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Climate change and its impact on cotton (*Gossypium* sp.)

K SANKARANARAYANAN[1], C S PRAHARAJ[2], P NALAYINI[3], K K BANDYOPADHYAY[4] and
N GOPALAKRISHNAN[5]

Regional Station, Central Institute for Cotton Research, Coimbatore, Tamil Nadu 641 003

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ABSTRACT

The earth temperature has increased by 0.74°C during the last century (1906 to 2005) due to increase in greenhouse gases through anthropogenic emissions as reported by IPCC. Thus, the increase in temperature is likely to be 1.8–4.0°C by the turn of 21st century resulting in anticipated greater instability in food, feed and fibre production. Increase in temperature can reduce crop duration, change pest populations, hasten mineralization in soils and increase evapotranspiration. It is reported that 40 and 50% less biomass is anticipated in cotton (*Gossypium* sp.) at 20/10°C and 40/30°C, respectively, with optimum temperature of 30/20°C. However, increase in atmospheric CO_2 increases the quantum of yield produced photosynthetically, net photosynthesis, biomass production and ultimate output. Besides higher output, increasing inputs-use efficiency in cultivated crops is also realized and the same at much greater pace in C_3 plants (cotton). Study showed that increase in seed cotton yield up to 43% was realized at elevated CO_2 of 550 ppm throughout the crop-growing period. Severe sucking pest problem and dominance of weeds are expected in cotton. Thus, in total, elevated CO_2 favours cotton growth and yield but higher temperature influences these negatively. The effect of climate change on national cotton production system interpreted that increasing CO_2 concentration could help to increase cotton production in all the 3 zones. However, increasing precipitation with decreasing temperature may prolong the vegetative growth and extend the crop duration, which pose difficulties in timely sowing of succeeding *rabi* crops in north zone. The expected increasing of temperature, decreasing rainfall with erratic distribution in central and south zone leads to frequent wet and dry spell with high evapotranspiration demands. Prolonged dry spell during critical crop growth periods may affect yield. The projected waterlogging coupled with drought by increasing intensity of rainfall may further induce reddening in *Bt* cotton. Shortening of crop growth periods induced by increasing temperature may facilitate to fit cotton crop into rice (*Oryza sativa* L.)–fallow cotton system in south zone.

Cotton belongs to the C_3 plant, which releases CO_2 during photorespiration. High external input and overuse of N fertilizers lead to more emission of nitrous oxide. The mitigation strategies should aim to reduce inorganic inputs utilization with more emphasis to nitrogen includes following of integrated nutrient management practice, use of N-fixing *Azotobacter* and *Azospirillum*, legumes rotation, application of slow-release nitrogenous fertilizers, adoption of drip-fertigation, incorporation of cotton stalk could reduce fertilizer nitrogen usage. It is evident that application of farmyard manure, mulching greengram (*Vigna radiata* L. Wilczek), glyricidia sp. and sunnhemp (*Crotolaria juncea* L.) as green manure recorded 15–32% increase in yield over control and there was considerable build-up of soil available nutrients.

Cotton crops grown in future environments will be subjected to a climate for which they are not bred. Cotton species of *G. barbadense* showed more sensitive than *G. hirsutum*. *G. arboreum* is suitable for low and erratic rainfall with drought situations. In saline environment *G. herbaceum* showed better adaptability. The available drought tolerance *hirsutum* genotypes, like 'LRA 5166', 'KC 2' and 'AKH 081' may show better adaptation. The risk and uncertainty imposed by climate change could be managed by adoption of location-specific intercropping and multi-tier cropping system. *In situ* soil moisture conservation techniques include contour bunding, graded, narrow or broad ridges or beds separated by furrows, ridges and furrow, opening of furrow after every rows of cotton, black polythene mulch (25 microns), and spreads of crop residue were found to be promising

Key words: Adaptation, Climate change, Elevated CO_2, Mitigation, Soil moisture, Temperature, Ultra violet-B radiation

India has achieved the rare distinction in becoming first in acreage of cotton (*Gossypium hirsutum* L.) in the world with 9.5 million ha under plough engaging nearly 5 to 5.5 million farmers. Although India's cotton area represents 25% of the global area, it contributed to only 12% of world production in the past, because our yields were low in

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[1] Senior Scientist (email: sankaragro@gmail.com) (Agronomy), [3] Senior Scientist (email: nalayiniganesh @gmail.com) (Agronomy), [4] Senior Scientist (Soil Science) (email: kk.bandyopadhyay @gmail.com), [5] Project Co-ordinator and Head (email: gopalcotton@gmail.com);

[2] Principal Scientist (email: cspraharaj@gmail.com) (Agronomy), Indian Institute of Pulses Research, Kanpur, Uttar Pradesh 208 024.

comparison to many countries in the world. Cotton is the major cash crop of India as it accounts for 75% of the fibre used in the textile industry with 1 500 spinning mills, thus contributing towards 4% of GDP. Cotton impacts the lives of an estimated 60 million people in India, including farmers who cultivate the crop, and a legion of workers involved in the cotton industry from processing to trading. With such an importance in national economy for providing livelihood security to 60 million people including all the stakeholders of cotton value chain, the climate change and its likely impact on cotton crop is fast gaining momentum.

Reports of Intergovernmental Panel on Climate Change (IPCC 2007) revealed that the earth temperature has already increased by 0.74°C between 1906 and 2005 due to increase in anthropogenic emissions of greenhouse gases. For Indian region under south Asia, the IPCC has projected 0.5–1.2°C rise in temperature by 2020, 0.88–3.16°C by 2050 and 1.56–5.44°C by 2080 depending on the pace in future development scenario. Study showed that global temperature increase might exceed to the extent of 1.8–4.0°C by the turn of 21st century resulting in anticipated greater instability in agricultural (food, feed and fibre) production (Aggarwal 2008). The increase in mean air temperature is influencing reduction of snow cover and discharge of river water. The expected rise in temperature in higher latitudes will be much more than at equatorial regions. Amongst the seasons, the temperature increases are likely to be much higher in winter (*rabi*) season than in rainy (*kharif*) season.

Agriculture contributes about 28% of greenhouse gas emissions, primarily due to methane emission, especially in rice cultivation, enteric fermentation in ruminant animals, and nitrous oxides from application of manures and fertilizers to the soils. Increasing atmospheric concentration of CO_2 at alarming rates (1.9 ppm/year) in recent years than the natural growth rate cause a concern. Although global atmospheric concentration of methane (CH_4) was at 1774 parts/billion (ppb) in 2005 and remained nearly constant thereafter, yet, increase in nitrous oxide concentration to 319 ppb in 2005 from pre-industrial value of about 270 ppb again switch on the alarm (IPCC 2007). Accordingly increase in rainfall commensurating with the global climate change is also expected to be variable. Many dry regions may experience a decrease in precipitation, while some others will become wetter.

Changes in the major independent variables, viz CO_2, temperature and water to the extent that they actually occur may alter plant growth rates, biomass reservoirs and plant community composition at local, regional and global scales.

Elevated Co_2

Of the 4 major greenhouse gases causing a concern regarding the global climate change, CO_2 is by far the most significant one in respect of cotton production. CO_2 in the atmosphere is observed to have increased by about 80 ppm/m^2 of air, since the beginning of the industrial revolution towards the end of the 18th century. The current value is about 379 ppm in 2005 and continued to increase further. This increase in CO_2 has profound implications on global warming and shifts in precipitation at regional and continental scale. In general, increase in atmospheric CO_2 increases the quantum of yield produced photosynthetically, net photosynthesis, biomass production and ultimate output in term of grain, seed, oil and fibre. Besides greater output, higher inputs (light, nutrient and water) use efficiency in cultivated crops are expected to be realized and the same at a much greater pace in C_3 plants (cotton, rice, wheat) over C_4 plants (maize, sugarcane).

In a typical cotton field, the plants will extract about 11.34 tonnes of CO_2/ha to make the fibre (lint), oil (seed), protein (feed) and other plant parts. Out of it, nearly one-tenth that is taken from the air is used to produce cotton fibres and about 0.5 tonnes is extracted to produce some 0.19 tonnes of vegetable oil. In the process, around 7.9 tonnes of O_2 is released back into the atmosphere. Thus more than 450 million tonnes of CO_2 were removed by cotton plants during whole growing season while more than 36.3 million tonnes of CO_2 that removed from the air were used to form the cellulose in the fibre and was bound in fibres for a considerable period of time and most of the CO_2 was deposited back as an amendment to the soil through carbon sequestration (return of carbon). Carbon sequestered in the world cotton fibre supply is equivalent of taking 7.25 million passenger vehicles from the highways (ICAC 2009).

Higher CO_2 concentration increased final leaf size and rate of leaf expansion (Reddy *et al.* 1994). Greater assimilation rate of plants grown in elevated CO_2 enables in incorporating 30% more biomass during the first 36 days of growth. Higher assimilation is due to higher chlorophyll—a concentration following CO_2 enrichment (550 ppm) than ambient condition even under different moisture regimes. Study showed average chlorophyll content was higher both in the wet (7.1%) treatment and dry (8.2%) treatments (Pinter *et al.* 1994b). The results clearly indicated that elevated CO_2 or its enrichment produced higher chlorophyll content and consequently, higher output in cotton plants. The increase in whole plant leaf area with doubling of CO_2 was due to small increases in individual leaf sizes and a large increase in the number of leaves on fruiting and vegetative branches. At 720 ppm of CO_2 enriched atmosphere, the plants had about 40% more squares and bolls across temperatures than the 360 ppm (Reddy *et al.* 1999).Effect of elevated CO_2 on cotton growth and development is more apparent through significantly greater leaf area and higher net photosynthetic rates associated with lower dark respiration and light compensation point than plants grown in ambient CO_2 (Zhao *et al.* 2004).

Cotton plants grown under elevated CO_2 atmosphere fixed 16% more CO_2 than the ambient grown plants (Khader *et al.*

Table 1 Effect of elevated CO_2 and water stress on photosynthetic rate (μmol/m^2/s) in cotton

Treatment		Days after imposition of stress (d)						Mean
		1	2	3	4	5	6	
Elevated CO_2 (650 ppm)	Unstressed	25.1	25.4	24.9	25.6	25.5	24.8	25.2
	Stressed	23.7	24.6	21.5	14.3	7.7	5.2	16.1
Ambient (330 ppm)	Unstressed	21.0	21.4	20.8	21.5	21.8	22.0	21.4
	Stressed	20.5	21.6	18.5	16.7	9.8	6.5	15.5

Source: Khader *et al.* (2004)

2004). At the onset of water stress, the photosynthetic activity declined from the initial level of 24 μ mol CO_2 to a level of 5 μmol CO_2/m^2/s within 6 days (Table 1). Even diurnal changes in photosynthesis rate were also observed under free-air carbon dioxide enrichment (FACE). Mid-day net photosynthesis rates of both leaves and canopies were 19–41% higher in the CO_2-enriched plots than in control plots since mid-day stomatal conductance values of leaves were 13–44% greater in control plants than in CO_2-enriched plants (Hileman *et al.* 1994). There was no effect of CO_2 enrichment on transpiration of crop, grown under well-watered and high-fertility conditions (Dugas *et al.* 1994) although the CO_2 fluxes were significantly higher in the free-air carbon dioxide enrichment (550 ppm) than at ambient level and also higher with wet than dry irrigation level (Nakayama *et al.* 1994).

Biochemical constituents in plants, viz leaf carbohydrate content were also increased by free air carbon dioxide enrichment and the increments were much more pronounced in the stems and roots. Starch and soluble sugars in leaves in free air carbon dioxide enrichment tend to be consistently greater than in control leaves. Thus, the significant effect of CO_2 enrichment on starch-accumulating plants is through increase of non-structural carbohydrate, especially starch, in non-leaf storage pools (Hendrix *et al.* 1994). Although N and protein concentrations in leaves, stems and roots were significantly lower in CO_2 enriched plants than in control, yet C : N ratios were higher for the free-air CO_2 enrichment plants than the control (Huluka *et al.* 1994) and there were no significant effects of interaction involving irrigation and CO_2. Reduction in tissue N and protein concentration and increase in C : N ratio following CO_2 enrichment has important ramifications in agriculture and natural systems.

Physiologically, leaf water relations in a cotton plant under CO_2 enriched environment was also improved (Bhattacharya *et al.* 1994). The atmosphere enriched with 550 ppm during the day light hours under full irrigation produced decreased stomatal conductance leading in increased leaf water potential. Under water stress conditions, free air carbon dioxide enrichment decreased the conductance throughout the season although the effect on leaf water potential is not consistent. Thus, free air carbon dioxide enrichment increased the season long biomass accumulation by 39% under full irrigation and 34% under deficit irrigation. The free air carbon dioxide enrichment treatment improved the water-use efficiency to the same amount in well irrigated and water stress plots. These were confirmed in many studies also (Radin 1992 and Kimball and Mauney 1993).

Free air CO_2 enrichment was also found to increase root dry weight and densities in cotton (Prior *et al.* 1994). Vertical root-pulling resistance, larger diameter taproots, dry weight and volume were also higher under CO_2 enrichment. The development of more robust taproot systems under CO_2-enriched environments may allow for greater carbohydrate storage to ensure root growth for continued exploration of the soil profile to meet nutrient and water needs during peak demand periods (Prior *et al.* 1995).

Evapotranspiration (ET), a better crop water-use parameter for water relation studies, was, however, not significantly influenced by CO_2 enrichment. This implies that irrigation water use would not have to be increased to produce cotton in a future high-CO_2 world. However, if a concomitant change in climate occurs, such as global warming, ET in cotton may change in response to the changed weather condition (Hunsaker *et al.* 1994).

Cotton plants, grown in elevated $CO_{2,}$ had significantly higher seed cotton yield over that in ambient CO_2 as increase in harvestable yield by 43% was observed at 550 ppm of CO_2 throughout the growing seasons (Nagy and Hendrey 1994). Similar results were also reported (yield increase to the tune of 40 and 43%) by Mauney *et al.* (1994) and Khader *et al.* (2004). Here, the increase in biomass and yield is attributed to increase in leaf area, more profuse flowering and longer period of root retention. Boll growth and developmental parameters under elevated atmospheric CO_2 did not affect any of the fibre parameters (Reddy *et al.* 1999).

Available data from greenhouse and laboratory studies suggest that leaf photosynthesis, crop growth and water-use efficiency of tropical plants might increase at higher CO_2 concentrations. However, under field conditions, abiotic (light, water or nutrients) or biotic (competition or herbivory) factors might limit these responses. In general, elevated atmospheric CO_2 concentrations seems to increase plant tolerance to stress, that include low water availability, high or low temperature and photo inhibition.

Temperature

Tropical plants may be more narrowly adapted to prevailing temperature regimes than are temperate plants, hence expected changes in temperature might be relatively more important in the tropics. Reduced transpiration due to decreased stomatal conductance could modify the effects of water stress as a sign for vegetative or reproductive phenology of plants in seasonal tropical areas (Hogan *et al.* 1991).

Cotton requires warm days and relatively cool nights for optimum growth and development. Temperature significantly affects phenology, leaf expansion, internodes elongation, biomass production and the partitioning of assimilates to different plant parts (Reddy *et al*. 2000). In the crop growth front, the seedlings were insensitive to rise in temperature from 20/12 to 40/ 32°C during the first 2 weeks of emergence, and after that, they were temperature sensitive (Reddy *et al.* 1994) since 40 and 50% less biomass at 20/10°C and 40/ 30°C, respectively were observed as compared to optimum temperature of 30/20°C (Raja Reddy *et al.* 1992). Biomass of 13, 15 and 43% were partitioned to 'squares and bolls' at 20/10°C, 25/15°C and 30/20°C, respectively which reflects to some extent slower development at the temperatures lower than 30/20°C. Most of the squares and bolls were aborted above 30/20°C. When the temperature increased from 20/10 to 30/20°C, total plant weight increased by 36%. Yet, boll weight was greatest at 30/20°C, and least at both higher and lower temperatures. Boll growth was more temperature sensitive than vegetative growth (Table 2). It was concluded from temperature studies that optimum temperature for maximum growth rate of leaves, main stem and fruiting branches was 30/22°C (Reddy *et al.* 1994). This was also the optimum temperature for the quantum of squares and bolls retained/plant since the number of fruiting branches did not increase above 30/22°C.

Moreover, the plants grown at high temperature regimes lost their reproductive capacity to a greater extent than their ability to produce biomass. High temperature environments were also associated with cotton sterility and boll retention problems. Cotton plants grown from seedlings at 40°C for 12 hr/day shed all their squares. Plants grown from seedlings in the natural environment and exposed to daytime temperatures of 30, 35 or 40°C during the fruiting period accumulated 47, 5.7, and <1%, respectively of their mass as bolls. Three-week exposure to 40°C for 2 or 12 hr/day resulted in 64 and 0% bolls, respectively retained on the plants (Raja Reddy *et al*. 1992). Developmental rates, as depicted by the number of main stem nodes produced, were sensitive to temperature at 40/32°C although the number of fruiting branches did not increase above 30/22°C. All flower buds abscise from the plant grown at 40/32°C (Reddy *et al.* 1994). High temperatures reduce the viability of the pollen at flowering. This reduces boll size and can reduce yield. The result is small bolls with uneven seed numbers between the locks caused by poor pollination/seed set, particularly in one lock (Mc Rae *et al.* 2007). Soil warming affects the rooting system as the soil temperature also increases.

Table 2 Effect of temperature on Stoneville 825 cotton plant growth harvested at 49 days after imposition of temperature treatments

	Day/night temperature (°C)				
	20/10	25/15	30/20	35/25	40/30
Total weight (g/p)	242	320	330	293	225
Gain	133	211	221	184	116
Bolls	17.4	62.7	143.3	16.7	0.8
Squares	12.0	1.3	0.8	6.8	2.1

Source: Reddy *et al*. (1992 b)

Changes in temperature, however, had a dramatic effect on boll set and fibre properties (Hodges *et al.* 1993, Reddy *et al.* 1999). Fibres were longer when bolls grew at less than optimal temperatures (25°C) for boll growth. As temperature increased, fibre length distributions were more uniform while fibre fineness and maturity increased linearly with the increase in temperature up to 26°C, but decreased at 32°C. Short-fibre content declined linearly from 17 to 26°C, but was higher at higher temperature. To the contrary, most fibre quality traits were little affected by varying the temperature regimes (Pettigrew 2007). If the predicted global warming occurs, temperature extremes are likely to be much higher which will have a deleterious effects on the existing cultivars adapted to a moderate temperature. Hence, heat-tolerant cultivar will be needed even more than today.

CO_2 with temperature

Predicting plant responses to changing atmospheric CO_2 and to the possible global warming by high temperature and their interaction are more important than the sole effect. Although rates of main stem node formation and the time required in producing the first square and first flower were not little influenced by atmospheric CO_2, yet these were very sensitive to temperature. Similarly, carbon dioxide levels did not alter the time required producing nodes; yet, number of branches produced was sensitive to both temperature and CO_2. The larger the number of bolls set on the lower branches of plants grown at high $CO_{2,}$ the larger is the sink for photosynthesis than plants grown at low CO_2. This may explain the reason for the observed reduction in number of fruit at the upper nodes of high CO_2-grown plants. More bolls and squares were produced and retained on plants grown in high-CO_2 environments, except that none were produced in either CO_2 environment at 40/32°C (Raja Reddy and Hodges 1995).

Cotton plants showed large responses to humidity and a very high level of CO_2 (700 ppm). In cotton plants, the enhanced dry matter yield due to doubled CO_2 concentration was 1.6 fold greater at low humidity than at high humidity (Wong 1993). Heagle *et al*. (1999) used field studies to examine the impact of higher O_3 levels on cotton growth under higher CO_2 conditions. They found that higher CO_2 compensates for growth suppression resulting from elevated O_3 levels.

The results further indicate that high temperature-tolerant cotton cultivars would be more productive in the present-day CO_2 world, and they would be essential in the future, if global temperature increases.

Soil moisture

Well-watered plants registered higher mean light utilization efficiency (LUE) of 1.97 g/ MJ for free air carbon dioxide enrichment and 1.56 g/MJ for controls. The deficit irrigation treatment produced significantly smaller plants that absorbed fewer PARS and had lower LUE than plants in the well-watered treatment ($P < 0.05$). No interaction was observed between CO_2 and irrigation treatments (Pinter *et al.* 1994a). Leaves of both well-watered and moderately water stressed plants in the free air carbon dioxide enrichment plots had greater chlorophyll– a concentrations (7.1% greater in the 'wet' treatment and 8.2% greater in the 'dry' treatment) over the ambient plots (with 370 ppm, Pinter *et al.* 1994b). Mauney *et al*. (1994) reported that partitioning of the dry weight to bolls was altered more by the irrigation treatment than the CO_2 treatment. The wet treatment appeared to change the partitioning pattern by lowering the fraction of biomass devoted to gain in boll weight while the dry plots experienced a time period when more than 100% of the dry weight gain of the crop was found in bolls (Table 3). Thus, water-use efficiency (WUE) was greater in the free air carbon dioxide enrichment plots although the magnitude of the FACE effect was the same as that for biomass increase. Khader *et al*. (2004) reported that with the induction of moisture stress there was a reduction of 42% in yield and 36% in biomass under normal ambient-grown plants (Table 4) as compared to 15 and 17% reduction in yield and biomass, respectively under elevated CO_2 conditions.

Table 3 Dry weight partitioning within the cotton crop during selected time periods of 1991 season

	Control + dry plot	FACE + dry plot	Control + wet plot	FACE + wet plot
Biomass gain ($g/m^2/day$)	10.2	17.6	14.6	18.2
Boll mass gain ($g/m^2/day$)	10.7	17.9	12.7	16.6
Partitioning (boll mass/total mass)	1.04	1.01	0.87	0.91
Water-use efficiency (in a biomass/kg water)				
1990	1.50	1.48	1.79	1.90
1991	1.22	1.20	1.67	1.67

Source: Mauney *et al*. (1994). FACE, Free air carbon dioxide enrichment

Irrigation in semi-arid climate is a major cause of secondary salinization. Elevated CO_2 may reduce the impacts of secondary salinization, although experimental work shows that any increase in temperature may negate these benefits and may even exacerbate problems of secondary salinity. Globally averaged mean water vapour, evaporation and precipitation are projected to increase (IPCC 2007).

Nutrient management

Less nutrient concentration with elevated CO_2 levels but at sufficient range for all the tested elements except N, which was below the sufficiency (Table 5) reported by Huluka *et al*. (1994). Free air carbon dioxide enrichment (550 ppm) often decreased tissue nutrient concentration but increased total nutrient accumulation. Under elevated CO_2, field-grown cotton was more nutrient efficient in terms of nutrient retrieval from the soil and nutrient utilization in the plant (Prior *et al*. 1998). This enables more efficient fertilizer utilization, better economic returns for fertilizer expenditures and reduced environmental impact from agricultural

Table 4 Effect of water stress and elevated CO_2 atmosphere on morphological attributes of cotton

Character	Elevated CO_2 (650 ppm)		Ambient CO_2 (330 ppm)		CD (P=0.05)
	Unstressed	Stressed	Unstressed	Stressed	
Plant height (cm)	45.2	38.3	37.6	29.7	2.8
Sympodia (no.)	17.8	17.2	17.4	16.0	NS
Node (no.)	21.4	20.0	20.8	18.2	0.7
Leaf (no.)	64.6	52.0	54.4	48.2	3.2
Boll (no.)	13.8	11.8	10.6	6.6	0.6
Single boll weight (g)	2.08	1.97	1.88	1.76	0.31
Yield (g)/plant	27.4	23.2	20.0	11.6	1.5
Total biomass (g)/plant	83.5	69.0	61.7	39.4	2.8
Harvest index	32.7	33.5	32.3	29.5	1.9

Source: Khader *et al*. (2004)

Table 5 Influence of CO_2 levels on mean leaf nutrient concentration

Element	Control (H≈370 µmol/mol)	FACE (H≈550 µmol/mol)	Sufficiency range
N (g/kg)	46.8	31.8	35–45
Ca (g/kg)	55.9	24.4	20–30
K (g/kg)	20.1	15.5	15–30
Mg (g/kg)	4.7	3.5	3–9
P (g/kg)	3.8	3.4	3–5
B (mg/kg)	93.6	76.2	20–60
Cu (mg/kg)	8.4	6.6	5–25
Fe (mg/kg)	275.0	208.0	50–250
Mn (mg/kg)	108.0	83.6	25–250
Zn (mg/kg)	41.0	33.4	20–200

Source: Huluka *et al*. (1994)

fertilization practices in the future. A significant CO_2 interaction with N observed for total bolls produced ($P < 0.01$) and retained ($P < 0.05$) (Reddy *et al*. 2004). The bolls produced and retained/plant were significantly higher for the plants grown at elevated CO_2 and N+ conditions. Plants grown at ambient CO_2 and N + condition and elevated CO_2 and N-condition performed similarly for total bolls produced and retained (Table 6). Leaf N concentration decreased with increasing CO_2 under low and high level of N. These low leaf N concentrations did not reduce the effect of elevated CO_2 producing higher lint yields and the response being highest for plants grown at elevated CO_2 and high N conditions (Reddy *et al*. 2004). Thus, the study suggests the greater possibility in realization of higher nutrient efficiency under elevated CO_2. It is inferred that future elevated CO_2 will not have any deleterious effects on fibre quality and yield, if N supply is optimum.

Crop residue

Assessing the impact of elevated atmospheric CO_2 concentration on the global environment is improved by understanding the global carbon (re)cycling. Carbon fixed within plant biomass ultimately enters the soil via plant residues. Residues of cotton (Torbert *et al.* 1995) growth under elevated CO_2, displayed increased C : N ratios, which may reduce their rate of decomposition in the soil and lead to an increment in ecosystem carbon stocks, similar to that observed in fertile grasslands. No significant difference was observed with respect to soil respiration or P mineralization-immobilization between CO_2 enrichment against ambient CO_2 conditions by application of crop residues grown in ambient condition. However, significantly greater net N immobilization was observed during the incubation in all soil types with elevated CO_2 treatment by application of crop residue. These results indicate that decomposition of plant residue may not be reduced by CO_2 enrichment, but N dynamics may be markedly changed (Torbert *et al.* 1995). High CO_2 environments without water stress, increased C storage in soil is likely, but it is less likely where water stress is a factor (Wood *et al.* 1994).

Ultraviolet-B radiation

Projections indicate that solar ultraviolet-B (UV-B) radiation will reach peak levels on the earth's surface in the coming years by climate change. UV-B radiation is readily absorbed by biomolecules, such as, amino acids, polypeptides and nucleic acids (Sullivan and Teramura 1989). Enhanced UV-B radiation caused a significant reduction in plant growth (Sullivan and Teramura 1989, Teramura *et al*. 1991), photosynthetic capacity (Ziska *et al.* 1993, Teramura and Sullivan 1994) and pigment levels (Strid and Porra 1992, Sullivan and Rozema 1999) and reduced crop productivity (Corlett *et al.* 1997). Crops subjected to UV-B radiation, respond by altering their morphology and mitigate by adopting shielding or repair mechanisms.

Exposure to high UV-B radiation reduced both vegetative and reproductive parameters and resulted in a smaller canopy, indicating sensitivity of cotton to UV-B radiation. Enhanced UV-B radiation increased epicuticular wax content on adaxial leaf surfaces and stomatal index on both adaxial and abaxial leaf surfaces. Leaf thickness was reduced following exposure

Table 6 Effect of CO_2 concentration + N levels on boll parameters and fruiting branches

Treatment		Boll parameters			Fruiting branches		
N	CO_2 (µmol/mol)	Total bolls	Retained bolls	Retention (%)	Number/plant	Length (cm)	Fruiting site (no./branch)
N+	Sub-ambient (180)	20.8	12.4	55.4	19.5	19.5	3.0
	Ambient (360)	50.7	24.4	45.1	20.9	31.2	4.5
	Elevated (720)	58.6	30.5	49.4	22.9	29.5	4.1
N-	Sub-ambient (180)	26.4	12.1	44.2	14.8	21.9	2.4
	Ambient (360)	39.1	16.1	38.8	17.5	31.7	3.3
	Elevated (720)	47.1	19.8	37.4	17.8	32.4	3.3
ANOVA	CO_2	S	S	NS	S	S	S
	N	S	S	S	S	NS	S
	$CO_2 \times N$	S	S	NS	S	NS	NS

Source: Reddy *et al*. (2004)

to UV-B owing to a decrease in thickness of both the palisade and mesophyll tissue, while the epidermal thickness remained unchanged (Kakani *et al.* 2003). Zhao *et al.* (2003) found that UV-B radiation at 7.7 kJ/m^2/day did not affect cotton growth and development, but higher levels of UV-B radiation, ie in the vicinity of 15.1 kJ/m^2/day, significantly reduced stem elongation rate, leaf area and dry matter accumulation. Forecasters predict that a 30% depletion of the ozone layer will enhance UV-B radiation from 7.7 to 15.1 kJ/m^2/day. They also observed that elevated atmospheric CO_2 could not counterbalance the detrimental effects of high UV-B radiation on net photosynthesis and growth in cotton.

Pest dynamics

Current and projected increases in the concentrations of CO_2 and other radioactively-active gases in the earth's atmosphere lead to concern over possible impacts on agricultural pests. All pests would be affected by the global warming and consequent changes in precipitation, wind patterns and frequencies of extreme weather events, which may accompany the greenhouse effect. Cotton cultivation is a bed of roses with thorns; because it is harbored by about 1 326 insects and mites all over the world; out of which 162 species are found on cotton in India; of these phytophagous pests, 24 have attained the pest status, out of which 9 are key pests (Dhawan 1998).

Studies on the relationship between insect incidence and weather factors would enable an ecological maneuvering, which may have economically relevant impact on pest incidence. The loss in seed cotton yield due to leafhopper is accounted to 390 kg/ha (Pandi 1997). Multiple regression analysis showed that leafhopper population on cotton plants under complete protection (during reproductive phase as well as vegetative phase) increased with the increase in maximum temperature (R^2 =0.53, Murugesan and Manish 2007). Morning relative humidity had positive and evening relative humidity had negative influence on the larval population of pink boll worm (Ramesh kumar *et al.* 2007). Other factors did not contribute significantly to the larval population. The contribution made by weather parameters on the larval population was 90.9% (Patil *et al.* 1992). These studies further evidenced the climate susceptibility of cotton pests.

Temperature is identified as the dominant abiotic factor directly affecting herbivorous insects. There is little evidence of any direct effects of CO_2 or UV-B. Temperature directly affects development, survival, range and abundance. Species with a large geographical range will tend to be less affected. Insect herbivores show a number of distinct life-history strategies to exploit plants with different growth forms and strategies, which will be differentially affected by climate warming (Jefferys 2002).

Plants, grown under low-nutrient conditions, do have higher concentrations of carbon-based allelo-chemicals than plants grown under high-nutrient conditions (Fazer *et al.* 1992). Host plants growing under enriched CO_2 environments exhibited significantly larger biomass (+38.4%), increased C/N ratio (+26.57%), and decreased nitrogen concentration (–16.4%), as well as increased concentrations of tannins (+29.9%) and other phenolics (Heagle 2003). In contrast to the C/N balance hypothesis, plants grown in elevated (700 ppm) CO_2 conditions had similar, or lower, concentrations of carbon-based allelo-chemicals than plants grown in ambient (350 ppm) CO_2 conditions. Larvae fed with foliage grown in elevated CO_2 with low N fertilization consumed significantly more plant material than insects fed with foliage grown in ambient CO_2; but, again, no differences were observed with high N fertilization and found that insects fed on low N plants had significantly higher mortality in elevated CO_2 (Coviella and Trumble 2000).

The production of the nitrogen-based toxin was affected by an interaction between CO_2 and N; elevated CO_2 decreased N allocation to Bt, but the reduction was largely alleviated by the addition of nitrogen, thus indicated that future expected elevated CO_2 concentrations by climate change, alter plant allocation to defensive compounds and have enough impact on plant–herbivore interactions. Increases of carbon-defensive compounds by elevated CO_2 or low N availability or both, adversely affected growth and survival of *Spodoptera exigua* in *Bt* cotton, was reported by Carlos *et al.* (2002). It was observed that feeding guild, in which some species have shown increases in population density in elevated carbon dioxide, are the phloem feeders (John 1999). It is likely that climate change will not minimize the outbreaks; on the contrary it might benefit some pests, which might increase the consumption of pesticide in the region of Andhra Pradesh (Flores Araya and Jesserina 2008).Chewing insects have shown no change or reduction in abundance, though relative abundance may be greatly affected since compensatory feeding is common in these groups

Densities of leaf miner species on host species were lower in every year in elevated CO_2 than they were in ambient CO_2 (Peter and Tatiana 2005). The results showed that elevated CO_2 significantly decreased herbivore abundance (–21.6%), increased relative consumption rates (+16.5%), development time (+3.87%) and total consumption (+9.2%), and significantly decreased relative growth rate (–8.3%), conversion efficiency (–19.9%) and pupal weight (–5.03%). No significant differences were observed among herbivore guilds. To the contrary, thrips population size was not significantly affected by CO_2, but laminar area scarred by thrips feeding was 90% greater at elevated than at ambient CO_2. Because of increased growth, however, undamaged leaf area was approximately 15% greater at elevated than at ambient CO_2 (Heagle 2003). Chakraborty *et al.* (2002) reported higher CO_2 levels will increase the severity of diseases, induce fungal growth, spore formation and will destroy more plant tissue.

The effect of chemical action of imidacloprid under high temperature was greater (Evangelos *et al*. 2008). This suggestion was supported by findings of reduced glutathione reductase in the imidacloprid-treated plants, indicating that the untreated plants were experiencing more stress, necessitating the activation of this defense mechanism.

Weeds

Weeds are likely to respond directly to the increasing CO_2 concentration. Higher CO_2 will stimulate photosynthesis and growth in C_3 weeds and reduce stomatal aperture and increase water-use efficiency in both C_3 and C_4 weeds. Respiration, and photosynthates composition, concentration, and translocation may be affected. Perennial weeds may become more difficult to control, if increased photosynthesis stimulates greater production of rhizomes and other storage organs. Changes in leaf surface characteristics and excess starch accumulation in the leaves of C_3 weeds may interfere with herbicidal control. Global warming and other climatic changes will affect the growth, phenology, and geographical distribution of weeds. Any direct or indirect consequences of the CO_2 increase that differentially affect the growth or fitness of weeds and crops will alter weed-crop competitive interactions, sometimes to the detriment of the crop and sometimes to its benefit (Patterson 1995). Work done in Turkey has shown that climate change will be beneficial to weeds due to the fact that genetic variations and selective ecological adaptation are more developed in weeds than in cultural plants (Grenz and Uludag 2006).

Regional impact of climate change

Demand for irrigation water is more sensitive to climate change; increased dryness may lead to increased demands (IPCC 2001). Cotton in India is an important cash crop which is grown under high evapotranspirative demand, using about 15% of the national water resources by providing irrigation to 40% of area making the crop vulnerable to changes in water availability. Here was a marginal increase in the rainfall by 141 mm in the past 100 years in the north-western India covering Punjab, Haryana, west Rajasthan and west Madhya Pradesh (Pant and Hingane 1988). Singh and Sontakke (2002) reported that the summer monsoon rainfall over western IGPR shows increasing trend (170 mm/100 years, significant at 1% level) from 1900 and over central IGPR shows decreasing trend (5 mm/100 years, not significant) from 1939. Ramakrishna *et al*. (2006) indicated decreasing rainfall trends in south-western and central parts of India and increasing rainfall trend in Punjab, western Rajasthan, Gangetic West Bengal and sub-Himalayan West Bengal. The studies for irrigated arid region of Ganganagar revealed an increase in annual rainfall, particularly during the last 3 decades at a rate of 1 mm/year was observed (Rao 2007). Intensity of precipitation events is projected to increase leads to longer periods between rainfall events, indicating a greater risk of droughts (IPCC 2007). Decrease in the number of rainy days in western and central part. There may be overall increase in the rainfall intensity by 1–4 mm/day except for small areas in the north-western India where the rainfall intensity may decrease by 1 mm/day predicted by Rupakumar *et al*. (2003).

Cotton is a heat-loving crop, hence temperature imposes dramatic influence on cotton throughout the crop growth periods. Extensive warming (by 4°C) in India could cause significant reduction in crop yields (25–40%) in the absence of adaptation and C fertilization (Rosenzeveig and Parry 1994). Rupakumar *et al*. (2003) reported that over the region south of 25°N the maximum temperature will increase by 2–4°C during 2050s. In the northern region the increase in maximum temperature may exceed 4°C. There may be a general increase in the minimum temperature up to 4°C all over the country. Kothwale and Rupkumar (2005) found that while the all India mean annual temperature has shown significant warming trend of 0.05°C/10 years during the period 1901–2003, the recent period of 1971–2003 has seen relatively accelerated warming of 0.22°C/10 years, which is largely due to unprecedented warming during the last decade. The recent accelerated warming over India is manifested equally in day time and night time temperatures. In contrary to increasing trend of temperature, there was a marginal fall in air temperature by –0.52ºC in the past 100 years in the north-western India covering Punjab, Haryana, western Rajasthan and western Madhya Pradesh (Pant and Hingane 1988). In general, decrease in the air temperature was observed in the region at a rate of 0.05°C/year at Ganganagar, 0.02°C/year at Bikaner and 0.01ºC/year at Jaisalmer (Rao 2007).

The InfoCrop cotton model simulated the temperature increase by 8°C reduced the yield by 40% while, 8°C reduced temperature decreased the yield by 86%. Higher temperature in addition to reducing the crop duration reduced the retention of bolls and boll weight. On the other hand, low temperature extends the crop duration and exposes the reproductive phase to very low temperature (December to February) (Hebbar *et al*. 2007).

Impact of climate change on cotton production in different zones

Global warming will have many consequences, but the 3 major impacts that are relevant to cotton production will be: increased atmospheric carbon dioxide, higher temperatures (both maximum and minimum) and potentially lower precipitation levels and altered rainfall patterns worldwide. In cotton, 60% of the yield losses is due to climate as compared to 30% recorded in other crops, like cereals, oilseeds and pulses (Dason 1996).Universal positive response with increasing carbon dioxide concentration could help to increase cotton production in all the 3 zones. Northern zone comes under irrigated cotton cultivation. Increasing trend of

Table 7 Average monthly rainfall of cotton season of 6 months

Centre	Monthly rainfall (mm)					
	1	2	3	4	5	6
North zone						
Punjab						
Jullandhar	20.4	69.7	155.2	183.6	60.0	1.5
Ludhiana	14.7	52.0	200.2	174.3	108.4	19.8
Haryana						
Hisar	17.3	39.7	133.1	130.6	74.5	29.2
Rajasthan						
Udaipur	16.9	75.2	175.1	195.3	89.4	16.3
Central zone						
Maharashtra						
Akola	144.9	217.2	196.6	122.7	47.7	18.7
Nagpur	341.7	280.5	183.1	56.8	16.6	13.2
Parbhani	148.4	237.6	214.7	183.2	72.2	20.5
Madhya Pradesh						
Indore	131.9	283.7	276.9	183.1	40.1	13.3
Gujarat						
Surat	212.8	440.8	233.4	169.7	33.5	12.4
Ahmedabad	88.8	280.9	296.1	185.0	36.6	9.3
South zone						
Andhra Pradesh						
Kurnool	93	127	118	150	83	22
Nandyal	70	76	76	76	75	72
Karnataka						
Dharwad	118.0	128.8	104.0	107.8	75.3	19.8
Raichur	59.8	112.3	68.3	140.3	77.3	10.8
Tamil Nadu						
Kovilpatti	179	164	63	28	20	26
Aduthurai	14	17	41	69	31	44
Coimbatore	28.4	57.3	136.7	119.3	40.8	6.6

Source: IMD (2010) and Dason *et al.* (1996)

precipitation may have less influence over irrigated cotton. However, further increase in existing rainfall range of boll development and bursting periods of 130.6–200.2 and 60.0–108.4 mm (Table 7), respectively may affect boll fixing and bursting and quality of *kapas*. Increasing precipitation and decreasing of temperature may prolong the vegetative growth and extend the crop duration, which pose difficulties in timely sowing of succeeding *rabi* season crops in cotton-based cropping systems of northern zone. The development of each phonological phase in cotton has an optimum temperature requirement (Hebbar *et al*. 2007). The existing maximum temperature range of 39.4–41.0°C and 37.3–41.2°C (Table 8), respectively for germination and early growth periods are higher than optimum and decreasing trend of temperature may favour for effective germination and early growth.

Central zone, most of the area comes under rainfed cultivation. The expected increasing of temperature, decreasing rainfall with erratic distribution leads to frequent wet and dry spell. Heavy rain curtails the sowing of cotton, particularly in black cotton soil affect the germination due to poor soil aeration (Raj and Dasan 1975). Continuous dry spell during critical crop growth periods of squaring, flowering and boll development may affect yield of the crop. Waterlogging coupled with drought may induce reddening in *Bt* cotton. Further increasing of existing temperature range of 31.2–39.8°C (Table 8) at sowing time may hamper the germination. The regions currently having lower temperatures are expected to be at an advantage by increasing temperature under the conditions expected to occur in 50 or more years but the regions having high temperature at close to 40°C would seem to be at disadvantage (ICAC 2009).

The expected erratic distribution leads to frequent wet and dry spell in southern zone. Increasing trend of temperature shortened the crop growth periods. Low rainfall with erratic rain favours for production of diploid cotton (eg. Kovilpatti (TN)). Shortening of crop growth periods induced by increasing temperature may facilitate to fit cotton in rice–fallow cropping system.

The potential water requirement was minimum in Khandwa, Khargone and Dhar (506.9 mm) and maximum in Rajkot (899.1 mm), primarily owing to the differences in the potential evaporation (PE), available water content (AWC) and length of crop season. The seasonal precipitation was more than the water requirement of cotton in Khandwa, Khargone, Dhar, Nanded, Adilabad and Nagpur districts while water deficit was the highest in Dharwad with a cumulative stress of 16.47, followed by Rajkot and Kovilpatti. Decreasing and erratic distribution of rainfall forecast may affect cotton production in Dharwad, Rajkot and Kovilpatti.

Adaptation strategies

Climate change requires two types of measures: adaptive measures and mitigation measures. A range of adoption measures are available to reduce vulnerability to climate change by enhancing adaptive capacity and increasing resilience. Cotton crops grown in future environments will be subjected to a climate for which they are not bred (Hebbar *et al.* 2007). 'LRA 5166', 'KC 2' and 'AKH 081' are example of drought-tolerant cultivar as an adaptation strategy.

The risk and uncertainty imposed by climate change could be managed by intercropping and multi-tier cropping in cotton. Reilly *et al.* (2001) and Butt *et al.* (2006) found that modified crop mix, and land use are all potential adaptation to climate. Multi-tier vegetable intercropping with short duration vegetables like coriander, radish, vegetable cowpea, clusterbean and beet root provide a suitable multi-tier combination along with cotton. Periodic and early harvest of intercrops resulted in less competition within the component of multi-tier crops leading to yield equal to sole cotton. Per hectare gross return of Rs 1 15 000, net return of Rs 75 000, B : C ratio of 2.9, land equivalent ratio of 1.7, diversity index of 3.5 and per day returns of Rs 500 were realized with multi-tier system involving radish, beet root, coriander with cotton

Table 8 Average monthly maximum and minimum temperature (°C) of cotton season of 6 months

Centre	Maximum temperature (°C)						Minimum temperature (°C)					
	1	2	3	4	5	6	1	2	3	4	5	6
						North zone						
Punjab												
Jallundhar	39.4	38.2	34.1	33.1	32.6	31.5	23.8	25.6	24.7	25.8	21.8	18.3
Ludhiana	40.2	40.7	35.9	34.4	34.7	33.3	23.9	27.1	26.7	25.9	23.7	17.6
Haryana												
Hisar	41.0	41.2	37.2	35.6	35.7	34.4	24.7	27.8	27.3	26.2	23.9	17.8
Rajasthan												
Udaipur	39.7	37.3	32.0	30.2	32.3	33.4	39.7	37.3	32.0	30.2	32.3	33.4
						Central zone						
Maharashtra												
Akola	37.6	32.4	30.6	32.5	34.1	31.7	25.5	23.5	23.0	22.5	19.7	15.6
Nagpur	31.2	30.5	31.7	32.6	30.2	28.1	24.0	23.6	23.1	20.0	15.3	12.1
Parbhani	36.6	31.8	30.7	31.5	32.4	30.5	24.6	23.0	22.5	22.2	20.0	15.9
Madhya Pradesh												
Indore	36.3	30.3	28.5	30.3	32.2	29.6	24.3	22.7	22.0	21.0	18.0	13.6
Gujarat												
Surat	33.8	30.8	30.4	31.8	35.3	34.3	26.7	25.5	25.1	24.6	23.0	19.2
Ahmedabad	39.8	34.0	32.5	33.0	33.0	29.2	28.5	26.6	25.9	25.0	20.2	13.5
						South zone						
Andhra Pradesh												
Kurnool	35.8	32.8	32.4	30.5	32.5	31.1	25.2	26.2	23.6	23.6	22.6	19.4
Nandyal	28.6	22.3	21.8	28.6	24.8	23.5	20.6	16.8	15.9	21.8	18.4	15.6
Karnataka												
Dharwad	27.6	25.0	25.3	26.3	28.1	26.4	21.4	21.1	21.1	21.2	20.2	15.3
Raichur	35.4	32.4	32.3	32.0	32.0	30.4	24.1	23.1	22.8	23.0	22.6	20.0
Tamil Nadu												
Kovilpatti	31.5	31.5	30.8	31.3	33.5	35.0	22.8	22.8	21.1	20.2	20.4	22.3
Aduthurai	29.6	33.5	35.8	37.0	36.2	32.9	20.1	20.7	23.5	24.9	26.3	25.4
Coimbatore	31.3	32.2	31.3	29.9	29.1	30.2	21.7	21.7	21.8	20.6	18.8	18.1

Source: IMD (2010) and Dason *et al.* (1996)

under irrigated condition as reported by Sankaranarayanan *et al*. (2007). Pulses like soybean, blackgram and greengram were found promising in many situations for intercropping with cotton (Sankaranarayanan 2010).

In situ soil moisture conservation techniques could reduce moisture stress by effectively conserving soil moisture. Preparatory tillage operation, viz ploughing and harrowing gave additional cotton yield of 100 kg/ha as compared to only harrowing before sowing at Dharward. Contour bunding is the effective soil and water management system should reduce run-off and soil erosion, while increasing infiltration of rainfall (Kampen and Krantz 1976). The other practices include graded, narrow or broad ridges or beds separated by furrows for drainage, reduce run-off and soil erosion and increasing infiltration of rainfall. Forming beds (120–180 cm wide) and furrows on a grade for *in situ* water harvesting is found to be efficient in deep black soils with a rainfall of 700–850 mm (Venkateswarlu 1980). Ridges and furrow method of water harvesting has been recorded 42% increase in cotton yield under rainfed condition besides holding higher moisture (Anonymous 1986). Significant increase in *kapas* yield (673 kg/ha) in the black polyethylene mulch (25 microns) observed as compared to non-mulched plot (436 kg/ha) (Ravi and Christopher Lourduraj 1991). Location-specific adoption of heat- and drought-tolerant varieties, intercropping and *in situ* soil moisture conservation play major role in management of climate uncertainties posed by global warming. Sow as rainfed cotton, utilizing supplemental irrigation strategies or modified row configurations (eg skip rows) to enhance crop access to soil moisture, offer significant insurance against losses in both yield and quality in those regions and years where rainfall is highly variable (Bange *et al*. 2005). Opening of furrow after every rows of cotton between 30 and 45 days after sowing and spreads of crop residue mulch were found to be promising at Maharastra (Giri *et al*. 2008).

Adaptability of cotton species

India is the unique country where all the 4 species of cotton are being commercially grown in some of the states. Studies on the effect of temperature in different genotypes (Reddy *et al*. 1992) revealed that pima cotton (*Gossypium* *barbadense*) (extra long staple) was found to be more sensitive to higher temperatures than the delta type of cotton plants (*G. hirsutum*). They reflected this high temperature sensitivity by producing no fruiting branches at 40/32°C, fewer branches at 35/27°C and more branches at 30/22°C, whereas the *G. hirsutum* plants produced the same number of fruiting branches in all these temperatures. Pima cotton exhibited greater damage to their reproductive structures at higher temperatures than the *hirsutum* cotton type. The study suggests that high temperature by climate change may affect the extra long staple cotton production.

Irregular and erratic distribution is expected by climate change; thus may result into wet spell and dry spell leads to water logging and drought. While considering the productivity of different species of cotton under rainfed condition, high rainfall year normally favours *hirsutum* over *arboreum*/*herbaceum* cotton and the reverse is true for a low or scanty rainfall year. For maximum utilization of rainfall under both high and low rainfall situation by intercropping of *arboreum*, *hirsutum* and *herbaceum* is one of the options. Species intercropping studies at Kovilpatti (TN) revealed that planting of *G. arboreum* (25%) + *G. herbaceum* (25%) + *G. hirsutum* (50%) found to record higher yield and stability among the different proportions and sole cropping both under the high and low rainfall situations. Krishnasamy *et al.* (1995) reported that *arboreum* genotypes registered higher seed cotton yield (430 kg/ha) with low and erratic rainfall (268 mm) in comparison to *hirsutum* cotton (262 kg/ha) at Kovilpatti (TN). Bhatade *et al.* (2008) found that *Gossypium arboreum*, viz J. Tapti and NA 398 were found to be the best performers compared to *hirsutum* hybrids/varieties (NHH 44/NH 545). Monoculture of *G. arboreum* cotton, out-yielded monoculture of *G. hirsutum* cotton in low rainfall years (9) out of 11 years except in years of heavy rainfall at Nagpur (Venugopalan and Pundarikakshudu 2009).

High temperature may result into high evapotranspiration, less soil moisture and salinity in semi-arid condition. Gopalakrishnan (2010) reported that *G. herbaceum* cotton is tolerant to salinity, drought and well adapted to marginal soils which are as bad as desert sands. Large-scale evaluation of 92 cotton genotype comprising *G. hirsutum* as well as *G.herbaceum* lines was carried out at Raichur, Karnataka by providing protective irrigation. As a group, *G.herbaceum* genotypes performed better than *G.hirsutum* genotypes and clear indication was evident about suitability of *G.herbaceum* genotypes in situations wherein only limited irrigation was possible. *G.herbaceum* 'RAHS-14' exhibited higher level of tolerance to salinity stress and recorded highest seed cotton yield.The review summarized that *barbadense* may be sensitive then *hirsutum* and diploid cotton perform better under climate aberration posed by climate change.

Mitigation strategies

Cotton belongs to the C3 type, and its photorespiration rate is almost 1/3 of its photosynthesis. Photorespiration, in real terms, is a loss of oxygen, CO_2 and light utilized during photosynthesis (ICAC 2007). High external input-based cotton cropping system has depleted soil organic matter/carbon (SOM/SOC) stocks and fertility of soils and overuse of N fertilizers lead to more emission of nitrous oxide. However, nitrogen fertilization indispensable component of current production practices, hence high emission by using inorganic nitrogen fertilizer use be restricted (ICAC 2009).The mitigation strategies should aim to reduce quantum of inorganic inputs used in cotton production system. The integrated nutrient management system (INMS), nevertheless, remains the maintenance and possible improvement of soil fertility for sustained crop productivity on long-term basis (Roy and Ange 1991), increasing yield @ 22% (Govil and Kaore 1997) and aimed also to reduce inorganic (N fertilizer) input utilization. In cotton, *Azotobacter* and *Azospirillum* were found useful in effecting N economy. Studies revealed that *Azotobacter* inoculation along with 40 kg N/ha was similar to application of 60 kg N/ha (a saving of 20 kg N/ha, Anon. 1985). Though the N-fixing potential ranged from 40 to 60 kg N/ha/y, yet saving to an extent of 20–40 kg N/ha/y was observed under field condition. Legumes rotation can fix atmospheric N to an extent of 135–488 kg/ha. It is estimated that cotton following a non-legume rotation crop required an application of 179 kg N/ha, while following the grain- and GM-legume system it required only 90 and 52 kg N/ha, respectively (Rochester *et al.* 2001). It is evident that application of FYM, greengram mulching, Glyricidia green foliage loppings and sunhemp as GM recorded 15–32% increase in yield over control and there was considerable build up of soil available nutrients following these (Blaise *et al*. 2004). It is usually recommended that slow-release nitrogenous fertilizers be applied to cotton at the pre-flowering stage and that nitrogen be made readily available at flowering when the demand is high (ICAC 2009).Irrigated conditions produce more greenhouse emissions than dryland farming. This might be due to the comparatively lower use of nitrogen fertilizers and lower methane emission in dryland farming (ICAC 2009).

In drip-fertigation, where fertilizer is applied through an efficient irrigation system, nutrient-use efficiency could be as high as 90%. The amount of fertilizer lost through leaching could be as low as 10% in fertigation, whereas it is 50% in the traditional one. In addition, fertilizer savings through fertigation could be to the tune of 25–50% (Haynes 1985). On medium deep clay soil at Parbhani, nitrogen application at 75kg/ha through drip recorded comparable yield to that of 100 kg N/ha by soil application in a hybrid cotton NHH 44 (Vaishnava *et al*. 1995). Fertilizer and water saving with high efficiency of inputs could be achieved with less cost by adopting poly tube drip system (system cost 70% less) (Sankaranarayanan 2005).

Majority of crop residues are burnt in cotton-based cropping system (eg cotton–wheat in northern zone) resulting in emission of greenhouse gases, in addition to loss of N, P, S and B. On the other hand, restoration of soil fertility is possible by incorporating the crop residues since the practice itself conserves/sequesters carbon as residue having wider C/N ratio possibly leaves more carbon in the soil. Study revealed that incorporation of cotton and wheat residues improved the productivity of these crops at Sirsa, Sriganganagar and Ludhiana in the northern zone since improvements in the soil fertility might stabilize long-term yields. At Coimbatore an integration of organics, viz FYM @ 5 tonnes/ha (15 days before planting), cotton residues @ 2.5 tonnes/ha (30 days before sowing) and sun hemp seeded @ 15 kg/ha simultaneously in interrows of cotton as green manure and buried at 45 days after planting gave significantly higher seed cotton yield and lower pest population over the recommended dose of fertilizers (Praharaj *et al*. 2004)

Increasing temperature could accelerate decomposition of soil organic matter, releasing stored soil carbon into atmosphere (Knorr *et al*. 2005, Fang *et al*. 2005, and Smith *et al* 2005). Low tillage practices are an example of win-win technology that reduces soil temperature in tropic, soil erosion and the use of fossils fuels. Adopting of INMS, drip fertigation, utilization of cotton stalks and conservation tillage could effectively utilize inputs and also act as mitigation strategies in cotton production system

Future thrust

- Research to prolong the duration of photosynthesis in green leaves by keeping them green for a longer time, or by increasing the photosynthetic rate of the plant enhance the consumption of atmospheric carbon.
- Developing of varieties capable of the lowest greenhouse gas emissions maintain and build good organic matter content in the soil
- Research into integrated effects of climate change (temperature, CO_2, and water stress) on cotton growth, yield and quality need further analysis.
- Breeding by conventional means as well as applying biotechnology tools and traits will develop cultivars with improved water-use efficiency and heat tolerance. The genetic resources, from areas where past climates mimicked the projected future climates could serve as the starting genotypes for building the genes for tolerance, maturity and yield features
- Identify the varieties that fit into new cropping system of cotton-based and seasons, development of varieties with changed duration, high fertilizer and radiation-use efficiency; inland salinity and varieties which respond to high CO_2 are some of the crop-based approaches for adaptation.
- The declining availability of water resources resulting under climate change will increase competition for these resources between irrigated cotton production, other crops and environmental uses. These issues emphasize the need for continual improvement in whole farm and crop water-use efficiencies
- Dissemination of *in situ* soil moisture conservation techniques to conserve soil moisture
- Promoting of cotton-based intercropping systems to reduce risk of climate uncertainties
- Muli-tier intercropping systems of CICR to be tested and modified/refined to make sustainable cotton production system
- Time of sowing for different regions to be tested and rescheduled
- Promoting of diploid cotton in low and high erratic rainfall and saline environment
- Promoting of high density narrow row cotton production system
- Approaches to increase soil carbon, such as, organic manures, residue management should be encouraged to reduce the impact of climate change
- Weather forecast and crop insurance to protect cultivators
- Regional impact on cotton will need to be assessed thoroughly.
- Coupling of pest and crop process modeling to estimate climate-induced pest impacts on crops
- Improved understanding of interactive effects of climate change and management on carbon source-sink relations in cotton ecosystems
- Exploration of the role of integrated management as a means for providing better management options for cotton ecosystems
- Development of biophysical-economic modeling of farm-level decision-making under climate change

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