Investigating critical growth stage of cotton subject to water deficit stress

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Abstract

Critical growth stage of cotton crop was investigated by artificially imposing water stress under field conditions. The crop was given water deficit stress for a period of 30 days at squaring (SS) and first boll split (BS) phases by maintaining the leaf water potential (ψ_w) at –2.2±0.2 MPa whereas in control plots ψ_w was maintained at -1.6± 0.2 MPa by irrigation scheduling. The average irrigation water applied during two years was 2432 m^3, 2174 m^3, and 2194 m^3 in NS, SS, and BS treatments, respectively. The results revealed that the imposed water stress, at either stage of crop, had adverse effects on cotton crop performance. The main stem height decreased by 12% and 7.4%, inter-nodal length by 9.2% and 4.3% in SS and BS, respectively over NS treatment. The decrease in dry biomass production was 4% and 7% in leaf; 21% and 11% in stalk and 20% and 13% in fruit in SS and BS treatments, respectively. Gas exchange characteristics were also adversely affected by imposed water stress showing a decrease of 18% and 28% in stomatal conductance, 16% and 22% in transpiration rate and 24% and 30% in net photosynthetic rate in SS and BS treatments, respectively. The decrease in seed cotton yield was 9.5% and 2.8% in SS and BS treatments, respectively. Chlorophyll (SPAD values), electrolyte leakage and cell injury values increased over non stressed crop. Lint percentage and fibre strength increased whereas fibre length decreased significantly in BS treatment. It was concluded that the squaring phase is more critical to water deficit stress in cotton.

Keywords: cotton; stress; gas exchange; yield; lint quality

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Introduction

Undoubtedly, cotton is recognized as being biologically drought tolerant. But, despite its xerophytic distinctiveness, it is widely grown as an irrigated crop. Water deficit is one of the most yield limiting factors as it affects growth and development (Umebese et al. 2009) by decreasing vegetative development, leaf area, photosynthetic and transpiration rates due to stomatal closure (Cornic and Massacci, 1996; Mwanamwenge et al., 1999). Several lines of evidence indicate that a decrease in photosynthesis due to water deficits has been attributed to both stomatal and non-stomatal limitations (Shangguan et al., 1999). The effect of water deficit, however, varies with the variety, degree and duration of stress and the growth stage of the plant (Adejare and Umebese, 2007). In several plants, growth and yield are slightly affected at the vegetative stage but drastically reduced at the reproductive stage (Adejare and Umebese, 2007; Ma et al., 2006). Since cotton plant is indeterminate in nature, the

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compensation capacity of a variety would determine the critical growth stage to cope with the water deficit conditions. Plants adapt to water deficits by changes in morphology, altered patterns of development and cellular metabolism (Umebese et al., 2009).

With the changes in climate and increasing demand due to intensified agriculture, water has become a scarce commodity for crop production (Reddy et al., 1996; Umar, 2006). Hence there is a great need to utilize the water resources in an efficient and intelligent manner. Apart from selection of water, efficient varieties for cultivation and identification of critical growth stage of a cotton cultivar may help to sustain its production under water stress environment.

Materials and Methods

A field experiment on cotton (cv. CIM-499) was conducted during 2008 and 2009 with three water stress treatments i.e. no water stress (NS) at -1.6± 0.2 MPa leaf water potential (ψ_w), stress at squaring (SS, 35 days after sowing) and stress at first boll split (BS, 85 days after sowing) phase. ψ_w was maintained at –2.2±0.2 MPa in water stress treatments for a period of 30 days by irrigation scheduling. The crop was sown in third week of May during both the years at a plant configuration of 75 x 30 cm in RCBD layout. ψ_w was measured by water potential apparatus (Chas W. Cook Div., England) from fully expanded youngest leaf excised at 11.00 hours. Gas exchange characteristics were measured by CI-340 hand held portable photosynthesis system (CID, USA). For dry biomass production plants from unit land area were harvested at maturity, partitioned into leaf, stalk, fruit portions and dried at 80 °C (Wells and Meredith Jr., 1984). Irrigation water applied was measured by "Cut Throat Flume". The irrigation water applied in 2008 and 2009 was 2632 m^3 & 2573 m^3, 2374 m^3 & 2342 m^3 and 2404 m^3 & 2385m^3 in NS, SS, and BS treatments, respectively. Annual precipitations received during the experiment years 2008 and 2009 were 64.5 mm and 79 mm, respectively.

Results

Impact on plant structure development

Imposition of water stress, at either stage of growth, caused a significant negative impact on plant structure development. Averaged across the years, main stem height ranged from 95 cm to 108 cm, nodes on main stem 29 to 30 and intermodal length from 3.16 cm to 3.48 cm in different treatments. With the imposition of water stress main stem height decreased, over NS, by 12% and 7.4% and inter-nodal length by 9.2% and 4.3% in SS and BS treatments, respectively. Although nodes on main stem decreased by 3.2% each in SS and BS treatment but the decrease was not statistically significant. Significant differences in plant structure development were observed between the years (Table 1).

Table 1
Impact of water stress imposition on plant structure development at maturity

Treatments	Plant structure development								
	Height (cm)			Node numbers			Inter-nodes (cm)		
	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
NS	101c*	115c	108C#	30^{ns}	32^{ns}	31^{ns}	3.37c	3.59c	3.48C
SS	87a	103a	95A	29^{ns}	31^{ns}	30^{ns}	3.00a	3.32a	3.16A
BS	94b	106b	100B	29^{ns}	31^{ns}	30^{ns}	3.24b	3.42b	3.33B
Mean	94A$	108B		29.3A	31.3B		3.20A	3.44B	

*Values with different letters in each column are statistically significant at p<0.05
#Means with different letters in each column are statistically significant at p<0.05
$Means with different letters are statistically significant at p<0.05 among years
ns: non-significant; NS: no stress; SS: stress at squaring; BS: stress at boll split

Impact on dry biomass production

Dry biomass production decreased significantly ($p<0.05$) with the imposed water stress at squaring and first boll split phases of crop. Averaged across the years, the leaf biomass ranged from 112.5 to 121.5 gm^{-2}, stalk biomass from 150 to 189 gm^{-2}, fruit biomass from 462 to 575 gm^{-2} and the total biomass from 728.0 to 885.5 gm^{-2} in different treatments. Here again the minimum dry biomass was produced by cotton plant in SS treatment. A comparison of the decreased dry biomass production over NS treatment revealed that leaf biomass decreased by 4% and 7%, stalk biomass by 21% and 11%, fruit biomass by 20% and 13% and total biomass by 18% and 12% in SS and BS treatments, respectively (Table 2).

Impact on gas exchange characteristics

Gas exchange characteristics like stomatal conductance (g_s), transpiration rate (E) and net photosynthetic rate (P_N) were affected significantly with water stress. Averaged data of two year show that the g_s ranged from 129 to 184 m mol CO_2 $m^{-2}s^{-1}$, E from 3.25 to 4.13 m mol H_2O $m^{-2}s^{-1}$, P_N from 27.2 to 38.8 μ mol CO_2 $m^{-2}s^{-1}$ and P_N/E from 8.4 to 9.4 m mol H_2O/μ mol CO_2. With the imposition of water stress g_s decreased by 18% and 28%, E by 16% and 22%, P_N by 24% and 30% and water use efficiency (P_N/E) by 9.6% and 10.6% in SS and BS treatments, respectively (Table 3).

Impact on boll production and seed cotton yield

Production of bolls, boll weight and seed cotton yield varied considerably among the stress treatments. Averaged data of two years revealed that the number of bolls per plant ranged from 19.5 to 22.0, individual boll weight from 3.03 to 3.18 g and seed cotton yield from 1908 to 2277 kg ha^{-1} in different treatments. The adverse effect of water stress was also reflected in decreased

Table 2
Impact of water stress imposition on dry biomass production at maturity

Treatments	Dry biomass production (gm^{-2})											
	Leaf			Stalk			Fruit			Total		
	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
NS	118c*	125c	121.5C#	180c	198c	189C	545c	605c	575C	843c	928c	885.5C
SS	113b	119b	116.0B	143a	157a	150A	400a	524a	462A	656a	800a	728.0A
BS	110a	115a	112.5A	160b	176b	168B	448b	554b	501B	718b	845b	781.5B
Mean	113.7A$	119.7B		161A	177B		464A	561B		739A	857.7B	

*Values with different letters in each column are statistically significant at $p<0.05$
#Means with different letters in each column are statistically significant at $p<0.05$
$Means with different letters are statistically significant at $p<0.05$ among years

Table 3
Impact of water stress imposition on stomatal conductance (gs), transpiration rate (E), net photosynthetic rate (P_N) and water-use-efficiency (P_N/E)

Treatments	Gas exchange characteristics											
	gs (mmol CO_2 $m^{-2}s^{-1}$)			E (mmol H_2O $m^{-2}s^{-1}$)			P_N (μmol CO_2 $m^{-2}s^{-1}$)			P_N/E (mmol H_2O/μmol CO_2)		
	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
NS	164c*	203c	184C#	4.06c	4.20c	4.13C	37.1b	40.5b	38.8B	9.1ns	9.7ns	9.4ns
SS	143b	156b	150B	3.37b	3.53b	3.45B	28.3a	30.4a	29.4A	8.4ns	8.6ns	8.5ns
BS	125a	133a	129A	3.14a	3.34a	3.24A	25.9a	28.4a	27.2A	8.3ns	8.5ns	8.4ns
Mean	144A$	164B		3.52A	3.69B		30.4ns	33.1ns		8.6ns	8.9ns	

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$Means with different letters are statistically significant at $p<0.05$ among years; ns means non-significant

production of bolls, their weight and total seed cotton yield. Over NS treatment, with imposed water stress bolls per plant decreased by 10% and 5%, boll weight by 4% and 5% and seed cotton yield by 16% and 10% in SS and BS treatments, respectively (Table 4).

Impact on chlorophyll, electrolyte leakage and cell injury

Accumulation of chlorophyll (SPAD values) was observed with water stress imposed at either stage of the crop. Averaged across the years, the chlorophyll content ranged from 45.0 to 47.9 in different treatment. The imposition of water stress at SS and BS phases caused an increase of 5% and 6%, respectively in chlorophyll content over NS. Chlorophyll content did not vary significantly between 2008 and 2009. Electrolyte leakage varied from 212 to 323 µ mhos cm^{-1} and cell injury from 80 to 96% in different treatments. Average data of the two years revealed that the electrolyte leakage increased, over NS, by 47% in SS and 36% in BS. The cell injury varied from 80 to 96% in different treatment irrespective of the years. The imposition of water deficit stress increased cell injury by up to 14% & 10% in SS and BS, respectively. Here again the cell injury did not vary significantly among the years (Table 5).

Impact on lint quality

Lint percentage increased significantly in BS treatment in 2008 only and a non significant change was observed in 2009. The average data of two years also showed significant increase of lint (%) in BS over the other treatments. However, the fiber length decreased significantly ($p<0.05$) from 28.8 mm in NS to 28.4 mm in SS and 27.7 mm in BS treatments. Fiber strength varied from 92.9 to 94.5 thousand pound per square inch (tppsi) in different treatments, irrespective of the years. In BS treatment, fiber strength increased significantly when compared with the other treatments. Although micronaire increased with water stress imposed at both stages of the crop over non water stress, the differences were not significant. Among the years of study no significant variations in fiber quality characteristics were observed (Table 6).

Table 4
Impact of water stress imposition on boll production and seed cotton yield

Treatments	Seed cotton yield and its components								
	Bolls per plant			Boll weight (g)			Yield (kg ha^{-1})		
	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
NS	20b*	24b	22.0B#	3.23c	3.13c	3.18C	2151c	2403c	2277C
SS	18a	21a	19.5A	3.15b	2.94b	3.05B	1730a	2086a	1908A
BS	19ab	23b	21.0B	3.14a	2.92a	3.03A	1879b	2239b	2059B
Mean	19A$	22.7B		3.17B	3.00A		1920A	2243B	

*Values with different letters in each column are statistically different at $p<0.05$
#Means with different letters in each column are statistically different at $p<0.05$
$[illegible]

Table 5
Impact of water stress imposition on chlorophyll (SPAD values), electrolyte leakage and cell injury

Treatments	Chlorophyll (SPAD value)			Electrolyte leakage (µS cm^{-1})			Cell injury (%)		
	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
NS	45.7a*	44.3a	45.0A#	216a	212a	214A	82a	80a	81.0A
SS	47.8b	46.6b	47.2B	323c	303b	313C	96b	93b	94.5B
BS	48.3b	47.4b	47.9B	294b	288b	291B	92b	90b	91.0B
Mean	47.3ns	46.1ns		278ns	268ns		90.0ns	87.7ns	

*Values with different letters in each column are statistically significant at $p<0.05$
#Means with different letters in each column are statistically significant at $p<0.05$
ns: non-significant

Discussion

Since water is the primary component of actively growing plants ranging from 70-90% of plant fresh mass (Gardner et al., 1984), limited water availability would have implications on the growth and physiological processes of all plants. Water deficit conditions have been reported to inhibit cell enlargement (Jaleel et al., 2009), thereby restricting the development of plant structure due to interruption of water flow from xylem to the surrounding elongating cells (Nonami, 1998). In the present studies the imposition of water deficit stress caused significant reduction in main stem height owing to the decreased intermodal length as nodes per plant did not change significantly among the treatments. The results are in conformity to the findings of Zhang et al. (2004) and Petropoulos et al. (2008) who also reported significant reduction in plant height in other crop plants due to water deficit stress. A comparison among the water stress treatments indicated that the maximum reduction in main stem height was observed when water stress was imposed at squaring phase. Variation in the plant response to water deficit among different varieties, degree and duration of stress and the growth stage of the plant has been observed (Adejare and Umebese, 2007; Jaleel et al., 2008). Since the squaring phase of cotton plant is the initial stage for plant architecture development, any stress at this stage of crop may limit the overall performance of short duration cotton varieties. The decreased dry biomass production was inevitable due to reduced plant growth and development as a result of water deficit stress. Reduced cell growth by loss of turgor pressure (Anjum et al., 2011; Taiz and Zeiger, 2006) under water stress is considered to be the main causal effect for decreased biomass production (Farooq et al., 2009; Zhao et al., 2006). Cotton genotypes showing tolerance to water deficit conditions tend to divert from vegetative to reproductive organs. Therefore, the productivity of cotton under drought stress would be determined by the processes of dry matter partitioning and temporal biomass distribution (Kage et al., 2004).

Drought-induced reduction in leaf area is ascribed to suppression of leaf expansion through reduction in photosynthesis (Rucker et al., 1995). The imposed water stress adversely affected the physiological processes as g_s, E, and P_N decreased significantly. Similar results have been reported by Anjum et al. (2011a) who found that drought stress in maize led to considerable decline in net photosynthesis (33.22%), transpiration rate (37.84%), stomatal conductance (25.54%), water use efficiency (50.87%) and intercellular CO_2 (5.86%) as compared to well water control. Among the treatments, the stress imposed at first boll split phase affected the physiological phenomena (g_s, E) of cotton plant more than the stress at squaring phase, except the P_N which did not differ significantly among treatments. Gas exchange characteristics varied marginally among the years of study. Many studies have shown the decreased photosynthetic activity under drought stress due to stomatal or non-stomatal mechanisms (Del Blanco et al., 2000; Samarah et al., 2009). Stomatal closure, an abscisic acid mediated response (Borel and Simonneau, 2002) that results in decreased stomatal conductance and photosynthetic rate (Sunkar et al., 2003) and

Table 6
Impact of water stress imposition at various stages of growth on lint percentage, fiber length, fiber strength and micronaire values

Treatments	Lint (%)			Length (mm)			Strength (tppsi)[¥]			Micronaire (μg $inch^{-2}$)		
	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean	2008	2009	Mean
NS	38.4a*	39.6^{ns}	39.0A[#]	29.2c	28.4b	28.8b	92.3a	93.4a	92.9A	4.48^{ns}	4.50^{ns}	4.49^{ns}
SS	38.5a	39.9^{ns}	39.2AB	28.7b	28.0b	28.4b	93.0a	94.2b	93.6A	4.50^{ns}	4.53^{ns}	4.52^{ns}
BS	39.0b	40.0^{ns}	39.5B	28.0a	27.4a	27.7a	94.4b	94.6b	94.5B	4.58^{ns}	4.59^{ns}	4.59^{ns}
Mean	38.6^{ns}	39.8^{ns}		28.6^{ns}	27.9^{ns}		93.2^{ns}	94.1^{ns}		4.52^{ns}	4.54^{ns}	

*Values with different letters in each column are statistically significant at p<0.05
#Means with different letters in each column are statistically significant at p<0.05
ns: non-significant

less leaf transpiration due to water stress (Osmond et al., 1987) help the plants to survive under adverse environmental conditions.

The adverse effects of water deficit stress on plant growth and development and physiological phenomena were reflected in terms of reduced fruit production and seed cotton yield. Although seed cotton yield decreased under water deficit stress imposed at both stages of growth, the maximum decline was observed in SS treatment, owing to the less number of bolls per plant. The results are in conformity to the previous findings where decreased cotton (*Gossypium hirsutum* L.) lint yield was associated with more fruit abortion, due to increased levels of abscisic acid (Borel and Simonneau, 2002) and decreased boll production under moisture deficits during the reproductive growth (Pettigrew, 2004). Moreover, the hormonal imbalance in squares and bolls, under water stress, plays a significant role in fruit shedding (Guinn et al., 1990).

The imposed water stress caused increase in chlorophyll (SPAD value) over control plots, however the water stressed treatments (SS & BS) were not statistically different from each other. The accumulation of chlorophyll under water stress conditions has been found to be a common observation in plants (Hamada, 1996; Jabeen et al., 2008) in order to protect themselves from photo-damage, thereby reducing the extent of absorbed light by changes in chlorophyll content (Murchie and Horton, 1997). The increase in electrolyte leakage and cell injury values, reflect water stress associated increased temperature effect on cell membrane damage. Iswari and Palta (1989) also reported increased cell membrane damage, due to loss of water potential under water deficit conditions.

The percentage of lint and its quality characteristics, although, did not vary greatly with the imposed water stress at either stage of the crop; however, fiber length decreased while fiber strength increased in BS treatment. The lint percentage has been reported to be negatively affected with the increased soil moisture levels (Grimes, 1969), due to the development of healthy and mature seeds (Saranga et al., 1998) under adequate soil moisture conditions. The decrease in fiber length in water stressed plots could be attributed to the increased levels of abscisic acid that inversely affected the final fiber length (Dasani and Thaker et al., 2006). Pettigrew (2004) also reported up to 2% decrease in fiber length under moisture deficit stress. Although micronaire increased with water stress at both stages of the crop over non-water stress, the differences were not significant. Furthermore, among the years of study no significant variations in fiber quality characteristics were observed.

Conclusion

Water stress imposed for a period of 30 days at either stage of crop exerted negative impact on plant structure development, biomass accumulation, gas exchange characteristics and seed cotton production. Water stressed plants showed increased chlorophyll, cell injury and electrolyte leakage, lint percentage, and fiber strength whereas fiber length decreased with water stress. Squaring phase of cotton plant, i.e., 35 days after sowing (DAS) was found to be more critical for water deficit stress as compared to first boll split phase, i.e., 85 DAS.

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