Chapter 18
Abiotic Stresses Mediated Changes in Morphophysiology of Cotton Plant

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Abstract Cotton plant is a warm-weather-loving perennial shrub and now has been domesticated to an annual crop cycle for commercial purposes. It belongs to genus *Gossypium* (*G. hirsutum* L., *G. barbadense* L., *G. herbaceum* L., *G. arboreum* L.), widely grown in arid, semiarid, and tropical climates. Globally, of these, *G. hirsutum* L. (the upland cottons) occupies about 95% of total 33–35 million hectares (2.5% of arable land) of land under cotton cultivation. Cotton crop is not only a natural fiber resource but also a food and feed for billions of humans and livestock. The projected increase in population is 9.0 billion by 2030, which would require an additional quantum of fiber and cotton seed production by more than 70% over the current level of productivity. Cotton plant having an indeterminate growth habit is highly vulnerable to occurrence of persistent and/or intermittent changes in the environments. The footprints of abiotic stresses are more visible on growth and development than those of biotic stresses. In the days to come, under the aegis of climate change, the sustainability of cotton productivity from productive and marginal lands rests by maintaining balance between vegetative and reproductive development from seedlings through maturity. The prevalence of imbalance state (either short or long

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duration) could lead to loss in farm income. The potential yield could be harvested by transitioning cotton plant from "green cotton" to "white cotton." This is an effort to manipulate the plant for transporting its greater photo-assimilates from source to sink organs. Farm manager is ought to be proactive and skillful in adopting certain management tools, monitoring crop development, selection of tolerant/resistant cultivars, nutrient management, and phytosanitary measures to reinforce cotton plant for abreasting the external vagaries.

Keywords Morphophysiological attributes · Abiotic stresses · Cotton · Plant mapping · Source-sink relationship

Abbreviations

AP	Ascorbate peroxidase
CAT	Catalase
CO_2	Carbon dioxide
DD	Degree-days
DPA	Days post-anthesis
EDU	Ethylene diurea
ET	Evapotranspiration
GHG	Greenhouse gas
GR	Glutathione reductase
HSP	Heat shock proteins
LEA	Late embryogenesis abundant
O_3	Ozone
Pn	Net photosynthesis
PPFD	Photosynthetic photon flux density
ROS	Reactive oxygen species
SOD	Superoxide dismutase

18.1 Introduction

Cotton plant is a perennial shrub or tree, which has been domesticated to an annual growth habit and highly prone to climatic conditions. It belongs to genus *Gossypium* (*G. hirsutum* L., *G. barbadense* L., *G. herbaceum* L., *G. arboreum* L.) and is comprised of 50 species, of which 45 are diploid and the remaining 5 being tetraploid. The major cultivated cotton types are "the Upland cottons" (*G. hirsutum* L.) and "Pima/Sea Island/Egyptian cotton/extra long staple" (*G. barbadense* L.). Cotton plant is a unique one and follows sigmoidal curve for its growth and development. Having an indeterminate growth habit has a periodic and well-defined predictable growth patterns. It is mainly grown in subtropical and tropical climates between 37 °N latitude and 32 °S latitude, covering an area of 33–37 million hectares across 100 countries.

Cotton is a rapidly renewable resource, a leading natural fiber and second largest oilseed crop in agricultural production (Ahmad et al. 2014, 2017, 2018; Abbas and Ahmad 2018; Ahmad and Raza 2014; Ali et al. 2011, 2013a, b, 2014a, b). It produces spin able fibers for commercial use in textile industry. It is also a major source of edible oil for humans and meal as a vegetable protein for livestock production (www.icac.org) (Giband et al. 2010). The best cotton produces now achieve more than two bales of cotton per mega liter (ML) of water. It is a vital agricultural commodity and multibillion US Dollar industries that underpin both developed and developing economies (Amin et al. 2017, 2018; Khan et al. 2004; Rahman et al. 2018; Tariq et al. 2017, 2018; Usman et al. 2009). More than 400 million people derive their livelihood by engaging in farming, processing, textile, and garment industries.

Currently, the primary challenge is to enhance tolerance to drought and salt stresses to maintain its productivity on marginal lands (Rasapula et al. 2011). Thereby, there is a greater need to understand the basics of certain physiological processes in response to changing climatic conditions (Boyles et al. 2005). The productivity of cotton will have to be increased by 70% over the current level of production, with simultaneous reduction in greenhouse gas (GHG) emissions without any loss in biodiversity and habitats under the expected vagaries of climate changes (Burney et al. 2010).

To make cotton crop to be sustainable, commercial, and cost-effective, it is necessary to know regarding plant growth along with its response to ecological stresses. A comprehensive understanding of physiological processes along with their response toward stress is necessary to design strategies for managing stresses for maximizing productivity and profitability.

18.2 Growth and Development

Cotton being a perennial one exhibits as an indeterminate growth habit. This means that fruiting bodies are developed over a longer period of times, and compensates its loss of fruiting bodies following the footprints of certain stresses, e.g., drought, salinity, pollutants, extreme temperature, insect-pests and disease attack, and other physiological disorders.

Cotton seedlings emerge 5–10 days after planting, and cotyledons are arranged directly opposite on main stem. Leaves on main stem along with branches are spirally arranged on the stem in a three-eighths polyllotoxy about the cotyledonary node (Fig. 18.1). The development of reproductive organs starts about 4–5 weeks after planting. The bolls develop rapidly after fertilization and reach at their full size within 3 weeks. During the growth period, plant produces two types of branches, monopodial (vegetative) and sympodial (reproductive) ones. The first sympodial branch generally arises from sixth or seventh node on main stem. The monopodial

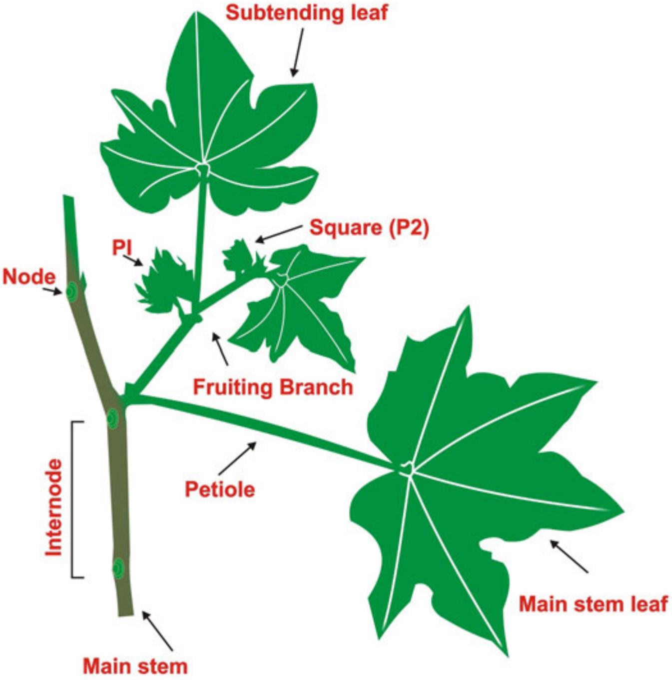


Fig. 18.1 Developing fruiting branch and other structures. (Source: Adapted after William and Bange 2018)

branch grows in zigzag manner along with arise manifold fruiting positions. With progressive growth, new sub-standing leaves are produced and supply carbohydrates to the developing fruits. As the plant enters into the reproductive phase, the vegetative growth is slowed down and the greater proportion of photo assimilates are diverted toward developing bolls. This is the pivotal stage, where balance between vegetative and reproductive growth has to be maintained progressive as long as weather favors for turning into cut out stage.

18.3 Source-Sink Relationship

The environmental stresses impact largely on the production of metabolites and its redistribution between source and sink organs. The development of imbalance between source and sink quantum and occurrence of osmotic adjustment results in reduction of photosynthetic process, leaf and root growth, and abscission of fruiting bodies (Kirkham et al. 1972; Terry et al. 1971; Baker and Boker 2010). The productivity of assimilates is dependent upon genetic make-up of species, architectural characteristics of cultivars degree of lobing, and eco-adophic factors (Baker and

Boker 2010). The rate of net photosynthesis (Pn) is maximal during leaf expansion (16–20 days) period and starts declining toward ontogeny (Constable and Rawson 1980; Reddy et al. 1991; Wullschleger and Oosterhuis 1990).

Photosynthetic rate and production of fruiting bodies is maximal at optimum temperature of 30/20 °C and declines at 40/30 °C (Reddy et al. 1990), while seedling growth is stopped below 16 °C (Warner and Burke 1993). The photosynthetic rate is declined drastically at water potential (ψ_i) of -1.2 MPa drought stress condition (Marani et al. 1985) and results in irreversible process (Bielorai and Hopmans 1975; Hsiao et al. 1982). The decrease in leaf expansion, vegetative growth, and leaf abscission leads to lowering in amount of capturing light (Sinclair and Ludlow 1985). Among the nutrients, nitrogen deficiency syndrome results in reduction in stem extension, leaf area index, and photosynthetic efficiency (Fernandez et al. 1993) and increases stomatal closure due to production of higher quantity of cytokinins and abscisic acid (Radin et al. 1987).

18.3.1 Sources of Assimilates

The synthesis of assimilates is affected by atmospheric CO_2, O_3, and agrochemicals, and exogenous application applied mineral nutrients and osmoprotectants (Baker and Boker 2010). These enrichment of CO_2 causes increase in photosynthesis and biological yield to the proportion of 37% and 40%, respectively (Reddy et al. 1997), whereas, its rate is reduced by 5.9% due to elevated O_3 concentration from 0.03 to 0.107 $\mu L\ L^{-1}$ (Reddy et al. 1989). However, application of plant growth regulators, viz., mepiquat chloride, gibberellic acid, and indolebutyric acid, causes increase in proliferation of roots and photosynthetic rate (Oosterhuis and Zhao 1993).

18.3.2 Sinks of Assimilates

Cotton plant accumulates starch in phloem and chloroplasts through photosynthetic process in the presence of higher quantum of CO_2 and radiance (photosynthetic photon flux density, PPFD) during day time and is translocated to growing points at night (Baker and Boker 2010). The supply of assimilates is shared equally between shoots and roots (Kimball and Mauney 1993); however, roots maintain sinks strength by more than six times than that of fruiting bodies (Fye et al. 1984). The growth rate is reduced at -1.2 MPa (leaf water potential (ψ_i)) during midday, which affects in balancing share between resource and sink (Marani et al. 1985). The growth and development of reproductive organs is enhanced at 27 °C and declines at 33 °C temperature (Baker et al. 1983), while greater proportion bolls are shed at 35/25 °C and eventually stopped at 40/30 °C temperature. The dray matter yield capsule of bolls is increased linearly with quantum of sink up to 20 DPA (days post-anthesis) and maximal at 30 DPA (Stewart 1986).

The occurrence of various physiological events is interacted by genetic makeup of genotypes, interception of light, photosynthetic rate, eco-edaphic factors, and farm management practices (Stewart 1986). The plastochron at main stem is 2–3 days leaf^{-1}, and 6–7 days leaf^{-1} at sympodial branches occurs at 27 °C temperature (Reddy et al. 1993). The source-sink relationship is imbalanced on the occurrence of reproductive organs (Baker et al. 1983). The shortfall of assimilates delays in initiation of nodal positions on main stem as well as on sympodia (Reddy et al. 1993). The quantum of production and redistribution pattern of assimilates leverage the loss in bolls and productivity (Constable et al. 1991).

18.4 Mapping of Cotton Plant

Plant diagrams are utilized to map bolls positions along with stages of development of all flowering on the day of sampling and to evaluate success of productivity input resources (Oosterhuis 1990). Opening of successive flowers on sympodia appears at interval of 6–7 days (horizontal interval), and first follower on successive branches opens at 3 days interval (vertical interval), besides second, third, and later flowers are likewise separated. This order is thus spirally outward and upward. The number of fruiting positions along sympodia varies greatly due to genetic constitution of the genotype, nutritional management, controlling insect-pest attack, and eco-edaphic and farm management factors. The retention of bolls on the first, second, and third sympodial positions contributes around 60%, 30%, and 10% toward total cotton productivity (Pervez et al. 2005a, b). Among these contributing factors, the meeting of nutritional needs cause substantial retention of harvestable bolls on the sympodia (Pervez et al. 2005a, b). Furthermore, the lint quality gathered from bolls on sympodia also tends to reduce away from main stem (Jenkins et al. 1990) (Figs. 18.2, 18.3, and 18.4).

Growth and maturation of cotton are temperature dependent, thereby occurrence of various growth stages can be predicted by calculating degree-days (DD) at threshold temperature of 15.6 °C (60 °F) and no upper threshold (Fry 1983). DD means the accumulation of heat units associated with everyday maximum besides minimum temperature during each day (El-Zik et al. 1980). The accumulated heat units for a particular growth stage help in maintaining the events during growing season (Landivar and Benedict 1996) (Table 18.1).

Under favorable growing environments, the plenty of irrigation water and excessive nitrogenous fertilization would result in rank growth, which causes heavy economic loss. The excessive vegetative growth may be checked by foliar spray of mepiquat chloride, for diverting its photo-assimilates from vegetative to reproductive organs. Thereby, developing bolls become great sinks for carbohydrates, H_2O, besides nutrients, and leaving a little food for vegetative development.

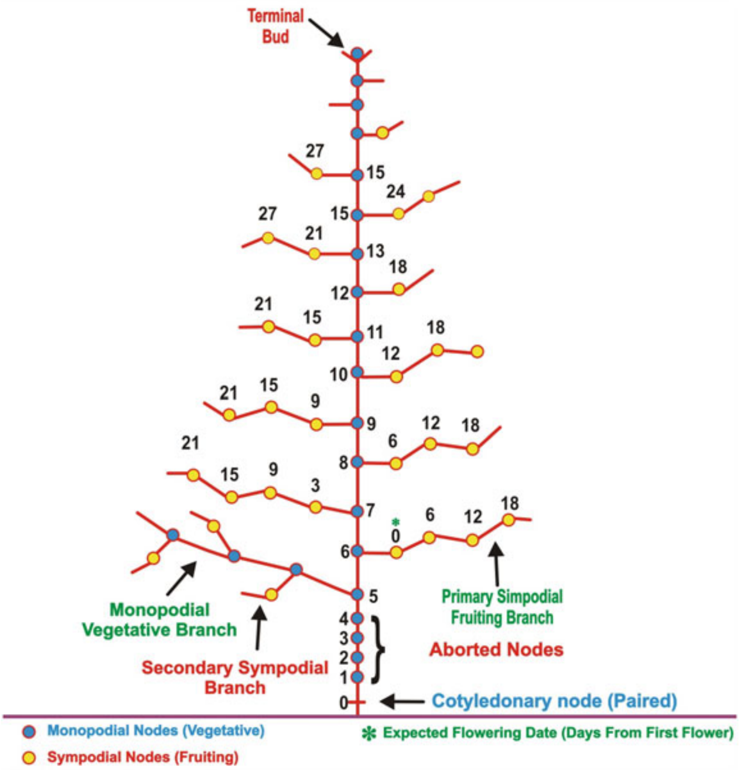


Fig. 18.2 Schematic cotton flowering pattern. (Redrawn from Oosterhuis 1990 and Pervez et al. 2005a, b)

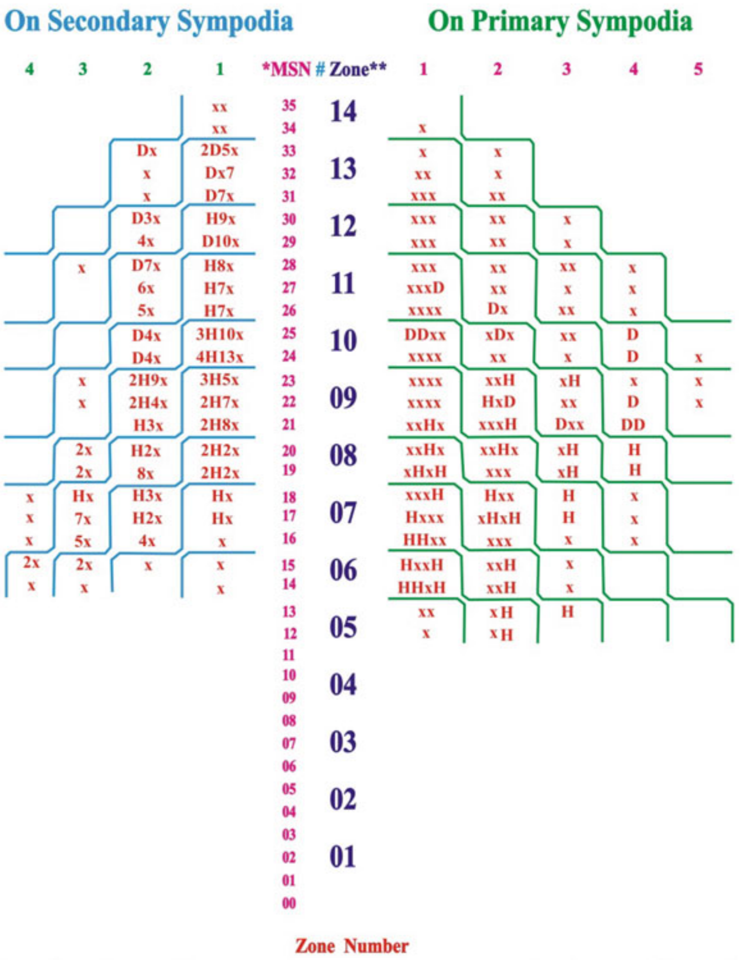
18.5 Fiber Development

Cotton fibers begin development as single cell that begin to form on unfertilized seeds called ovules (William and Bange 2018). On the physiological basis, quality of fiber is determined by interaction of genetic potential of genotype and environmental fluctuations experienced during growth period by cotton plant (Bradow and Davidonis 2010) (Table 18.2).

18.6 Abiotic Stresses

18.6.1 *Extreme Temperature Stress*

The temperature is the predominant among cardinal ecological aspects which influences crop growth and productivity since the beginning of germination/emergence

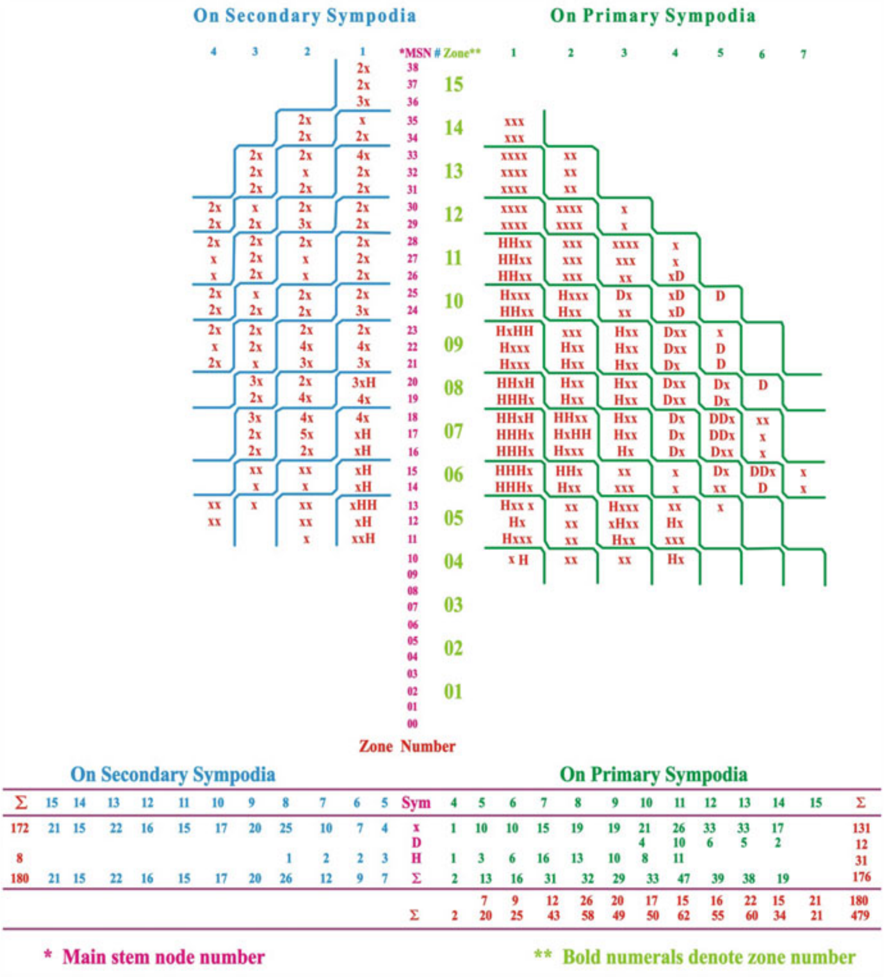


On Secondary Sympodia											On Primary Sympodia										
Σ	14	13	12	11	10	9	8	7	6	Sym	5	6	7	8	9	10	11	12	13	14	Σ
214	7	24	37	32	46	46	16	4	2	x	3	5	12	14	18	17	19	15	17	11	131
10	1	5	2	2						D						3	3	4	2		12
33			1	3	12	9	6	2		H		7	6	6	4	5	3				31
257	8	29	40	37	58	55	22	6	2	Σ	3	12	18	22	22	25	25	19	19	11	176
												2	6	22	55	58	37	40	29	8	257
										Σ	3	14	24	44	77	83	62	55	48	19	433

* Main stem node number

** Bold numerals denote zone number

Fig. 18.3 Fruit production efficiency without fertilizer application. (Modified and adapted after Pervez et al. 2005a, b)



Σ	15	14	13	12	11	10	9	8	7	6	5	Sym	4	5	6	7	8	9	10	11	12	13	14	15	Σ
172	21	15	22	16	15	17	20	25	10	7	4	x	1	10	10	15	19	19	21	26	33	33	17		131
												D							4	10	6	5	2		12
8								1	2	2	3	H	1	3	6	16	13	10	8	11					31
180	21	15	22	16	15	17	20	26	12	9	7	Σ	2	13	16	31	32	29	33	47	39	38	19		176
														7	9	12	26	20	17	15	16	22	15	21	180
												Σ	2	20	25	43	58	49	50	62	55	60	34	21	479

Fig. 18.4 Fruit production efficiency at 125 kg K ha^{-1}. (Modified and adapted after Pervez et al. 2005a, b)

Table 18.1 Phenological stages

Phenological event	Temp (°C)	Days after planting	References
First square	27	27	Reddy et al. (1993)
Square to bloom	27	20	Hesketh and Low (1968)
		24	Reddy et al. (1993)
		26	Hesketh et al. (1972)
Bloom to open boll	27	48	Reddy et al. (1992)
		61	Hesketh and Low (1968)

Table 18.2 Phenological events of cotton plant (*Gossypium hirsutum* L.)

Growth stages	Calendar days		Degree days[a] (Base 15.6 °C)
	Range	Average	
Sowing to emergence	5–20	10	50
Emergence to square	40–60	50	450
Square to bloom	20–27	23	330
Bloom to open boll	40–80	58	950
Normal crop production	190–210	200	>2800

[a] Degree days (DD) = Max temp −15.6 °C + Min temp 15.6 °C/2

stage and throughout one's life span (Burke and Wanjura 2009). Although cotton originates from hot climates, its yield is decreased appreciably due to higher temperatures especially during reproductive phase (Zhao et al. 2005). The minimum temperature for planting seed is 15.5 °C (60 °F) (Christiansen and Rowland 1986) and temperature of 35 °C for root development (McMichael and Burke 1994) for irrigated, while thermal kinetic window is 23.5–25 °C for rainfed cotton. The lowering of temperature from 30 to 18 °C causes reduction in hydraulic conductivity of roots, resulting in reduced proliferation of roots (Bolger et al. 1992).

The prevalence of higher temperature during early stage of growth affects the productivity to a greater proportion (Burke and Wanjura 2010). During reproductive phase, the increased in temperature from 18 to 28 °C resorts to increased fruiting branches from 5 to 16, while no fruiting branches are produced beyond 36 °C in Pima cottons. The phenomenon of sterility in flower occurs at temperature greater than 38 °C (Taha et al. 1981) and progression of fruiting structures (Reddy et al. 1995). The higher temperature causes increase in oxidative stress, lowers photosynthesis, and depletes ATP and carbohydrates (Oosterhuis and Snider 2010). The efficiency of metabolic activity in Upland cotton is the highest at its optimal thermal window of 23–32 °C (Snider et al. 2009). However, metabolic activity and membrane functions are diminished at 20–23 °C and below 15 °C, respectively.

18.6.2 Mineral Nutrients Stress

The success of cotton cultivation depends upon an adequate availability of macro- and micronutrients and eco-edaphic factors during the season (Mullins and Burmester 2010). Cotton having an indeterminate growth habit, contrarily to determinate ones, requires greater quantity of nutrients during its reproductive phase compared to vegetative phase (Pervez et al. 2005a, b). However, availability of nutrients during each growth period is pertinent to avoid any deficiency syndrome (Hodges and Constable 2010; Rochester 2012) (Table 18.3). The proportionate amount of translocation and/or relative redistribution of nutrients from vegetative to reproductive organs causes causal effects on cotton productivity. Nitrogen nutrient is more mobile than those of K, S, Ca, Mg, Fe, Mn, and B for their translocation

Table 18.3 Physiological basis of fiber development

Fiber development	Description
Initiation	It occurs just pre-flowering and at flowering. It is initiation of fiber cells on seed coat which can take up to 3 days. Thereafter, second set of fiber cells are initiated and develop into the fuzz
Elongation	This is rapid expansion besides growth of fiber cell's primary wall. Finally, fiber length is affected by length of besides rate of fiber elongation
Secondary wall thickening or fiber thickening	The secondary wall is formed where cellulose is laid down in layers inside fiber cell's primary wall. Deposition is affected due to fluctuations and formation of fiber growth rings. Due to fluctuations in photosynthesis on an everyday basis and formation of fiber growth rings. Cellulose layers are composed of two layers. The thicker is formed during day besides porous layer is formed at night
Maturation	Fiber cells dry out and fiber becomes a twisted ribbon-like structure. Mature fiber is easily detached from fuzzy seed

from leaves, stems, and capsule wall (Rosolem and Mikkelsen 1991). A greater quantum of N, P, and Zn is accumulated in the bolls and thereafter removed to seedcotton produce (Rochester 2007). The in-season nutritional status could be assessed by leaf tissue and petiole-nitrate analysis (Constable et al. 1991). The chlorophyll meters (Makhdum et al. 2002) and leaf/canopy reflectance sensors are also becoming more commonplace (Constable et al. 1991). The deficiency syndrome could be corrected by foliar and/or side dressing of nutrients (Makhdum et al. 2002).

Cotton plant follows sigmoidal curve for growth, dry matter production, and nutrient uptake after greatly during course of development (Oosterhuis 1990). The accumulation of nutrient is maximal at peak flowering for utilization of assimilates between vegetative and reproductive organs (Schwab et al. 2000). It accumulates 29%, 22%, and 21% of nitrogen, phosphorus, and potassium nutrient, at full flowering stage under irrigated condition (Halevy et al. 1987) (Tables 18.4, 18.5, 18.6, 18.7, and 18.8).

Cultivars vary in their nutrient uptake due to difference in demand between upper ground parts and root system (Kerby and Adams 1985), and also amount of externally application of fertilizers; e.g., N uptake is increased from 110 to 322 kg N ha^{-1} by adding nitrogenous fertilizer from 0 to 180 kg N ha^{-1} (Pervez et al. 2005a, b).

The appearance of deficiency syndrome is an outcome of inhibition of chlorophyll formation and/or occurrence of oxidative stress due to limited utilization of photo assimilates (Hodges and Constable 2010). During the discourse of growth, concentration of N, P, K, Fe, Cu, and Zn drops, while Ca, Mg, Na, Mn, S, and B increased in leaf tissues with advancement in age (Boquet and Breitenback 2000). The fruiting bodies especially bolls are the major sinks of nutrients, and their accumulation vary appreciably due to eco-edaphic factors, genetic makeup of

Table 18.4 Uptake of nutrients at maturity

Nutrients	Maximum uptake (kg ha^{-1}), (g ha^{-1})	Maximum uptake rate (kg ha^{-1} day^{-1})	Time of maximum uptake (days from sowing)	Percentage taken up during flowering
Nitrogen	332	2.1	102	55
Phosphorus	49	0.7	110	75
Potassium	312	3.2	115	61
Sulfur	71	0.8	101	63
Calcium	289	2.6	112	55
Magnesium	72	0.7	108	61
Iron	2592	24.0	130	46
Manganese	829	6.5	123	49
Boron	652	6.5	118	60
Copper	77	0.9	119	61
Zinc	272	3.7	109	73

Source: Hodges (1992)

cultivars, temperature and drought stresses, amount of nutrients in the rhizosphere, and other agronomic practices under different ecologies (Constable et al. 1988).

The removal of nutrients by harvestable portion determines the amount of nutrients required for gathering the targeted yield. Thereby replenishment of nutrients in consonance with nutrient(s) removal is pertinent to maintain soil fertility (Rochester 2007).

18.6.2.1 Boron Stress

Boron is most vital micronutrient for cotton (Rosolem and Costa 1999). The deficiency syndrome appears on younger growing parts due to limited translocation in plant system (Rosolem and Bogiani 2011). There is a very narrow range between sufficiency and toxicity levels of boron. Its toxicity causes negative effects on photosynthesis, chlorophyll constituents, cell division, and lignin development (Reid 2007). The reproductive phase is highly prone to boron deficiency (Zhao and Oosterhuis 2002). The requirement is about 340 g B ha^{-1}, of which 12% is retained in seed cotton and remaining is stored in other plant parts (Zhao and Oosterhuis 2003).

18.6.3 Drought Stress

Among the abiotic stresses, drought is the most limiting aspect for growth besides development of cotton. Cotton is being grown extensively is arid and semiarid regions, where irrigation supplies are limited most of times. Cotton is “xerophyte,”

Table 18.5 Pattern of nutrients uptake at full bloom stage

Nutrient	Total uptake (kg ha^{-1}), *(g ha^{-1})	Uptake index (kg/100 kg lint), *(g/100 kg seed cotton)	Peak uptake rate (kg ha^{-1} day^{-1}), *(g/ha^{-1} day^{-1})	% of total uptake at full bloom stage	Reference
Nitrogen	51–301	8–51	2.54–3.87	23–39	Mullins and Burmester (1991)
Phosphorus	8.2–72.3	1.3–3.3	0.31–0.48	21.36	Mullins and Burmester (1991)
Potassium	53–393	12.1–27.0	2.2–3.5	35	Mullins and Burmester (1991)
Magnesium	35–104	3.0–6.4	0.3–0.8	30–52	Mullins and Burmester (1992)
Calcium	60–70	6–77	1.5–3.1	46–49	Mullins and Burmester (1992)
Sulfur	15.6–25.1	1.0–6.8	0.34–0.49	30	Mullins and Burmester (1993)
Zinc	25–38	5–7	1.9–4.1	25–45	Mullins and Burmester (1993)
Manganese	451 ± 175	30.0	8.2–14.4	35–47	Mullins and Burmester (1993)
Copper	28 ± 14	4.0	0.34–1.33	29–58	Mullins and Burmester (1993)
Iron	600–814	242	23–27	41–60	Mullins and Burmester (1993)
Boron	66–17	9.3	–	–	Alimov and Ibragimov (1976)

(continued)

Table 18.5 (continued)

Nutrient	Total uptake (kg ha^{-1}), *(g ha^{-1})	Uptake index (kg/100 kg lint), *(g/100 kg seed cotton)	Peak uptake rate (kg ha^{-1} day^{-1}), *(g/ha^{-1} day^{-1})	% of total uptake at full bloom stage	Reference
Molydenum	1.97–4.03	–	–	–	Alimov and Ibragimov (1976)
Cobolt	2.44–4.35	–	–	–	Alimov and Ibragimov (1976)
Sodium	4.3–17.1	–	–	–	Bassett et al. (1970)

Table 18.6 Uptake of nutrients at various growth stages

Uptake (kg ha^{-1})				
Stage of growth	Plant organ	Nitrogen	Phosphorus	Potassium
First flower bud	Leaves	7.3	0.47	6.0
	Stems	1.6	0.14	8.9
	Total	8.9	0.61	14.9
First flower	Leaves	21.4	1.23	19.7
	Stems	9.1	0.64	19.7
	Capsule	5.7	0.66	4.9
	Total	36.2	2.53	44.3
Peak flowering	Leaves	28.0	1.32	28.3
	Stems	11.2	0.97	26.4
	Capsule	3.7	0.77	7.3
	Seed	13.5	1.47	10.1
	Lint	1.1	0.27	4.3
	Total	57.5	4.80	76.4
First boll split	Leaves	29.8	1.29	35.1
	Stems	12.6	1.15	31.4
	Capsule	3.2	1.09	15.0
	Seed	28.5	3.97	24.3
	Lint	1.2	0.71	9.4
	Total	75.3	8.21	115.2
Maturity	Leaves	10.6	0.54	11.2
	Stems	8.9	0.75	16.9
	Capsule	3.2	0.72	18.3
	Seed	46.5	7.61	22.8
	Lint	1.0	0.40	7.6
	Total	70.2	10.02	76.8

Table 18.7 Pattern of accumulation and timings of nutrients by cotton boll

Nutrient	Maximum uptake per boll (mg/boll), (µg/boll)	Maximum uptake (per day)	Time of maximum uptake (days from anthesis)
Nitrogen	111	36	19
Phosphorus	21.4	0.71	19
Potassium	10.3	3.2	19
Sulfur	17.5	0.37	26
Calcium	31.0	0.82	27
Magnesium	17.2	0.45	21
Iron	221	5.6	24
Manganese	111	2.5	22
Boron	118	3.8	18
Copper	30	0.91	19
Zinc	104	3.0	18

Adapted after Constable et al. (1988)

Table 18.8 Proportional nutrients uptake towards differential yield level

	Nutrients uptake (kg ha^{-1}), ^{a}(g ha^{-1})			% Exported		
Lint yield (kg ha^{-1})	1000	1800	2400	1000	1800	2400
Nitrogen	63	175	290	66	52	46
Phosphorus	13	27	41	82	69	60
Potassium	77	167	250	21	17	15
Sulfur	10	39	62	42	21	18
Calcium	71	94	155	3	3	2
Magnesium	16	36	63	45	34	25
Iron[a]	227	820	1620	40	17	11
Manganese[a]	152	355	655	5	3	2
Boron[a]	75	320	560	22	13	11
Copper[a]	25	52	81	51	38	31
Zinc[a]	58	119	203	99	73	61

Adapted after Rochester (2007)
[a] Nutrients uptake (g ha^{-1})

a plant which requires less water, and tolerant to heat besides drought. Cotton plants avoid adverse weather possibly due to deep well-distributed root system along with indeterminate growth pattern. Evapotranspiration (ETc)-based requirement of water is to be 2.0 mm day^{-1} (20,000 L ha^{-1}) through vegetative stage besides 6 and 8 mm day^{-1} during flowering and early-bulling period (termed as critical window). It requires around 80–85% of total water during this “critical window”; however, moisture stress during this stage caused severe yield losses. Contrarily, excessive moisture coupled with higher amount of nitrogenous fertilizers during vegetative and boll opening stages results in reduced growth and lowering of yields.

Plants undergo a series of integrated events, varying from signaling stress and transduction to the gene expression as an effort to acclimatize under the stressful conditions. The drought stress is evidenced at whole plant, cellular and molecular levels (Chaves et al. 2009). Water stress caused reduction in photosynthesis and growth, because of stomatal closure along with lowered activity of photosynthetic enzymes (Chaves et al. 2009) and efficiency of chloroplast to fix carbon dioxide (Bota et al. 2004). At the cellular level, the oxidative stress is occurred due to generation of reactive oxygen species (ROS) with concurrent working in stress signal transduction pathway (Foyer and Noctor 2009). The appreciable changes occur in protein synthesis and biological functions at molecular level in response to drought stress. The gas exchange parameter, viz., net photosynthesis, stomatal conductance, and transpiration rate, while fluorescence parameters, i.e., effective quantum yield of PSII (Φ psII), and electron transport rates are declined in response to drought. However, quantum of hydrogen peroxide, malondialdehyde (MDA), and anthocyanin levels are enhanced under drought stress (Deeba et al. 2012).

The plant having intrinsic self-defense system accumulates heat shock proteins (HSP) besides late embryogenesis abundant (LEA) proteins and also accumulates compatible solutes and potassium to maintain water potential gradient (Loka et al. 2011; Oosterhuis and Wullschleger 1987). Under the stressful conditions, the production of abscisic acid and ethylene causes abscission of bolls and other fruiting bodies (Dumka et al. 2004), thereby, results in retention of lower amount of fruits, boll weight, and loss in yield (Saini 1997; Ritchie et al. 2009).

The water use efficiency is reduced because of reduction in photosynthesis and transpiration rate (Loka et al. 2011). It varies greatly due to fruiting habits of varieties, load of fruiting bodies, and stage of growth (Parida et al. 2007). Water under water stress ROS, like peroxide radicals, hydrogen peroxide besides hydroxyl radicals are generated (Faria et al. 1997) and cause oxidative stress. Under this condition, antioxidant defense comes into play its role as scavenger. The major role is played by antioxidant species, viz., superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (AP), glutathione reductase (GR), and carotenoids along with α-tocopherol come in to action to work as scavenger (Gaspar et al. 2002).

Deleterious effects of draught stress can be ameliorated by foliar spray of some asmoprotectants, viz., glycine betaine, salicylic acid, RGR-IV (containing gibberellic acid and indolebutyric acid), and 1-methylcyclopropene. These chemicals enhance production and accumulation of osmolytes in the plant system to protect enzymatic system, lipid peroxidation, and photosynthetic apparatus (Allakhverdiev et al. 2003; Gorham et al. 2000; Waseem et al. 2006; Zhao and Oosterhuis 1997; Loka and Oosterhuis 2011).

On an average, irrigation water usage is 1214 L to produce 1.0 kg lint plus 2.0 kg seed. Globally, 87% of total production is harvested by using 644 L irrigation water kg^{-1} lint. The water productivity can be enhanced by rainwater harvesting, irrigation with precision timing based on ET, irrigation through alternate furrows, sprinklers, or subsurface drip irrigation. The soil and moisture conservation methods like minimum tillage, mulching, cover crops or intercrop, and efficient pest besides weed control could result in improving water use efficiency and water productivity.

18.6.4 Salinity Stress

Salinity in topsoil and subsoil is one of key abiotic ecological stresses to cotton production. Globally, one-third of total agricultural land is salt affected, which lies in arid and semiarid environments. Although, cotton is categorized as one of the most tolerant crops (Maas 1990), however, its growth and development and economic yield are affected to a greater proportion (Higbie et al. 2010; Khorsandi and Anagholi 2009). The salt stress reflects differential response in cotton, due to quality of irrigation water, amount of rainfall, and proportionate amount of salts in soil. Among the cotton species, viz., varieties of *Gossypium barbadense* L. has greater tolerance capacity compared to *G. hirsutum* L., besides *G. arboretum* L. (Abul-Naas and Omran 1974).

At onset of growth and development, germination besides seedling stages is highly prone to salt stress (Oliveira et al. 1998; Malik and Makhdum 1987; Gorham et al. 2010). The presence of salinity at >282 mol m^{-3} (NaCl) causes damaging effects on root growth (Silberbush and Ben-Asher 1987). The shoot growth is inhibited due to reduction in soil water potential and vapor pressure deficit (Shalhevet and Hsiao 1986; Gorham et al. 2010). The toxicity of salts can be ameliorated through adequate nutrition (Brugnoli and Björkman 1992). During the reproductive development, the photo-assimilates from source to sink are restricted, causing burden on reduced number of fruiting bodies, heavy fruit drop, and lowering in retention of bolls, thereby leading to economic loss in yield and fiber quality (Moreno et al. 2000; Ahmad 1994), and reducing the values of fiber length, fiber strength, fiber fineness, and amount of oil content in seed (Muhammed and Makhdum 1973; Ahmad 1994).

The salt stress causes stomatal closure and increased resistance to CO_2 diffusion rapid senescence (Gorham et al. 2009), chlorophyll constituents ‘a’ and ‘b’ (Ahmad and Abdullah 1980; Jafri and Ahmad 1995), excessive buildup of Na^+ along with Cl^- in leaf tissues leading to osmotic stress (Zhang et al. 2012) and reduced movement of osmolytes from source to sink (Jafri and Ahmad 1995).

The salt-tolerant varieties maintain lower K^+/Na^+ ratio than salt-sensitive ones (Läuchli and Stelter 1982; Nawaz et al. 1986). The higher K^+/Na^+ ratios occur due to restricted movement of K^+ and Cl^- in the phloem (Abdullah and Ahmad 1986). The assimilation of Ca^{2+} and Na^+ ions from root cells causes greater efflux of K^+ (Cramer et al. 1985) and maintenance of selectivity of K^+ over Na^+ in plasma membrane (Gorham et al. 2010). The plant accumulates greater proportion of protein (Brugnoli and Björkman 1992), while assimilation of N, P, and K is decreased (Subbarao et al. 1995) enhancing leaf phosphorylase activity in leaf (Rathert 1983). Cotton plants develop salt tolerance and water stress by greater production besides accumulation of K^+, sucrose, glucose, amino acids, proline, and glycine betaine (Lin et al. 1995; Gorham 1996). The presence of antioxidant defense system (catalase, ascorbate peroxidase, superoxide dismutase, glutathione reductase) improves salt tolerance in cotton (Banks et al. 2000; Li et al. 1998).

The tolerance capacity can be enhanced by soaking cotton seed with $CaSO_4$ and foliar spray of kinetin solution, MC BU TTB, and polystimuline K (10–20 ppm) (Gorham et al. 2000; Stark and Schmidt 1991). The exogenous application of gibberellic acid (GA3) mitigates the burden of salinity by enhancing growth, greater uptake of K^+ with simultaneous reduction in Na^+ ion (Ibrahim 1984; Gossett et al. 2000). Cotton may be successfully cultivated by adopting certain agronomic measures, e.g., cultivation on furrows with plastic mulching (Dong et al. 2010), maintaining plant density at 4–5 plants m^{-2} (Zhang et al. 2012), alternate irrigation with saline and non-saline water (Moreno et al. 1998), furrow irrigation and/or drip irrigation (Ghani et al. 2007), sprinkling system (Meiri et al. 1992), application of nitrate nitrogen rather than ammonium nitrogen (Leidi et al. 1991), addition of soil amendments (sand, gypsum (calcium sulphate)), growing sesbania alone, or intercropping (Tiwari et al. 1993; Tiwari 1994). Apart from these, cultivation of salt-tolerant cultivars would be more valuable and cost-effective (Malik and Makhdum 1987; Iqbal et al. 1991; Gorham et al. 2010).

18.6.5 Air Pollution Stress

The footprints of air pollution comprised of primary (N_2, O_2, CO_2, methane, and anthropogenic compounds) and secondary (O_3, peroxyacetyl nitrate, H_2O_2, and oxygenated compounds) pollutants affect growth and development (Temple and Grants 2010). Among these, ozone (O_3) causes deterioration in cell membrane and partial and/or complete loss of turgor pressure at 0.25 ppm on higher (Runeckles and Chevone 1992; Heagle et al. 1986). The net photosynthesis (Pn) in appreciably reduced at >0.20 ppm (Grantz and Farrar 2000).

In response to O_3 exposure, the attributes of photosynthetic efficiency, abscission of leaves, and yield are reduced due to decreased efficiency in CO_2 assimilation (Miller et al. 1988). However, cotton plant has an in-built compensatory mechanism to tolerate the adverse effects of O_3 (Temple 1990). The root organ is highly prone to O_3 stress compared to shoot organ, because of reduced root hydraulic capacity (Grantz and Yang 1996). Cotton varieties vary greatly in their relative tolerance to O_3 and other pollutants (Runeckles and Chevone 1992), and yield is reduced from 15% to 20% (Heck et al. 1988).

Cotton is quite responsive to increased concentration of CO_2 from 550 to 650 ppm and causes enhancement I growth by 65% and yield by 50% (Kimball and Mauney 1993; Mauney 2010), net photo synthesis from 65% to 70% (Inoue et al. 1990); total biomass by 37%, increase in LAI of 4 (Mauney et al. 1994), C/N in ratio leaves and stems (Hendrix 1992), boll loading period and yield (Mauney et al. 1994), and water use efficiency by 19–28% (Dugas et al. 1994). However, under changing climatic condition, the cotton yield may decrease due to interactive effect of increased temperature and carbon dioxide (Reddy et al. 1996). The adverse effect of O_3 could be scavenged by exogenous application of some antioxidants, viz., citrate, ascorbate, and ethylene di-urea (EDU) ([*N*-2-(2-oxo-1-imidozolidimyl) ethyl]-*N*′-phenyl urea) (Manning and Krupa 1992), overhead sprinkler (Grantz et al. 1997) and breeding of varieties resistant to O_3 by employing conventional and molecular engineering technology (Grantz and McCool 1992).

18.7 Future Perspective

A number of advances have been made in revealing basics of physiology of cotton in consonance with rapid development of highly productive varieties and be resilient to external environment. In the present times, primary challenge is to enhance the tolerance level to drought and salinity for maintaining the productivity on the marginal lands. Presently much progress has been made in the development of biotech cotton varieties, which has accounted for more than 50% of world cotton production. The development of drought tolerant and/or water-efficient varieties would be required in the wake of declining freshwater supplies for irrigation purpose.

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