pendimethalin) @ 2.5 l/ha. Two sprays of imidachlorpid @ 100 ml/ha were applied for controlling of sucking pests. Four irrigations of 75mm each on 4 June, 18 July, 19 September and 30 September were applied. Plant phenological stages and climatic factors were recorded during the crop season. The crop was harvested on 11 Nov in both years of the study.

Description of the CropSyst model

CropSyst model was chosen as it is a process based, simple, multi-year, multi-crop, daily time step cropping system simulation model and also has already been calibrated with the data of two independent experiments (Jalota *et al.* 2008 and Prahraj 1991) and is shown in Fig 1. The observed and simulated yields matched closely having coefficient of correlation of 0.94.The model is designed to study the effect of soil, climate and crop/cropping system management on crop productivity and water balance (Stockle *et al*. 1994). Simulations were made by selecting a location and soil, and building crop file with management schedule. The location parameters included longitude, latitude, weather files and ET models. The soil parameters included specification of soil layers, thickness, texture, bulk density, cation exchange capacity, *p*H, volumetric water content at water potentials of –30 kPa (field capacity) and –1500 kPa (wilting point). The

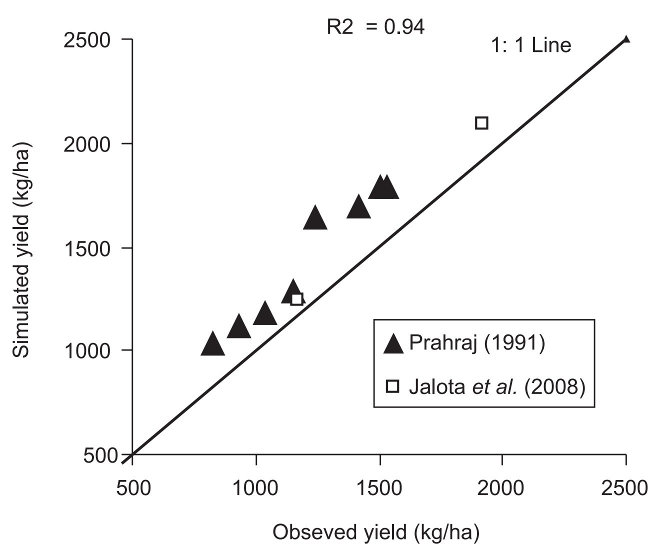

Fig 1 Comparison of observed and CropSyst model-simulated seed cotton yield

management options in the model included cultivar selection, irrigation, nitrogen fertilization, tillage operations and residue management. The crop file comprised common set of parameters related to classification, growth, morphology and phenology of the crop to represent different crops and crop cultivars. Model outputs taken were duration of different pheno-phases, daily evapo-transpiration (ET) and seed cotton yield at the end of the experiment.

The calibrated CropSyst model was validated on yield of cotton using the observed phenological parameters (flowering, boll formation and physiological maturity) and harvest (harvest index) of the *Bt* crop from the experiment. The other parameters for the crop file were taken as default with slight adjustments. These adjustments were made within the range from the experience or reported elsewhere (Jalota *et al*. 2006) so that the periodic crop growth like phenological stages, periodic biomass production and final grain yield were matched with the experimentally observed values. The crop parameters used in the model are given in Table 1. During the first step simulated phenological stages (germination, flowering and physiological maturity) were matched with the observed by adjusting the degree days. The observed degree-days were 1 400 for beginning of flowering, 2 400 for boll formation and 2 750 for physiological maturity, respectively. Soil file for the experimental site was prepared using the actually observed data (at the start of the experiment) on soil texture, bulk density and hydraulic conductivity, EC, *p*H, OC, ammonical-nitrogen and nitrate-nitrogen, which are given in Table 2. Location file was prepared from the weather parameters of rainfall, maximum temperature, minimum temperature, maximum and minimum relative humidity and wind speed actually recorded at the station. The solar radiation data used from 1991 to 1996 was the observed and for the rest of the years was the generated with ClimGen model (Stockle and Nelson 1999). In a separate study it has been found that ClimGen model generates solar radiation close to the observed in different climatic situations in Punjab (Bal *et al.* 2008). The crop management file for cotton crop was also prepared from the management operations performed on different dates in the experiment. The prediction capability of the model was evaluated by root mean square error (RMSE) using the equation (1):

$$RMSE=\frac{\left[\sum_{i=1}^{n}(P_i-O_i)^2/n\right]^{0.5}}{\overline{O}} \quad (1)$$

where Pi and Oi are the predicted and observed values, respectively, Ô is the average of the observed data, and n is the number of observations. The value equal to zero for a model showed perfect fit between the observed and predicted data.

Simulations

Simulations were run for 15 years from 1991to 2005 to

Table 1 Crop parameters (estimated from the experiments, standard calibrated) used in validation for different crops

Crop parameter	Cotton	Unit
Classification		
Land use	Row crop	
Photosynthetic path	C3	
Growth		
Above ground biomass-transpiration coefficient	8.5	K Pa Kg/m^2
Light to above ground biomass conversion	3.6	g/ MJ
Actual to potential transpiration ratio that limit leaf area growth	0.20	
Actual to potential transpiration ratio that limit root growth	0.20	
Optimum mean daily temp. for growth	27.5	°C
Maximum water uptake	10	mm /day
Leaf water potential at the onset of stomatal closure	–1000	J/Kg
Wilting leaf water potential	–1500	J/Kg
Morphology		
Maximum rooting depth	1.80	m
Initial leaf area index	0.011	m^2/m^2
Maximum expected leaf area index	4.0	m^2/m^2
Fraction of maximum leaf area index at physiological maturity	0.70	
Specific leaf area	10.0	m^2/ Kg
Stem/leaf portioned coefficient	0.80	
Leaf duration (degree days)	2100	°C- days
Extinction coefficient for solar radiation	0.50	
Leaf duration sensitivity to water stress	1.0	
ET crop coefficient at full maturity	1.0	
Phenology		
Degree days emergence	100	°C- days
Degree days peak leaf area index	1400	°C- days
Degree days begin flowering	1400	°C- days
Degree days boll formation	2400	°C- days
Degree days physiological maturity	2750	°C- days
Base temperature	21.0	°C
Cut-off temperature	45.0	°C
Phenological sensitivity to water stress	2.0	
Harvest		
Harvested part	Cotton-seed	
Unstressed harvest index	0.23	
Translocation of grain factor	0.30	
CO_2		
Baseline reference atmospheric CO_2 concentration	350	ppm

Table 2 Physical and chemical properties of the soil profile of the experiment site

Depth(cm)	Sand (%)	Silt (%)	Clay(%)	Bulk density (Mg /m^3)	Hydraulic conductivity (mm /hr)	*p*H	EC (dS/m)	OC %
0–15	80.0	12.5	7.5	1.58	8.7	8.8	0.366	0.420
15–30	92.5	5.0	2.5	1.58	39.3	8.9	0.284	0.315
30–45	81.3	10.0	8.8	1.54	36.9	8.7	0.311	0.120
45–60	72.5	17.5	10.0	1.55	4.7	8.5	0.332	0.150
60–75	72.5	17.5	10.0	1.49	32.9	8.5	0.229	0.105
75–90	68.8	20.0	11.3	1.59	12.8	8.8	0.303	0.090
90–105	72.5	17.5	10.0	1.72	2.60	8.8	0.297	0.405
105–120	70.4	17.5	12.2	1.73	4.6	8.7	0.379	0.240
120–135	71.6	18.8	9.7	1.75	1.9	8.5	0.372	0.210
135–150	69.1	20.0	10.9	1.73	2.1	8.6	0.369	0.210
150–165	51.6	31.3	17.2	1.81	0.7	8.7	0.342	0.150
165–180	37.9	42.5	19.7	1.75	1.2	8.7	0.310	0.075

assess the effects of temperature on phenology, evapotranspiration, seed cotton yield and crop water productivity. Real crop water productivity (RCWP) and apparent crop water productivity (ACWP), as reported in the literature (Jalota *et al*. 2006), were estimated as:

RCWP = marketable seed cotton yield/ evapotranspiration (kg/ m^3) (2)

ACWP = marketable seed cotton yield/irrigation water applied (kg /m^3) (3)

RESULTS AND DISCUSSION

The seed cotton yields of five *Bt* hybrids varieties (RCH 134, RCH 317, MRC 6301, MRCH 6304, Ankur 651 and Ankur 2534) were simulated with the CropSyst model by inputting the observed data on duration of different pheno-phases (Buttar *et al*. 2007) during 2004 and 2005 under field conditions. The data is presented in Table 3. The simulated yields of these varieties were closer to the observed seed cotton yield as is evident from the only 3.6% RMSE, irrespective of variety. It gave a confidence that the model can be used for simulating the effects of temperature on duration of phenological phases and subsequently cotton seed yield.

Relationship between duration of phenol-phases and temperature

From the simulated results of 15 years, data for mean temperature in °C (T) and duration of each crop growth stage in days (D) as well as cotton seed yield in kg/ha (Y) were taken for each year (from 1991 to 2005) and quantitative relationships between temperature, duration of different pheno-phases and cotton seed yield were developed. The relationships and coefficient of determination (R^2) were:

Sowing to flowering

D= -4.02 T+289.18 R^2 = 0.93 Y = 153.83 D+8716.9 R^2 = 0.91

Flowering to boll formation

D= -3.55 T+172.97 R^2 = 0.99 Y = 9.18 D^2 + 271.1 D- 4030.7 R^2 = 0.97

Boll formation to physiological maturity

D= -2.73 T+194.16 R^2 = 0.99 Y =100.16 D+277.9 R^2 = 0.909

Total crop period

D= -10.52 T+489.87 R^2 = 0.97 Y = 1.00D^2 + 419.22 D- 38952 R^2 = 0.92

Cotton is considered as warm season crop. It requires optimum temperature of 21–27°C for vegetative growth,

Table 3 Phenology and seed cotton yield of different *Bt* cotton hybrids during 2004 and 2005

Bt hybrid	Days to emergence		Days to squaring		Days to flowering		Days to boll formation		Days to physiological maturity		Seed cotton yield (kg/ha)	
	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005
RCH 134	7.8	8.0	52.0	53.0	85.2	86.0	147.2	149.0	173.3	175.0	2 990	3 150
RCH 317	7.2	7.3	50.0	51.0	75.0	77.0	127.1	129.0	149.7	150.0	2 340	2 383
MRC 6301	6.9	7.0	46.1	47.0	61.3	63.0	112.5	112.0	142.5	143.0	2 280	2 268
MRC 6304	7.0	7.0	47.2	48.0	69.2	70.0	119.1	120.0	149.5	151.0	2 815	2 904
Ankur 651	7.0	7.0	46.1	47.0	56.7	58.7	126.5	127.0	153.5	155.0	2 490	2 503
Ankur 2534	6.5	6.3	49.2	50.0	62.3	64.0	124.9	126.0	156.0	157.0	2 390	2 304
LSD (*P*=0.05)	NS	NS	NS	NS	5.1	5.5	3.4	3.5	4.4	4.9	291	317

25°C for stimulating flowering (Mauney 1966) and 27–32°C during flowering to fruiting stage (Lenka 1998). The simulation results showed that with increase in temperature duration of different stages are shortened. The shortening of duration from sowing to vegetative phase, flowering to boll formation and from boll formation to maturity was 3.2, 3.0 and 2.9 days/°C, respectively. Reddy *et al.* (1999) also reported decrease in maturation period of bolls and their size with increase in temperature. With increase in temperature from 28 to 32°C the total crop duration was shortened by 10.7 days/°C. With shortening of durations of sowing to flowering by 14 days, flowering to boll formation by nine days, boll formation to maturity by 21 days and sowing to maturity by 45 days the cotton seed yield was reduced by 236, 140, 116 and 75kg /ha/ day, respectively. These results are in line with the results of Rosenzweig and Hillel (1998), which indicate that with increase in temperature, crop productivity is decreased owing to shortened duration of different growth stages and subsequently crop growth period. In the literature it is reported that relatively small change in annual temperature in semi-arid regions could markedly decrease in yield by reducing dry matter accumulation because of increased respiration, reduced photosynthesis and cellular energy (Abrol and Ingram 2006) and by causing boll abscission (Reddy *et al.* 1999).

Temperature and crop water productivity

With increase in temperature evaporative demand is increased due to increased vapour pressure gradient (Jalota and Prihar 1998, Goyal 2004). But actual ET may decrease due to decreased duration of the crop. In the present study with increase in temperature from 28.0 to 31.8 relative ET and yield were reduced to 0.78 and 0.43, respectively (Figure 2) This indicates that both the components of crop water productivity are decreased with temperature, but relative reduction was more in yield component that caused reduction in crop water productivity. Total water supply (rain + irrigation) to the crop was from 600 to 1200 mm. The relationship of cotton seed yield was found to be linear with evapotranspiration (Fig 3) and quadratic with water supply (Fig 4). Yield increased with water supply up to 900 mm and decreased there after. The RCWP and ACWP were 0.362 ±0.129 and 0.485±0.120 kg/m^3. These values are of the same range as indicated by Jalota *et al.* (2006) and Zwart and Bastiaanssen (2004). Water productivity based on total water supply was 0.120± 0.049 kg/ m^3.

CropSyst model can be used for assessing the effect temperature on duration of phenol-phases and subsequent yield of cotton crop. Yield decreased with temperature due to decrease in duration of pheno-phases and total growth period of the crop. Crop water productivity decreased with temperature mainly through its effect on yield.

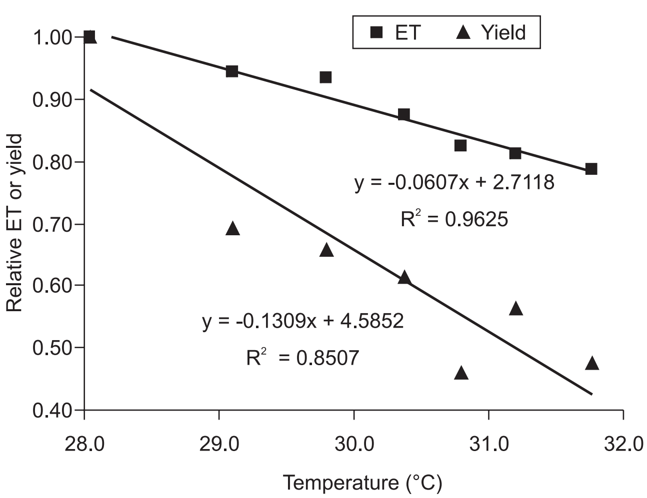

Fig 2 Evapotranspiration and seed cotton yield of *Bt* cotton as influenced by temperature

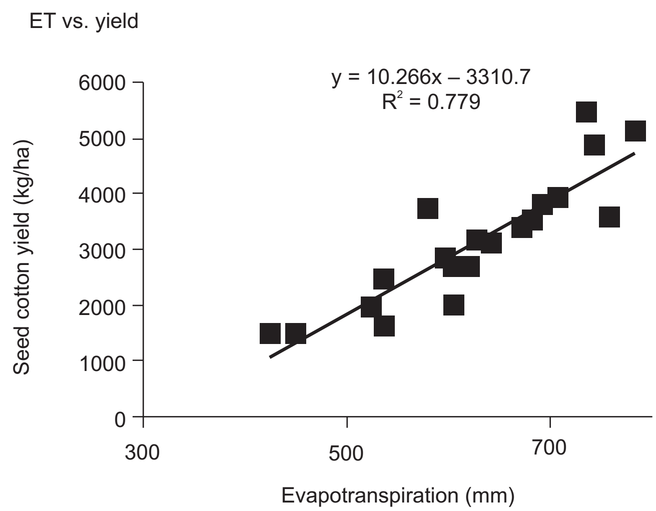

Fig 3 Seed cotton yield and evapotranspiration relationship

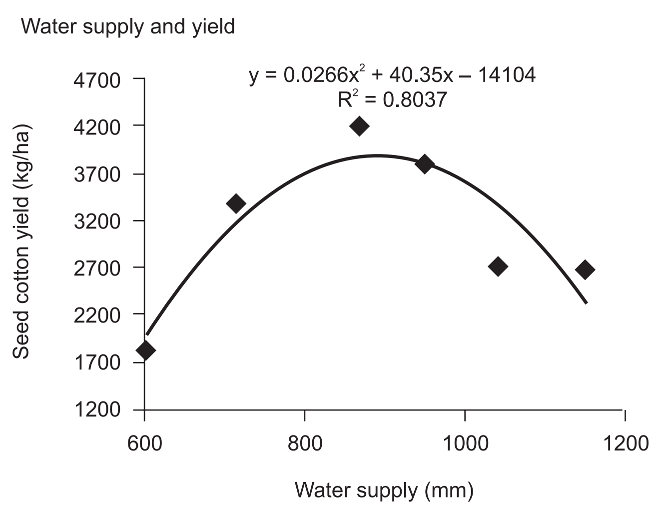

Fig 4 Seed cotton yield of *Bt* cotton and water supply relationship

REFERENCES

Abrol Y P and Ingram K T. 2006. Effects of higher day and night temperatures on growth and yield of some crop plants (*in*) *Global Cilamte Change and Agricultural Production,* pp 1–19. Fakhri, Bazzaz and Wim Somroek (Eds). John Wiley & Sons Ltd, Baffins Lane, Chichester, West Sussex PO 19 IUD, England.

Alse U N and Jadhav A S .2010. Agronomic efficiency of Bt and non Bt cotton hybrids under irrigated conditions. *Journal of Cotton Research and Development*.**25** (1): 38–41.

AICCIP 2008. *Annual Rreport.* All India Coordinated Cotton Improvement Project. ICAR New Delhi.

Bal S K, Choudhury B U, Sood A and Jalota S K. 2008. Evaluation of Climgen model to generate weather parameters under different climatic situations in Punjab. *Journal of Agrometeorology* **10**: 39–45.

Blake G R and Hartage K H.1986. Bulk density (*in*) *Methods in Soil Analysis,* Part 1, pp 363–75. Klute A (Ed.). Agronomy No 9 WI. American Society Agronomy, Madison.

Buttar G S, Singh S and Singh S. 2007. Phenology and quality of different recommended *Bt* hybrids of American cotton (*Gossypium hirsutum*, L) cultivated in Punjab. *Journal of Cotton Research and Development* **21**: 55–7.

Gee, CW and Bauder J W 1986. Particle size analysis (*in*) *Methods in soil analysis,* Part 1, pp 383–411. Klute A (Ed.) Agronomy No 9 WI. American Society Agronomy, Madison.

Goyal R K. 2004. Sensitivity of evapotranspiration to global warming: a case study of arid zone of Rajasthan (India). *Agricultural Water Management* **69**: 1–11.

Hodges H F, Reddy K R, Mckinion J M and Reddy V R. 1993. *Temperature Effects on Cotton*. Department of Information Services, Division of Agriculture, Forestry and Veterinary Medicine,Mississippi State University.

Jackson M L. 1973. *Soil Chemical Analysis,* pp 38–56 and 234–46. Prentice-Hall of India, Private Ltd, New Delhi.

Jalota S K, Buttar G S, Sood A, Chahal G B S , Ray S S and Pangrahy S. 2008. Effects of sowing date, tillage and residue management on productivity of cotton (*Gossypium hirsutum* L.)–wheat (*Triticum aestivum* L.) system in northwest India. *Soil & Tillage Reserach* **99**: 76–83.

Jalota S K, Khera R and Ghuman B S. 1998. *Methods in Soil Physics,* pp 91–3. Narosa Publishing House, New Delhi.

Jalota S K and Prihar S S. 1998. *Reducing Soil Water Evaporation by Tillage and Straw Mulching,* pp 7–31. Iowa State University Press, Ames, USA

Jalota S K, Sood A, Chahal G B S and Choudhary B U. 2006. Crop water productivity of cotton (*Gossypium hirsutum* L.) – wheat (*Triticum aestivum* L.) system as influenced by deficit irrigation, soil texture and precipitation. *Agricultural Water Management* **84**: 137–46.

Keeney D R. 1982. Nitrogen availability indices. (*in*) *Methods of Soil Analysis,* Part 2, 2nd edn, pp 711–30, A l (Ed.) American Society Agronomy, Madison. WI.

Lenka D. 1998. *Climate, Weather and Crops in India.,* pp 84. Kalyani Publishers, Ludhiana, New Delhi, Noida, Hyderabad, Chennai, Calcutta and Cuttack.

Mauney J R . 1966. Floral initiation of upland cotton (*Gossypium hirsutum* L.) in response to temperature. *Journal of Experimental Botany* **17**: 452–9.

Pettigrew WT 2007. High temperature effects on cotton yield, yield components and fibre quality ASA-CSSA-SSSA Annual Meeting, *Abstracts,* 261pp

Prahraj, C S. 1991. 'Irrigation and nitrogen management of American cotton (*Gossypium hirsutum* L.)'. M Sc thesis, Punjab agricultural University, Ludhiana-India.

Reddy R K , Gayel Davidonis H , Johnson A S and Vinyard B T . 1999. Temperature regime and carbon dioxide enrichment alter cotton boll development and fiber properties. *Agronomy Journal* **91**: 851–8.

Rosenzweig C and Hillel D. 1998 *Climate Change and the Global Harvest*. Oxford University Press, UK.

Sankaranaryanan K, Praharaj C S, Nalayani P, Bandyopadhyay K K and Gopalakrishanan N. 2010. Climate change and its effect on cotton (*Gosssypium* sp.) *Indian Journal of Agricultural Sciences* **80**: 561–75

Stockle C O, Martin S A and Campbell G S. 1994. CropSyst a cropping system simulation model: Water/nitrogen budgets and crop yield. *Agricultural Systems* **46** 335–59.

Stockle C O and Nelson R. 1999. *ClimGen, Manual,* 28 pp. Biological Systems Engineering Department, Washington State University, Pullman, WA.

Walkley A and Black C A 1934. An examination of the digestion method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* **37**: 29–38.

Zwart S J and Bastiaanssen W G M. 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management* **69**: 115–33.