3.1 Cotton growth responses to water stress

Dallas Gibb
formerly NSW Agriculture

Greg Constable
CSIRO Plant Industry

James Neilsen
formerly CSIRO Plant Industry, Narrabri

Key points

- Cotton plant responses to water stress will vary depending on the stage of growth at which the stress occurs, the degree of stress and the length of time the stress is imposed.
- The plant aims to establish a balance between carbohydrate supply and demand. Water stress at any stage of growth will impact on both the production and distribution of carbohydrates throughout the plant. Carbohydrate demands placed on the plant primarily by developing bolls restricts excessive vegetative growth.
- Through adaptation, the cotton plant survives during periods of water stress by prioritising the maintenance of different physiological processes to ensure the production of viable seed and therefore cotton fibre. The impact of water stress on final yield will depend on the degree to which each physiological process is affected.

By understanding some of the principles of plant growth and how cotton plants have adapted to reduce the impact of water stress on growth, growers may better utilise their available water resources to improve water use efficiency.

Plant growth = carbohydrate supply and demand.

Cotton has an indeterminate growth habit and therefore under favourable conditions the number of leaves, new nodes, fruiting branches and squares, can increase rapidly unlimited by a phenological time frame and will continue to be produced while conditions remain favourable. During the pre-flowering stages of growth, production of carbohydrates (through photosynthesis) is in excess of demands and as a result vigorous vegetative growth occurs.

As plant growth continues, the demands for carbohydrates by the component plant parts such as bolls increase, and production becomes limited by environmental conditions. Boll growth exerts large demands for carbohydrates and it is through the balance between boll demand and leaf production that vegetative growth is restricted. The over production of squares by the plant is an adaptation by the cotton plant which ensures that a balance is achieved between carbohydrate supply and demand. Square shedding during periods of cloudy weather for example are mediated through reduced carbohydrate supply and are examples of how plant growth is balanced between carbohydrate supply and demand.

Water stress can restrict both vegetative and boll growth. It has been shown that no matter what degree of water stress is imposed on a crop, the proportionality between vegetative growth and boll development remains relatively constant. Similar results have been achieved with crops receiving different amounts of nitrogen. This implies that independent of water or nutrient supply, the plant will always attempt to form a balance between vegetative growth and boll development.

Table 3.1.1 shows distribution of dry matter in cotton plants grown under different irrigation frequency and nitrogen fertiliser (average over three seasons data).

Table 3.1.1. Distribution of dry matter in cotton 140 days after sowing

Irrigation	Fertiliser kg N ha^{-1}	Dry weight of tops gm^{-2}	Distribution of dry weight (%)		
			leaf	stem	boll
Frequent	0	450	15	34	51
Frequent	150	747	15	42	43
Infrequent	0	460	18	34	48
Infrequent	150	695	18	39	43

Source: Constable and Hearn 1981

Carbohydrate production and water stress

Production of carbohydrates through the process of photosynthesis and their storage are the primary functions of leaves. Leaf age is an important plant factor affecting daily photosynthesis. In non-stressed plants, peak carbohydrate production from an individual leaf occurs when the leaf is around 20 days old. Peak plant carbohydrate production will occur when the combination of photosynthesis per unit leaf area and leaf area is maximised. In non-stressed plants this usually occurs some 60 to 70 days from the unfolding of the first true leaf (75 to 85 days after planting). Decline in daily carbohydrate production after this date results from increasing canopy leaf age and increased self shading and the increase in boll demand for carbohydrates, which restricts any new leaf development.

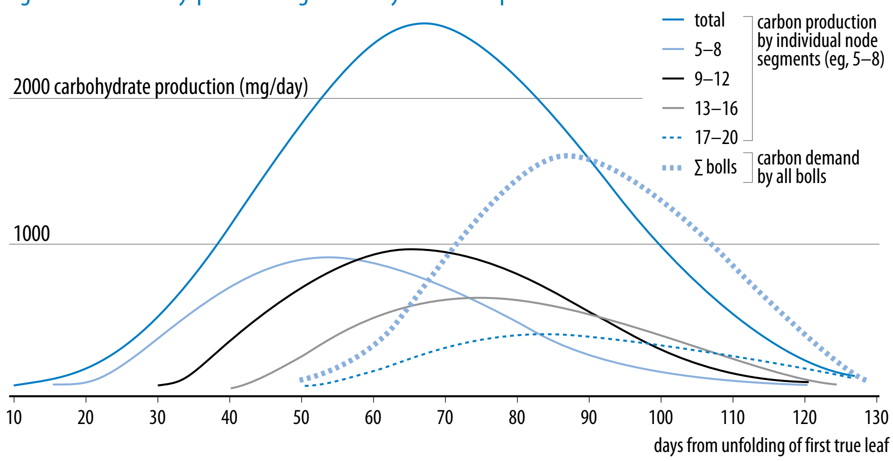
Figure 3.1.1 shows daily potential carbohydrate production for individual node segments and an accumulated total for the total canopy, boll demand has been superimposed over production.

It is evident from this data that factors which impact on leaf development, particularly early leaf development, will affect total plant carbohydrate production and therefore yield potential. Water stress has been shown to reduce whole plant leaf area largely through reductions in total leaf numbers. However the rate of leaf expansion is also reduced, which in turn reduces the size of individual leaves.

Reduction in leaf area will obviously impact on the level of total canopy photosynthesis. Photosynthesis is maintained in priority over leaf expansion and development. This allows the plant to maintain current photosynthetic capacity but limits future capacity. The value is that it also stops demand for water increasing when there is not enough to meet even current demands.

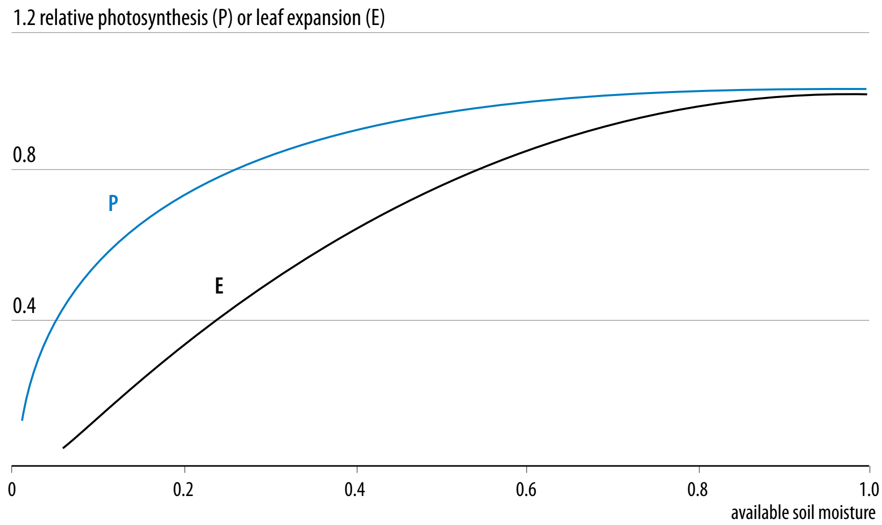
Figure 3.1.2 shows the relationship between available soil water and relative leaf net photosynthesis and daily leaf expansion.

Figure 3.1.1. Daily potential growth by a cotton plant



Source: Constable and Rawson 1980

Figure 3.1.2. Available soil water and its effect on relative net photosynthesis and relative daily leaf expansion



Relative refers to the ratio between stressed and non-stressed plants.

Source: Constable and Rawson 1982

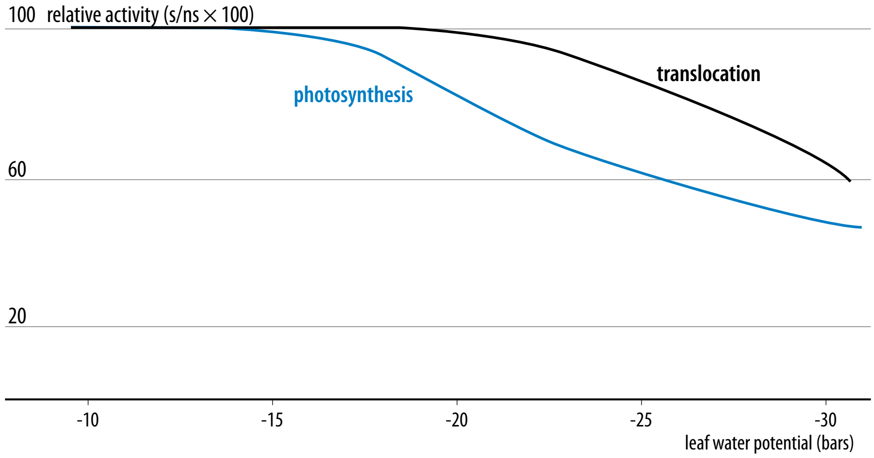
It can be seen that leaf expansion has been greatly reduced by the time photosynthesis has started to decline. In terms of plant growth, the maintenance of photosynthesis will enable boll and root growth to continue longer during periods of water stress than vegetative growth. This drought adaptation will also allow the plant to recover quickly from small periods of mild stress, particularly during early, pre-flower growth stages

Carbohydrate re-distribution

The export or re-distribution of carbohydrate from an individual leaf is initially small, so as to allow effective leaf growth. Once leaf growth has stopped at around 20 days of age, however, carbohydrate in excess to leaf requirements is produced and this can either be stored as starch for later use or be directly exported to actively growing plant parts.

The rate of export of carbohydrate from the leaves is determined by the demand imposed by other plant parts. Actively growing organs such as roots, bolls and growing terminals act as sinks which will actively compete for the available carbohydrate. The pattern of distribution will depend on the leaves capacity to satisfy the requirements of individual sinks. Since it is particularly important for the plant to have the capacity to utilize excess carbohydrate during periods of stress. plant adaptation allows the processes involved in transferring carbohydrates away from the leaves to continue at higher water stress levels than those that reduce photosynthesis (Figure 3.1.3). Therefore, water stress not only effects production of carbohydrate but also alters its distribution.

Figure 3.1.3. Relative activity of photosynthesis and translocation in cotton leaves as a function of leaf water potential



s = stressed; ns = non-stressed

Source: Krieg and Sung 1986

Root development

At the time of flowering, around 80% of the plant's root system may be developed and thus the root system imposes the greatest demand for excess carbohydrates during early plant growth. After flowering, boll development begins to compete with the root system for carbohydrates and the rate of root expansion declines. Under water stress, however, the plant is adapted to place priority on root growth. As a result, root expansion occurs at the expense of vegetative and boll growth. Figure 3.1.4 compares vegetative and root dry matter levels for crops produced with adequate moisture and moisture stress (dotted line).

Figure 3.1.4. Pattern of dry weight over time

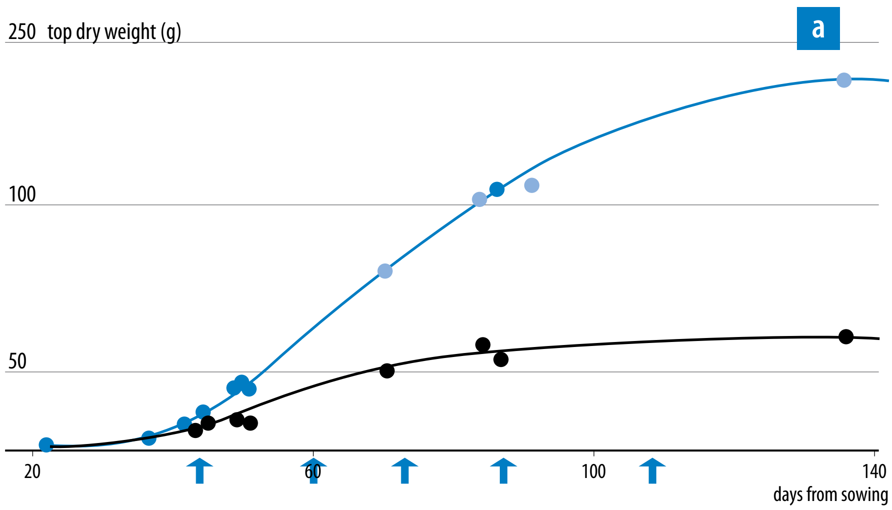
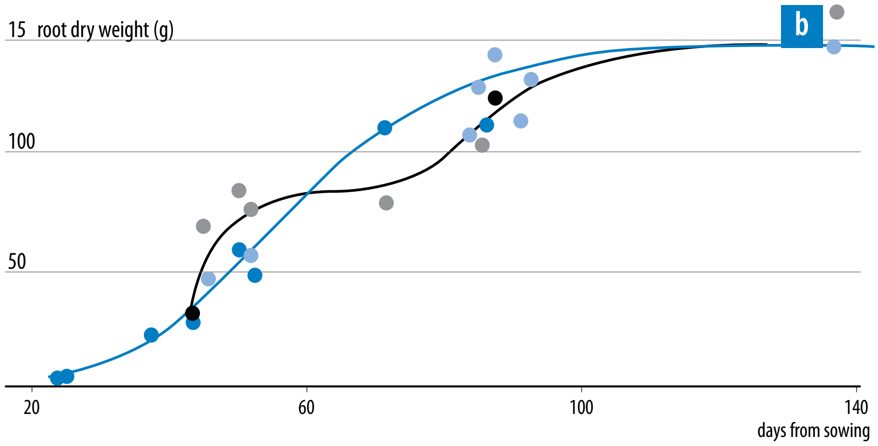


Figure 3.1.4. (cont.)



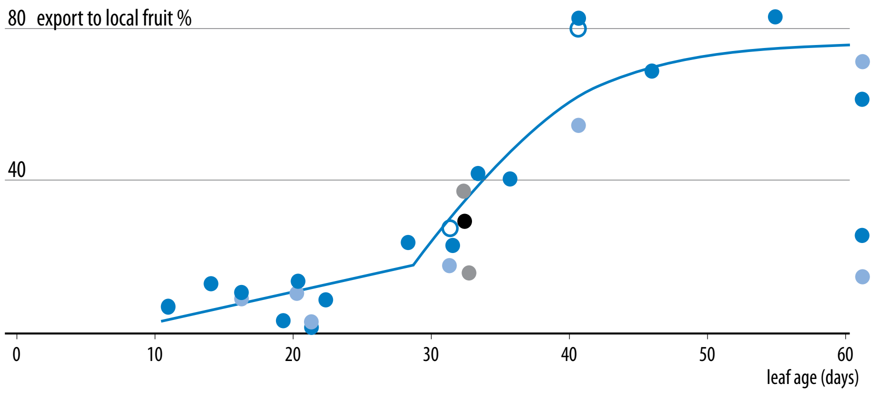
(A) top vegetative growth and (B) roots as affected by moisture stress.
Blue line = adequate moisture, black line = moisture stress

Source: Constable and Rawson 1982

Boll development

Squares exhibit little carbohydrate demand on the plant during early growth, with bracts supplying the majority of their requirements. A rapid increase in demand for carbohydrates occurs after flowering (Figure 3.1.5) This is the reason that the majority of fruit is shed as flowers and/or two or three day old bolls. Shedding of bolls can occur up to an age of 10 to 14 days, after which cell wall thickening between the boll and stem prevents an abscission layer from forming. In the case of a rapid onset of water stress, young bolls in which growth has stopped may be retained by the plant and appear as 'mummified' dry bolls. Figure 3.1.5 illustrates that up to 80% of the carbohydrate produced by this leaf is exported to the local boll. It has also been shown that the proportion of carbohydrate distributed from leaf to boll is not effected by water stress. This implies that boll development is affected by total carbohydrate supply and not by the rate of distribution from adjacent leaves. This is consistent with the fact that redistribution of carbohydrate can occur at stress levels beyond those that effect production (Figure 3.1.3) .

Figure 3.1.5. Relationship between leaf age and the proportion of carbon export from the leaf found in the adjacent fruit as affected by soil water

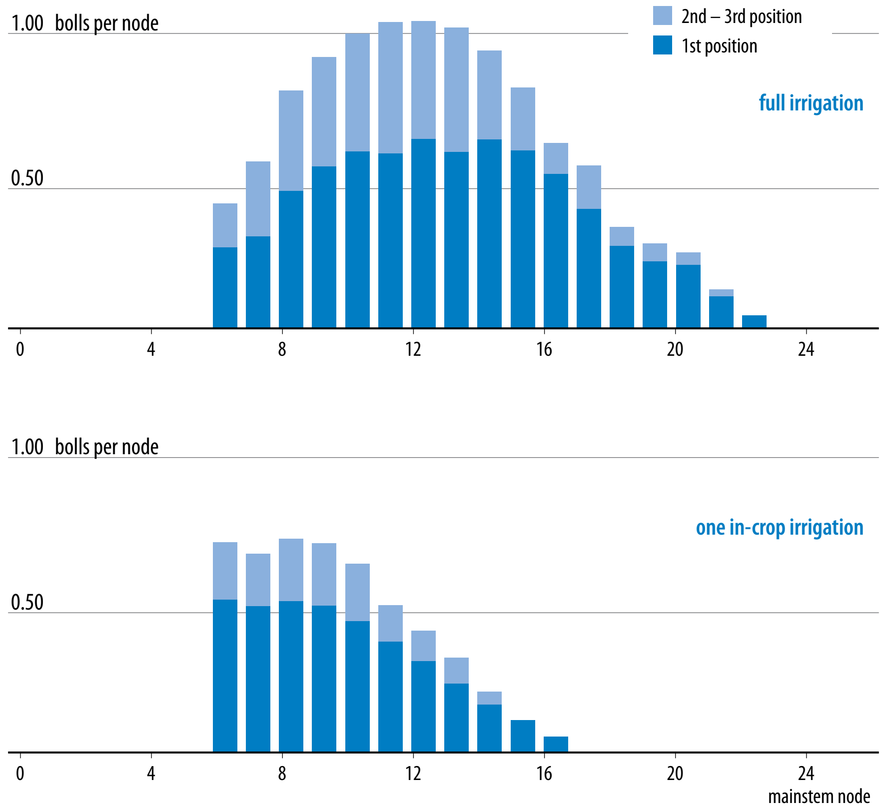


Source: Constable and Rawson 1982

As boll demand exceeds supply from the adjacent leaf, inter-boll competition for further carbohydrate occurs. Older bolls compete more effectively than younger bolls and this results in the movement of carbohydrates away from the extremities of the main stem and individual fruiting branches. Those bolls unable to compete effectively are either shed by the plant or are reduced in size hence the occurrence of smaller boll towards the top of the plant. It is for this reason that the majority of fruit, particularly secondary position bolls, are retained by lower fruiting branches.

In non-stressed irrigated crops, increased early vegetative growth results in shading of lower leaves and this causes reduced retention and boll size on the first two or three fruiting branches. The final results of this combined inter-boll competition and leaf shading in fully irrigated crops is the common bell shaped distribution of bolls throughout the plant (Figure 3.1.6). In the case of crops under water stress, the same inter-boll competition occurs, however there is generally less total carbohydrate to be distributed amongst bolls. Reduced vegetative growth also minimises shading of lower leaves, resulting in the higher boll retention and boll size occurring amongst the first fruiting branches. Figure 3.1.6 shows the differences in boll distribution throughout the plant that can occur between a fully irrigated crop and a crop that had received one in-crop irrigation.

Figure 3.1.6. Pattern of boll distribution as affected by water stress



Source: D Gibb and Colly Farms

Water stress and crop yields

The degree of plant response to stress will vary depending on the level of stress which occurs and the timing at which the stress is imposed, relative to crop growth. Table 3.1.2 summarises the plants responses to differing degrees of water stress, the effects on final crop yield, fibre development, maturity and water use efficiency are also discussed.

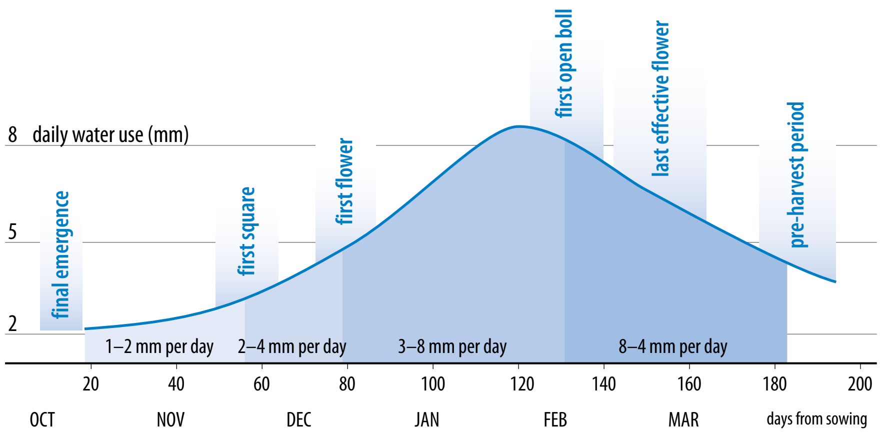
Table 3.1.2. Summary of responses to water stress

Degree of water stress	Possible causes	Physiological plant responses	Yield effects on maturity and WUE
Minimal stress	Reduced irrigation deficit	Excessive vegetative growth	Reduced yield
	Excessive rainfall	Increase in leaf area	Reduced boll size
	Cloudy weather	Extended flowering cycle	Delayed maturity
	Excessive early insect damage	Reduced carbohydrate surplus for bolls	Normal fibre length but low micronaire
	High plant stands	Reduced root development	Poor WUE
		High boll capacity but poor boll retention	
Mild stress	Optimum irrigation deficit	Optimum vegetative growth rate	Maximum yield
	Average temperatures (not excessively hot)	Leaf expansion restricted	High quality cotton
		Photosynthesis remains unaffected	No delay in maturity
		Maximum carbohydrate surplus	Maximum WUE
		Maximum boll development	
		Good fibre development	
Moderate stress	Increased irrigation deficit	Reduced vegetative growth and leaf expansion	Reduced yield
	Extremely hot temperatures with low humidity, windy conditions	Reduced photosynthesis	Early maturity
	Little cloud cover	Reduced surplus carbohydrates	Increased short fibre micronaire
		Reduced boll carrying capacity	Slight decrease in WUE
		Increased fibre development	
Severe stress	Less than 3 irrigations	Vegetative growth greatly reduced - stops after flowering	Low yields
	Dryland crops	Greatly reduced carrying capacity	Short fibre
		Little surplus carbohydrates	High or low micronaire depending on stress pattern
		Low boll retention	WUE depends on rainfall

Crop water use and plant growth

A cotton crop's requirement for water changes throughout the growing season, following the pattern of evapotranspiration. The rate of evapotranspiration is determined primarily by meteorological factors and the availability of soil water. Total crop evapotranspiration will vary with canopy size, or leaf area. Crop leaf area peaks some 3 to 5 weeks after the start of flowering and this results in a peak in daily water use of between 8 and 10 mm (Figure 3.1.7).

Figure 3.1.7. Nominal seasonal daily water use (mm/day) for cotton production



Maximum demand for water also coincides with the growth period between peak flowering and early boll development. Exposing the plant to water stress at this stage of growth can result in significant yield reductions. The impact of water stress at different crop growth stages on final yield is directly related to the water demands expressed by the crop. Stress during periods of high water demand can produce large reductions in yield. Table 3.1.3 shows yield reductions resulting per day of stress for different crop growth stages. Stress during peak flowering can double yield losses compared to early or late seasonal stress. The impact of any one stress period is increased if followed by further stress. For high yielding, Bollgard II crops the impact of water stress during late flowering can equate to a yield loss of 2.7% for every day that an irrigation is delayed.

Table 3.1.3. Yield loss (%) per day of water stress (extraction of > 60% plant available water) (Source Yeates et al. 2010#; Hearn and Constable 1984*)

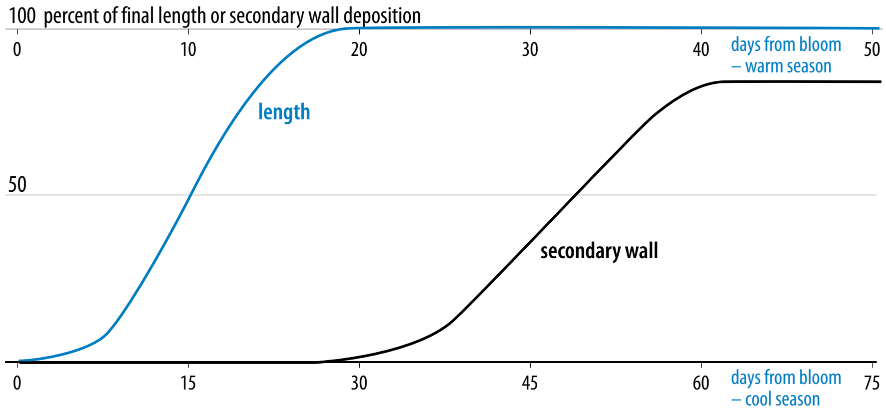
	Past Conventional*	Bollgard#
Squaring	0.8	1.1
Peak flowering	1.6	1.7
Late flowering	1.4	2.7
Boll maturation	0.3	0.69^

^ 14 d post cut out

Fibre development

Fibre development begins the day after flowering and is a two stage process with fibre elongation (length) preceding secondary wall development (thickening). In a non-moisture stressed situation, fibre length reaches a maximum between 20 and 30 days post flowering with fibre wall development being completed some 40 to 60 days post flowering, depending on temperature (Figure 3.1.8).

Figure 3.1.8. Time of biological maturation of cotton fibres as effected temperature



Although temperature is the main determinant of the length of the period between flowering and boll opening, carbohydrate supply directly effects the degree of fibre development and final boll size. As discussed previously, under water stress younger bolls are shed to enable the development of older bolls. The plant has increased its adaptation for survival during drought by placing priority on seed and fibre development over total fruit retention. This is demonstrated by the fact that young boll shedding can occur at lower moisture stress levels (-19 bars), while fibre development is not effected until higher stress levels (-26 bars) are reached. The increase in micronaire generally associated with cotton suffering from water stress at the end of flowering is a good example of this plant adaptation. Increase in micronaire occurs because younger bolls are shed, and more carbohydrate becomes available to lower bolls. With fibre development continuing under higher stress levels, any extra carbohydrate available is allocated to increases in fibre cell wall thickening, leading to increases in micronaire.

Moisture stress during peak flowering will tend to affect fibre length rather than fibre maturity, while stress later in the season will primarily affect fibre maturity.

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