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# Development of Mathematical Model for Abiotic Stresses and Cotton Fiber Quality

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# Development of mathematical model for abiotic stresses and cotton fiber quality

By

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Abiotic stresses cause extensive losses to agriculture production worldwide. Cotton (*Gossypium hirsutum* L.) is an important fiber crop grown widely in subtropical region where temperature, water and nutrients are the common factors limiting crop production. Such losses could be more severe in the future climate as intensity and frequency of those stresses are projected to increase. The overall goal of this study was to evaluate effects of abiotic stresses on cotton reproductive performance and develop functional algorithms for fiber properties in response to different stress factors. Three experiments were conducted to evaluate the effects of temperature, water, and nitrogen in naturally-lit growth chambers. Influence of potassium nutrition was conducted in outdoor pot culture facility. In all experiments, upland cotton cultivar TM-1, a genetic standard, was used by imposing treatments at flowering. In all experiments, growth and photosynthesis measurements were recorded frequently during the treatment period. Biomass of various plant- and boll-components determined at harvest when 80% bolls were opened. Boll developmental period was tracked by daily tagging of flowers and open bolls. Bolls were grouped on the basis of onset of anthesis and lint samples were

pooled together for fiber analysis. Fiber quality was assessed using High Volume Instrumentation and Advanced Fiber Information System. Total plant biomass, boll weights, and numbers significantly declined for plants grown under low and high temperature, severe water stress and nitrogen and potassium deficient conditions compared to optimum conditions for the respective stresses. Gas exchange processes were severely affected by moisture, nitrogen, and potassium deficient conditions. Time required from flower to open boll was mostly affected by growing temperature but not modified by other stresses. Fiber micronaire was most the responsive to changes in temperature, followed by strength, length and uniformity. Water limiting conditions and nitrogen defficiency severely affected strength and micronaire, whereas potassium deficiency had significant effect on fiber micronaire. This study was used to develop functional algorithms between abiotic stresses and fiber properties, once integrated into the crop simulation model. The improved crop model will be useful assist producers in optimizing planting dates, scheduling irrigation and fertigation to improve and fiber quality.

# DEDICATION

I dedicate this dissertation to my mother Shrimati Kaushalya Lokhande, my father Late Shri Bajirao Lokhande, and my beloved wife Kanchan. Without their love, affection, teachings, inspiration, encouragement and sacrifices this episode of my life was never possible.

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## ABBREVIATIONS

| | |
|---|---|
| AFIS | Advanced Fiber Information System |
| BMP | Boll Maturation Period |
| CMTS | Cell Membrane Thermostability |
| CSI | Chlorophyll Stability Index |
| DAT | Days After Treatment |
| ET | Evapotranspiration |
| HVI | High Volume Instrument |
| K | Potassium |
| LSD | Least Square Difference |
| LWP | Leaf Water Potential |
| MPa | Mega Pascal |
| N | Nitrogen |
| SPAR | Soil-Plant-Atmosphere-Research |
| TM-1 | Texas Marker-1 |

# CHAPTER I

# INTRODUCTION

The world population is currently approximately 7.1 billion (U.S. Census Bureau, 2012) and has been projected to reach up to 10.75 billion by 2050 (U.N. Population Division, 2008). In order to provide goods and services for an exponentially increasing world population, agricultural product output will have to double over the next 50 years. Therefore, there is great need to develop the capacity to increase the quantity and quality of food and fiber to meet the demands of the rising population. In an era of changing climate, diminishing natural resources, and global conflict, the increase in productivity can be achieved only with the help of technological knowledge and improved agricultural practices. In production agriculture, every season is different in terms of amount and intensity of rain events, temperature and light energy received. Therefore, overall plant growth and development are all sensitive to variables or adverse environmental conditions (Lewis et al., 2000). In addition, management strategies such as selection of cultivars, timing and frequency of irrigation, and nutrient availability and application rates add additional complexity that farm managers have to consider in making daily management decisions in the field (Jones et al., 2003). In modern agriculture practice, there are various tools to help farmers. Decision support system tools such as crop models will be of great help in assisting the decision making process to optimize crop inputs and maximize yield. Such tools have great potential for numerous improvements

in crop production efficiency, management, and in guiding and improving policy decisions.

Changes in environmental conditions and plant nutrients availability have substantial impact on agricultural production and productivity. Among the various environmental stresses, drought and temperature are the two most important stresses affecting crop production globally (Boyer, 1982; Saini and Westgate, 2000) along with primary plant nutrients, nitrogen and potassium (Shah, 2008; Morrow and Krieg, 1990). During the last century, changes in climate have resulted in 0.6 °C increase in global surface temperature, but projections of future levels of greenhouse gases indicate an increase in surface air temperature of between 2 to 5 °C by 2100 (IPCC, 2001). Changes in the climate are always associated with changes in the other climatic variables such as precipitation patterns (Giorgi and Lionello, 2008). As a result, drought affected areas are expanding and the trend is accelerating over time (Delmer, 2005). This trend will not only modify the rainfall distribution spatially, but also increase the intensities of heat and drought in the future climate (Giorgi and Lionello, 2008). Presently, one third of the total world cultivated area experiences inadequate supply of water (Massacci et al., 2008), and future world crop production will be substantially affected by any changes in climate that cause reduction of fresh water resources. Lobell and Field (2007) reported a negative correlation between worldwide crop yields and recent changes in temperature and precipitation patterns. Nitrogen and potassium are the key elements in biomass production, partitioning and the most growth-limiting factors (Shah, 2008) and therefore needed relatively in larger amounts, consistently, during the crop growing season. Excessive or deficient nitrogen and potassium applications have detrimental effects on

crop growth, development and yield (Gerik et al; 1998; Zhao et al., 2003, 2005; Oosterhuis, 1997). Therefore, it is important to monitor plant nutrient status in order to optimize management decisions to enhance the yield (Pettigrew 2008; Hou et al; 2007) and fiber quality. The interaction between projected environmental changes in temperature and precipitation along with nutrient availability may intensify the effects on crop yield quantity and quality in the future climatic conditions.

Cotton (*Gossypium hirsutum* L.), a $C_3$ crop, is being used as a source of fiber for the textile industry worldwide. At the farm level, the production of each year's crop involves the purchase of more than $5.3 billion worth of supplies and services (National Cotton Council, 2010). Cotton is grown in a wide geographic area (Niles and Feaster, 1984) and exhibits plasticity in growth to environmental stresses because of its indeterminate growth habit, perennial nature, and sympodial fruiting pattern (Lee, 1984; Reddy et al., 2007). Also, cotton cultivars used in present agriculture have become more dependent on grower to provide inputs in terms of water and nutrients. This dependency has created variability in the yield due to genetics, management practices, and unfavorable weather conditions (Oosterhuis, 1994).

Although cotton originated in semiarid climates, it did not yield best at excessively high temperatures (Oosterhuis, 2002). The optimum temperature for cotton growth is reported to be in between 20 to 30 °C (Reddy et al., 2001), whereas, optimum temperature for boll retention is about 27-28 °C and temperature above 33 °C inhibits the retention to a large extent (Reddy et al., 1992a, b). High temperature affects all stages of cotton development, but plants showed more sensitivity during reproductive developments. Excessive high temperature decreased seed size, fibers per seed and length

(Oosterhuis, 1999). Several studies have been conducted to isolate the effects of weather on cotton growth characteristics across multiple locations and years (Krieg, 2002; Wanjura et al., 2002). Also, several aspects of cotton growth and development (Krieg, 2002; Reddy et al., 1992b), biomass (Haigler et al., 1991), reproductive potential, lint yield and quality (Reddy et al., 1999) as affected by temperature have been previously reported. The early stage of fiber elongation is highly temperature dependent (Gipson and Joham, 1969) affecting fiber length. Fiber properties, which are dependent on deposition of photosynthate in fiber cell walls, are sensitive to changes in the growth environment (Pettigrew, 2008; Powell and Amin, 1969; Roberts et al., 1992). One of the major reasons for the decline in yield potential and lint quality is attributed to temperature stress during boll development which needed to be addressed.

Water is a primary component of active plant nutrient transport, cell reactions, cell expansion, and transpiration of growing plants (Hsiao et al., 1917; Gardner, 1984). Therefore, the cotton production, like most major agricultural crops, is negatively impacted by moisture deficit. Cotton has relatively low water use efficiency because of its $C_3$ physiology and therefore the duration, intensity, and developmental stage at which water stress occurs will affect for boll retention and causes reductions in lint yield (Kramer, 1983; Dimitra and Oosterhuis, 2011). Changes in plant water status modifies the indeterminate growth and complex fruiting pattern in cotton (Oosterhuis, 1999; Gerik et al., 1996; Grimes and Yamada, 1982), limits the productivity by affecting fruit production (Onder et al., 2010; Grimes et al., 1969; Kimball et al., 1993) square and boll-shedding, lint yield (Pettigrew, 2004) and fiber quality (El-Zik and Thaxton, 1989). Severe water stress during fiber elongation stages reduces fiber length (Hearn, 1994) due

to direct mechanical and physiological processes of cell expansion. Johnson et al. (2002) reported a negative correlation between fiber strength and elongation with soil water deficits, whereas, Davidonis et al. (2004) reported that adequate soil water supply before and during boll development increased fiber maturity. Water stress duration, timing of flowering and boll setting results in complex physiological interaction between water deficit and fiber properties. Therefore, these interactions needed to be addressed at optimum temperature and nutrient conditions to isolate water deficit effects on fiber properties for modeling.

Correlation between nitrogen content and cotton leaf photosynthesis has been demonstrated as a major fraction of leaf nitrogen is associated with the photosynthetic enzyme rubisco (Shiraiwa and Sinclair, 1993). The strong relationship between plant nitrogen content and photosynthesis is widely recognized and reported in many studies (Wong, 1979; Radin and Boyer, 1982). Leaf N concentration is an important indicator of the plant N status (Gerik. 1994) and major portion of the leaf N is located in the chloroplast (Hak et al., 1993). Therefore, in $C_3$ plants like cotton, lowering N content results in a decrease in chlorophyll content (Reddy et al., 2002; Zhao et al., 2003) which affects the functionality of photosynthesis apparatus (Ciompi et al; 1996; Lu et al; 2001) and subsequently inhibits plant growth and development (Jaynes et al., 2001), reduces plant biomass and yield (Fritschi et al., 2003), and affects fiber quality (Bradow and Davidonis, 2000; Reddy et al., 2004). Additionally, the timing and intensity of N stress is equally important to study due to its effect on fiber quality (Ramey et al; 1986). Several studies have emphasized nitrogen nutrition effects on cotton reproductive performance, yield (Boquet et al., 1994; Pettigrew and Meredith, 1997; Bondada and Oosterhuis,

2000), and fiber quality (Reddy et al., 2004; Read et al., 2006). But these studies did not provide the isolated effect of nitrogen on reproductive performance and fiber properties due to interference from other environmental parameters.

Potassium acts as osmoticum to balance the turgor pressure (Kaiser, 1982), and is a key element in enzyme activation (Evans and Sorger, 1966) and other physiological functions of the cells (Humble and Raschke, 1971). It also influences the transportation of photoassimilates from leaves to the other plant parts (Ashley and Goodson, 1972; Pettigrew, 1997) and restricts fruit production at lower concentrations (Kerbey and Adams, 1985). Only a small portion of total soil K is soluble and in an exchangeable form and readily available to plants (Reddy et al., 1994). Potassium plays a very important role in increasing turgor pressure during growth and elongation of fiber which takes place during 0 to 20 days after anthesis (Ramey Jr., 1986). Under K deficient condition, there is a restriction on transport of photosynthate which leads to accumulation of sugars in leaf tissues (Pettigrew, 1999; Bednarz and Oosterhuis, 1999). Therefore, K deficiency during the late fruiting period results in a reduction in plant biomass (Cassman et al 1989) in many cotton producing areas. Several researchers have documented the importance of potassium nutrition on yield and fruiting efficiency (Boquet and Breitenbeck, 2000; Pettigrew and Meredith, 1997). Although efforts have been made to study fiber quality affected by various abiotic factors in the field and semi-controlled environments, these studies have not been able to provide a complete understanding of individual factors because of confounding effects from other abiotic stress factors.

Many of the issues facing cotton production can be better understood by implementing process-based cropping system models (Boote et al., 1996). Process-

oriented crop growth models are composed of mathematical equations which represent processes in crop growth and development, and simulated plant carbon balance, soil-plant-water balance, soil-plant-nitrogen, and energy balance (Boote et al., 1998). Development and application of crop growth models were historically linked with the cotton industry. In mid-1970, fundamental equations had been developed to describe cotton growth and development (Baker et al., 1972; McKinion et al., 1975). Over last three decades, continuous efforts made by team of researchers to improve and predictability and applicability of GOSSYM, a cotton simulation model, across wide range of climatic and soil conditions. Several controlled environmental studies were carried out to quantify cotton growth and development (Reddy et al 1992a, b; 1993; 1997a, b) and derived mathematical functions were incorporated into the cotton simulation model. GOSSYM is a mass-balance dynamic model that simulates C, N, and water processes along with the basic biological and physical processes involved in the growth and development in the plant and soil root zone throughout the cotton life cycle (Baker et al., 1983; Boone et al., 1995). It predicts crop growth, phenology, and yield by taking into account its responses to environmental stresses, primarily from temperature, water, and nitrogen and potassium.

Apart from GOSSYM, other simulation models for cotton have been developed more recently. It includes COTCO2 (Wall et., 1994), Cotton 2K (Marani, 2004), CROPGRO-Cotton (Jones et al., 2003), and OZCOT (Hearn, 1994). All these models differ largely in approaches and simulating various plant processes and cultural practices. But till date none of the model reached their full potential. In past two decades, among the variety of applications, these models have been applied to asses nutrient and irrigation

alternatives (Hearn and Bange, 2002), potential changes in the temperature (Reddy et al., 2002a) and in remote sensing (Hebbar et al., 2008). GOSSYM model has been used routinely in commercial cotton production to validate numerous comprehensive datasets and tested for various fields (Fye, 1984; Whisler et al., 1993; Reddy et al., 1990; 1995., Staggenborg et al., 1996; Reddy et al., 2002a, b) and policy arenas (Dorethy et al., 2003; Liang et al., 2012a, b).

Accurate prediction of growth, developmental characteristics, and yield of cotton plants under wide range of environmental conditions is important for management decision making (Reddy et al., 2004). Processing, performance, and marketing of textiles are directly affected by fiber quality (Bradow and Davidonis, 2000) and introduction of new weaving technology in textile manufacturing are driving farmers to produce higher quality cotton fibers (Landes et al., 2005). Therefore, models are needed to assist farm producers to optimize not only yield but also lint quality. However, the existing cotton models including GOSSYM do not have a fiber quality submodel to effectively predict fiber properties. The functional relationships between environmental factors and fiber properties are urgently needed for modeling. The objectives of these studies were (a) to study the effect of temperature, water, and nutrients (nitrogen and potassium) stresses on cotton growth and reproductive performance (b) to investigate and quantify the effects of temperature, water and nutrients stresses on fiber quality parameters, and (c) develop mathematical functional algorithms relating abiotic stresses and fiber properties.

# CHAPTER II

# QUANTIFYING THE TEMPERATURE EFFECTS ON COTTON REPRODUCTIVE EFFICIENCY AND FIBER QUALITY


## Abstract

Temperature is one of the major abiotic stress factors affecting cotton growth, yield, and fiber quality traits. Quantitative functional relationships between temperature and fiber quality are needed to improve predictive capability of cotton simulation models. An experiment was conducted in sunlit plant growth chambers by varying four day/night temperature treatments (22/14, 26/18, 30/22, and 34/26 °C) imposed at flowering. Upland cotton cultivar, Texas Marker-1, was seeded in the chambers utilizing fine sand as the rooting medium. Optimal quantities of water and nutrients were provided during the experiment. Flowers and bolls were tagged daily to estimate the boll maturation period. Plant height and node numbers were recorded from emergence to 21 days after treatment. Stem, leaf, boll dry weights, and boll numbers were recorded at the end of the experiment. Measured fiber quality parameters were regressed against temperature to develop mathematical functions for modeling. The optimum temperature for total biomass was between 18.1 and 21.5 °C and biomass declined at the two higher temperatures by 10 and 19%, respectively. More numbers of bolls were produced at 25.5 °C and boll numbers declined sharply at higher temperature. Reproductive potential, measured by boll mass per unit total weight, peaked at 25.5 °C (496 g $kg^{-1}$) and was

lower by 21 and 53% at 18.1 °C and 29.5 °C respectively. Fiber micronaire and uniformity increased with temperature up to 26 °C and declined at higher temperature while fiber strength increased across tested temperatures. Fiber length, on the contrary, increased linearly from 18 to 22 °C, and declined at higher temperatures. Fiber micronaire was more responsive to changes in temperature followed by strength, length and uniformity. The functional relationships between temperature and fiber properties will be useful to develop fiber sub-model under optimal water and nutrient conditions.

## Introduction

Changes in the weather and climatic conditions will have substantial impact on agricultural production and productivity. Among the environmental stresses, drought and temperature are the two most important stresses affecting crop production globally (Boyer, 1982; Saini and Westgate, 2000). Lobell and Field (2007) reported a negative correlation between worldwide crop yields and recent changes in temperature. Past changes in climate have resulted in about 0.6 °C increase in global surface temperature during the last century, but future changes in greenhouse gases are projected to increase surface air temperature between 2 and 5 °C by the end of this century (IPCC, 2001) resulting in more frequent incidents of heat and drought intensities (Giorgi and Lionello, 2008). These changes in temperature and could potentially alter crop production in many parts of the world (IPCC, 2007; De Costa et al., 2007; Fitzgerald and Resurreccion, 2009). The interaction between projected environmental changes such as temperature and drought may intensify the rate and direction of individual climatic stress factors, and their effects on crop yield and quality.

Even though cotton is grown under a wide geographic area (Niles and Feaster, 1984) and is capable of exhibiting plasticity in growth to environmental stresses because of its indeterminate growth habit, it grows and produces bolls under a narrow range of temperature conditions (Lee, 1984; Reddy et al., 2007, 2008). The minimum, optimum and high temperatures for cotton vary depending on growth and developmental processes (Reddy et al., 1997b). The optimum temperature for boll retention is about 27-28 °C and maximum temperature for boll retention is between 32 and 33 °C (Reddy et al., 1992a, b, 1997b). During the growing season, it is not uncommon for air temperature to be above or below the maximum temperature for boll development (Reddy et al., 1995).

There have been many studies addressing various facets of cotton growth and development as affected by temperature (Krieg, 2002; Reddy et al., 1992b). Also, studies were conducted to isolate the effects of weather on cotton growth characteristics across multiple locations over the years to isolate individual factor effects (Krieg, 2002; Wanjura et al., 2002). Cotton reproductive performance is mostly determined by fruit setting, retention, and boll weight. Studies conducted in controlled environmental experiments by Reddy et al. (1992a, b; 1993, 1997a, b) quantified several growth and developmental aspects of upland cotton and many of those functions were incorporated into cotton simulation model, GOSSYM, for field and policy arena applications (Reddy et al., 2002a, b; Dorethy et al., 2004; Liang et al., 2012a, b). However, the improved model of GOSSYM and other cotton models in the market do not have fiber modeling components for effective use in the production environment to optimize fiber quality.

Fiber and seed development proceeds simultaneously during boll growth with the maturation period initiated at anthesis followed by termination within a few days before

boll dehiscence (Gipson and Joham, 1969). Few studies have addressed temperature effects on cotton reproductive potential and lint quality (Reddy et al., 1999). It has been reported that cotton lint yield along with fiber quality parameters such as fiber length, strength, fineness and micronaire were affected by temperature (Pettigrew, 2008; Powell and Amin, 1969, Haigler et al., 1991). Initial fiber elongation which takes place during early boll development, 0-15 days after anthesis, was more sensitive to temperature than late fiber elongation stage (Gipson and Joham, 1969; Wuzi et al., 1993). Fiber properties which are dependent on deposition of photosynthate in fiber cell walls are sensitive to changes in the growth environment. Low and high temperatures generally inhibit the rate of cellulose synthesis and thus fiber maturity, and fiber elongation adversely resulting in poor fiber quality (Roberts et al., 1992). Therefore, it is important to address and quantify the effects of temperature on fiber developmental processes and fiber quality under optimum water and nutrient conditions.

As processing, performance, and marketing of textile properties are directly affected by fiber quality (Bradow and Davidonis, 2000) and introduction of new weaving technology in textile manufacturing are prompting farmers to produce high quality cotton fibers (Landes et al., 2005), models are needed to assist the farm producers to optimize not only yield but also the lint quality. There have been efforts to study temperature effects on fiber properties in the field and semi-controlled environments (Liakatas et al., 1998; Pettigrew, 2008; Rousspoulos et al., 1998). However, the functional relationships needed for modeling are sparse and additional data is needed to develop a fiber quality sub-model in many cotton models currently available (Wall et al., 1994; Marani, 20004; Jones et al., 2003, Hearn 1994). Also, existing cotton simulation models are unable to

predict fiber quality parameters due to the lack of relationships between temperature and fiber properties (Bradow et al., 1997; Reddy et al., 1997a). The objectives of this study were to evaluate the effects of temperature on cotton reproductive performance and fiber properties under optimum water and nutrient conditions and to develop functional equations for temperature and fiber parameters for modeling.

## Meterials and methods

### Experimental facility

The experiment was conducted in four sunlit, controlled environment chambers known as Soil-Plant-Atmosphere-Research (SPAR) units located at the R.R. Foil Plant Science Research Center, Mississippi State University, Mississippi, USA. The SPAR units have the capacity to precisely control air temperatures and chamber atmospheric carbon dioxide concentration at determined set points and at near ambient levels of photosynthetically active radiation. Each SPAR chamber consists of a steel soil bin (1 m deep by 2 m long by 0.5 m wide) to accommodate the root system, a Plexiglas chamber (2.5 m tall by 2 m long by 1.5 m wide) to accommodate plant canopy and a heating and cooling system connected to air ducts that pass conditioned air through the plant canopy to cause leaf flutter. Variable density shade cloths, designed to simulate canopy spectral properties and placed around the edges of the plant canopy, were adjusted regularly to match canopy height and to eliminate the need for border plants. During this experiment, the incoming daily solar radiation (285 - 2800 nm) outside of the SPAR units, measured with a pyranometer (Model 4–8; The Eppley Laboratory Inc., Newport, RI, USA), ranged from 1.4 to 27.2 MJ $m^{-2}$ $d^{-1}$ with average of 15.6 MJ $m^{-2}$ $d^{-1}$. The SPAR units supported by an environmental monitoring and control systems are networked to provide automatic

acquisition and storage of the data, monitored every 10 s throughout the day and night. Many details of the operations and controls of SPAR chambers have been described by Reddy et al. (2001). The units are sealed to allow monitoring of canopy gas exchange processes continuously. The relative humidity (RH) of each chamber were monitored with a humidity sensor (HMV 70Y, Vaisala Inc., San Jose, CA, USA) installed in the returning path of airline ducts.

**Temperature control**

Conditioned air was passed through the chamber from top and returned to the back of the unit at approximately 1.3 m $s^{-1}$. This rate of flow was sufficient to cause leaf flutter, reduce boundary layer resistance, and to maintain uniform temperature throughout the chamber. Four day/night temperatures of 22/14, 26/18, 30/22, and 34/26 °C were imposed from flowering to maturity stage of the cotton crop for plants grown at optimum temperature (30/22 °C) since seeding. The temperature control was maintained to the desired set points using chilled ethylene glycol supplied to the cooling system via several parallel solenoid valves that were opened and closed depending on the cooling requirements, an electrical resistance heater which provided short pulses of heat and a fan which circulated the air through the chamber (Reddy et al., 2001). Carbon dioxide concentration in each SPAR chamber was monitored and adjusted every 10 s throughout the day and maintained at 400 μmol $mol^{-1}$ during daylight hours using a dedicated LI-6250 $CO_2$ analyzer (Li-COR, Inc., Lincoln, NE, USA). The environmental data for mean temperature and daytime $CO_2$ concentration are presented in Table 2.1.

Table 2.1 The set treatment day/night temperature conditions, and measured chamber $CO_2$ from a typical day during the experimental period for each treatment

| Treatments | Measured variables | |
|---|---|---|
| Day/Night temperature (°C) | Mean Temperature (°C) | $CO_2$ ($\mu mol\ mol^{-1}$) |
| 22/14 | †18.01 ± 0.04 | 408 ± 3.2 |
| 26/18 | 21.54 ± 0.03 | 406 ± 4.1 |
| 30/22 | 25.46 ± 0.05 | 409 ± 2.1 |
| 34/26 | 29.50 ± 0.03 | 404 ± 3.8 |

†Each value represents the mean ± SE for one typical day for [$CO_2$], and 4 August to 15 October 2009 for temperature.

**Plant culture**

Upland cotton (*Gossypium hirsutum* L.) cultivar, Texas Marker (TM)-1, a genetic standard for many breeding and molecular studies (Saha et al., 2008; Stelly et al., 2005; Wu et al., 2008) was seeded June 16, 2009 in the SPAR units using fine sand as the growing medium similar to many experiments conducted in the facility (Reddy et al., 2001). Fifty percent emergence was observed in 5 days after seeding. Four rows with five plants per row were maintained in each chamber until harvest. Plants were harvested in each SPAR unit when the plants reached over 80% of the harvestable bolls. Plants were well-watered and fertilized with full-strength Hoagland nutrient solution (Hewitt, 1952) based on treatment-based evapotranspiration measured daily (Reddy et al., 2001).

**Measurements**

*Growth, biomass, and yield components*

Plant height from the cotyledonary node to the newest unfolded mainstem leaf was recorded from emergence to 21 days after initiation of temperature treatment at 4-

day intervals. Similarly, the number of nodes on the mainstem was recoded at the same intervals. Flowers and open bolls were tagged daily throughout the experiment in all units. On the day of anthesis, cotton flowers are creamy-white in color and will turn into purple the day after anthesis, and thereby aiding the tagging of flowers. The day when the lint appeared between the carpel walls is defined as open boll. Based on these dates, boll maturation period for each boll was estimated in all units (Reddy et al., 1999). Total number of bolls produced and matured (opened) bolls were recorded at the final harvest in all treatments. Stems, leaves, and reproductive structures were separated from each plant and total biomass per plant was calculated by adding dry weight of the separated plant parts. Reproductive potential was estimated by the ratio of reproductive biomass to total biomass produced on per plant basis. Also, bolls were separated into burr, seed, and lint with weights for each recorded.

*Fiber properties*

The fiber quality parameters were analyzed using advanced Fiber Information System (AFIS; Zellweger Uster Inc., Knoxville, TN, USA) and with High Volume Instrumentation (HVI) by the Fiber and Biopolymer Research Institute at Texas Tech University, Lubbock, Texas, USA as described by Davidonis and Hinojosa (1994) and Reddy et al. (1999). The HVI provides reports on five important quality characteristics describing the fiber length, strength, fineness, elongation, and uniformity. The AFIS, equipped with neps and maturity modules which estimates short fiber and neps content, fiber maturity, and immature fiber content with accuracy and speed as described by Reddy et al. (2004) and Schleth and Peter (2005).

**Data analysis**

To test the significance of temperature on growth and biomass components of cotton plants, analysis of variance was performed by using general linear model PROC GLM (SAS Institute Inc., 2003). Fisher protected LSD tests at P = 0.05 was used to determine significance of treatment effects. To determine the best-fit equations relating temperature and fiber quality, regression and graphical analysis was carried out using SigmaPlot 11.0 (Systat Software Inc., San Jose, CA, USA).

## Results and Discussion

**Temperature conditions**

Imposing temperature few days prior to flowering of plants grown at optimum temperature worked well in this study to quantify cotton reproductive potential and fiber quality parameters. The day/night treatments and the season-long average temperatures of 18.1 °C (very low), 21.5 °C (low), 25.5 °C (moderate) and 29.5 °C (high) (Fig. 2.1) represents the temperature variability of current and projected future climatic conditions across the US Cotton belt (Reddy et al., 1995; Dorethy et al., 2003). This is the first study to address temperature effects on biomass production, reproductive potential and fiber quality of the upland cotton genetic and molecular standard, TM-1 cultivar (Stelly et al., 2005; Wu et al., 2008). The qualitative functions will be valuable not only for cotton modelers but will also be useful for many studies in molecular biology of cotton reproductive potential and fiber traits in response to temperature (Kohel et al., 2001).

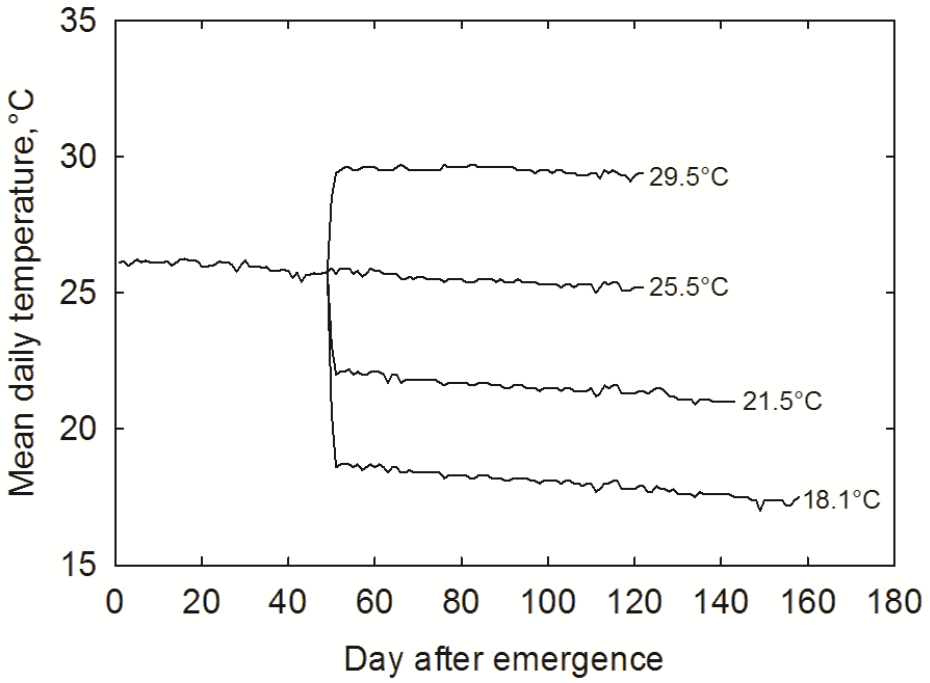


Figure 2.1 Temperature trends Daily average temperature regimes plotted for four different temperature treatment (day/night) °C.

Season-long treatment means values for each treatment are also presented in the graph. Plants were harvested as they reached 80% open bolls; the higher temperature treatments were therefore harvested earlier than the cooler treatments

**Growth and biomass attributes**

Plants height increased faster at the middle two temperatures (22 and 25.5 °C) and were 9 and 6% ($P < 0.001$) shorter at the low and high temperatures, respectively, compared to the average values at the two optimum temperatures (Table 2.2). On the contrary, mainstem node numbers increased with temperature ($P < 0.021$). The decreased plant height at the low and high temperature treatments was attributed to shorter internode lengths than the number of mainstem nodes produced similar to other reports (Reddy et al., 1992b; Reddy et al., 1998). The total above-ground biomass produced was not different among the two low and the moderate temperature treatments, and on average, produced 258 g plant$^{-1}$. However, the biomass production at the high

temperature declined by 16% compared to the average values at the three other temperature treatments (Table 2.2).

The numbers of bolls retained were about 22 plant$^{-1}$ at the two lower and the moderate temperatures, but declined significantly (42%) at the highest temperature tested compared to the other treatments (Table 2.2). The numbers of open bolls were higher at the two medium temperatures (an average 13 bolls plant$^{-1}$) and declined by 36% at the highest and the lowest temperature tested (Table 2.2). The fewer numbers of bolls at the very low temperature was due to the increase in time required to develop mature bolls at this temperature. Fewer numbers of bolls retained at high temperature were due to several causes. Studies in cotton have shown that reduction in pollen production and increase in pollen sterility at daytime temperatures over 35 °C are the causative factors for reduced boll retention at high temperature in addition to increased respiration and declining photosynthetic capacity (Krieg, 1997; Meyer, 1969; Powell and Amin, 1969; Reddy et al., 1998). Similar declines in reproductive potential have been reported in other species such as soybean (Koti et al., 2007) and dry bean (Prasad et al., 2002) at high temperatures.

The reproductive potential, expressed as the dry weight of bolls per total dry weight, increased as temperature increased from 18 to 25.5 °C, and then declined rapidly (57%) at the highest temperature (29.5 °C compared to optimum temperature (25.5 °C) due to decreased boll retention. Individual boll component weights, on the other hand, were significantly different at very high temperature compared to other temperatures tested (Table 2.2 and Fig. 2.3). Similarly, seed numbers per boll were not different among

the three lower temperatures tested; 28 seeds boll$^{-1}$, on average, but declined at the highest temperature by 24% compared to other temperatures.

Table 2.2 Treatment means and least square differences (LSD) for all plant and boll biomass attributes studied.

| *Plant Parameters* | Mean day/night temperature, ºC | | | | LSD |
|---|---|---|---|---|---|
| | 18.1 | 21.5 | 25.5 | 29.5 | |
| Plant height, cm plant$^{-1}$ | †205.0 a | 227 b | 222 b | 212 c | 8.1 |
| Mainstem nodes, no. plant$^{-1}$ | 20.1 a | 21.8 b | 21.2 b | 22.6 c | 0.61 |
| Total biomass, g plant$^{-1}$ | 265.0 a | 268 a | 241 ab | 217 bc | 35 |
| Total bolls, no. plant$^{-1}$ | 21.6 a | 19.8 a | 20.9 a | 11.6 b | 4.1 |
| Open bolls, no. plant$^{-1}$ | 4.6 a | 12.8 b | 13.2 b | 4.7 a | 3.1 |
| Reproductive potential, g kg$^{-1}$ | 390.0 | 458 | 496 | 229 | NA |
| *Boll Components* | | | | | |
| Boll weight, g boll$^{-1}$ | 6.50 a | 6.57 a | 6.31 a | 5.02 b | 0.51 |
| Seed cotton weight, g boll$^{-1}$ | 4.88 a | 4.95 a | 4.69 a | 3.43 b | 0.46 |
| Lint weight, g boll$^{-1}$ | 1.51 a | 1.55 a | 1.43 a | 0.86 b | 0.125 |
| Seed weight, g boll$^{-1}$ | 3.27 a | 3.34 a | 3.22 a | 2.51 b | 0.301 |
| Seed number, no. boll$^{-1}$ | 27.3 a | 28.1 a | 28.4 a | 21.2 b | 3.14 |

†Values in each row followed by same letter are not significantly different ($P < 0.05$) according to Fisher's LSD.

Plant attributes include plant height, main stem nodes, total dry weight while boll parameters include total bolls, open bolls and reproductive potential); boll components (Boll, seed cotton, lint and seed weight per boll). Final harvest was carried out at 80 % of boll opening in each treatment (20 plants per treatment).

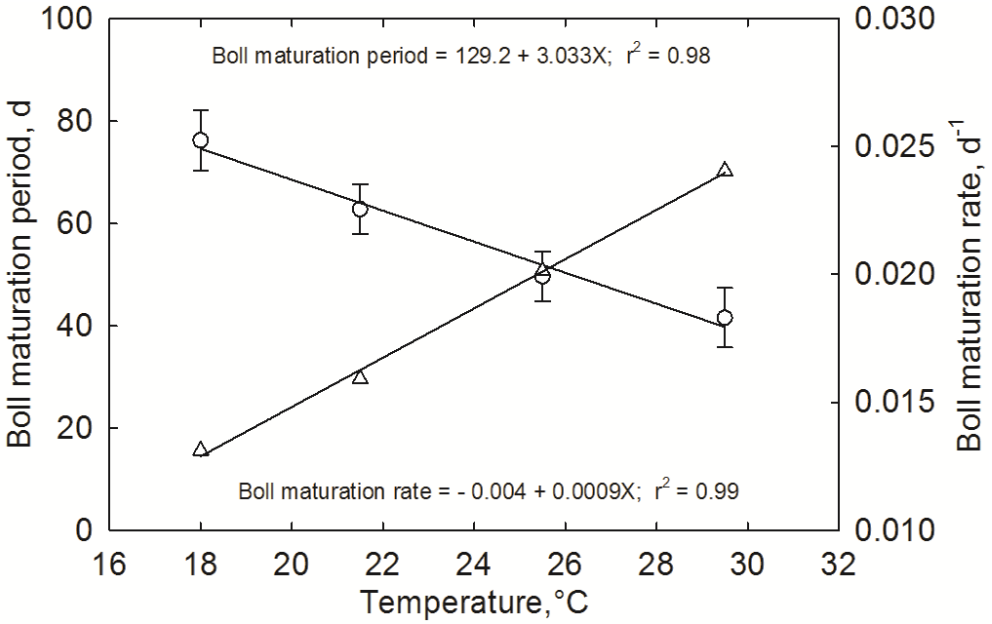


Figure 2.2 Temperature effects on cotton boll maturation period and boll maturation rate as a function of temperature.

Measurements were taken by tagging daily flowering and open bolls in each treatment. The values are mean ± standard error of bolls produced in each treatment.

Boll maturation period, defined as the time interval between flowering and boll opening, declined linearly with temperature from 18 to 30 °C (Fig. 2.2; $r^2 = 0.98$) and boll maturation rate, the inverse relationship with boll maturation period, increased with temperature similar to many other studies in cotton (Reddy et al., 1997a; 1999). The net result of shorter boll maturation period at high temperature resulted in smaller bolls and reduced boll component weights (Table 2.2).

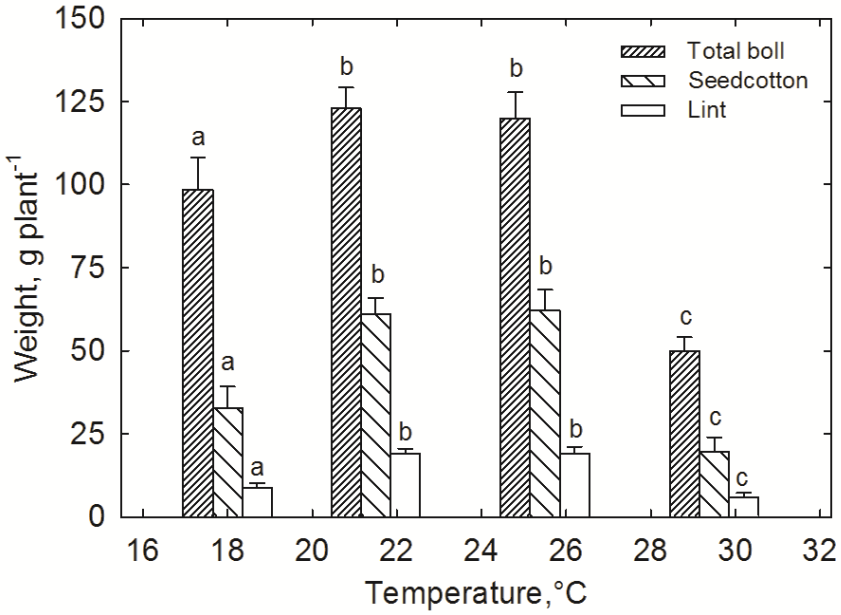


Figure 2.3 Temperature effects on cotton total boll weight, seed cotton weight and lint weight measured at final harvest.

The values are mean ± standard error of 20 plants.

**Fiber properties**

Although fiber is the main economic product of a cotton crop, few studies have addressed temperature and management effects on fiber quality parameters (Reddy et al., 1999, 2004). In general, fiber length, micronaire, and fiber uniformity showed quadratic trends with temperature while fiber strength increased linearly with increase in temperature (Fig. 2.4). Longer fibers (>30 mm) were observed at 22 °C and fiber length declined slightly at the lower temperature tested, but the decline at the high temperature was much sharper than at the lower temperatures (Fig 2.4a). Fiber length was inhibited at high temperature of about 29.5 ºC (< 28 mm). However, fiber uniformity exhibited a quadratic trend with temperature; increasing from 18 to 26 °C and declining thereafter ($r^2$ = 0.99, 2.4d). Similar temperature effects on fiber length were observed in several other

controlled environment (Reddy et al., 1999) and field studies (Haigler et al., 1991; Kim and Triplett, 2001). At optimum temperature, cotton fiber elongated over 2000 - 3000-fold within approximately 20 days after anthesis (Ruan et al., 2005). High temperature stress during this stage affects the elongation processes which, in turn, shortens the fiber length and lowers fiber uniformity. Optimum growing temperature produced longer fibers as compared to high temperature which supports previous findings by Reddy et al. (1999).

Fiber strength increased linearly with increase in temperature ($r^2$ = 0.86, Fig. 2.4c). Fiber micronaire, measured with the HVI instrument, however, exhibited a quadratic trend with temperature; increasing from 18 to 26 °C and declining thereafter ($r^2$ = 0.99, Fig. 2.4b). The important process of secondary wall thickening after elongation provides strength to the cotton fiber (Seagull, 1993). Changes in temperature during secondary cell wall cellulose synthesis will affect the fiber strength (Yong-Ling, 2007). Fiber strength and micronaire are mostly related to secondary wall thickening which is affected by high growing temperature (Hesketh and Low, 1968; Yfoulis and Fasoulas, 1978). Therefore, the fiber produced under high temperature conditions was stronger because of enhanced secondary wall thickening. Fiber micronaire is the indicator of fiber maturity and fineness that depends on both fiber diameter and secondary wall thickness. A low micronaire fiber (< 3.5) results in knots of broken fiber whereas high micronaire (> 4.9) will not convert into a bean shape structure that facilitates spinning process (Basra and Malik, 1984; Haigler et al., 2005). The lower micronaire readings at low and high temperature shown in this experiment are similar to the findings by Reddy et al. (1999) in controlled environment experiments and Bradow and Davidonis (2010) and Johnson et al.

(2002) in field conditions where low temperature during later stages of fiber development produced micronaire within the penalty (< 3.5) range (Bradow and Davidonis, 2000).

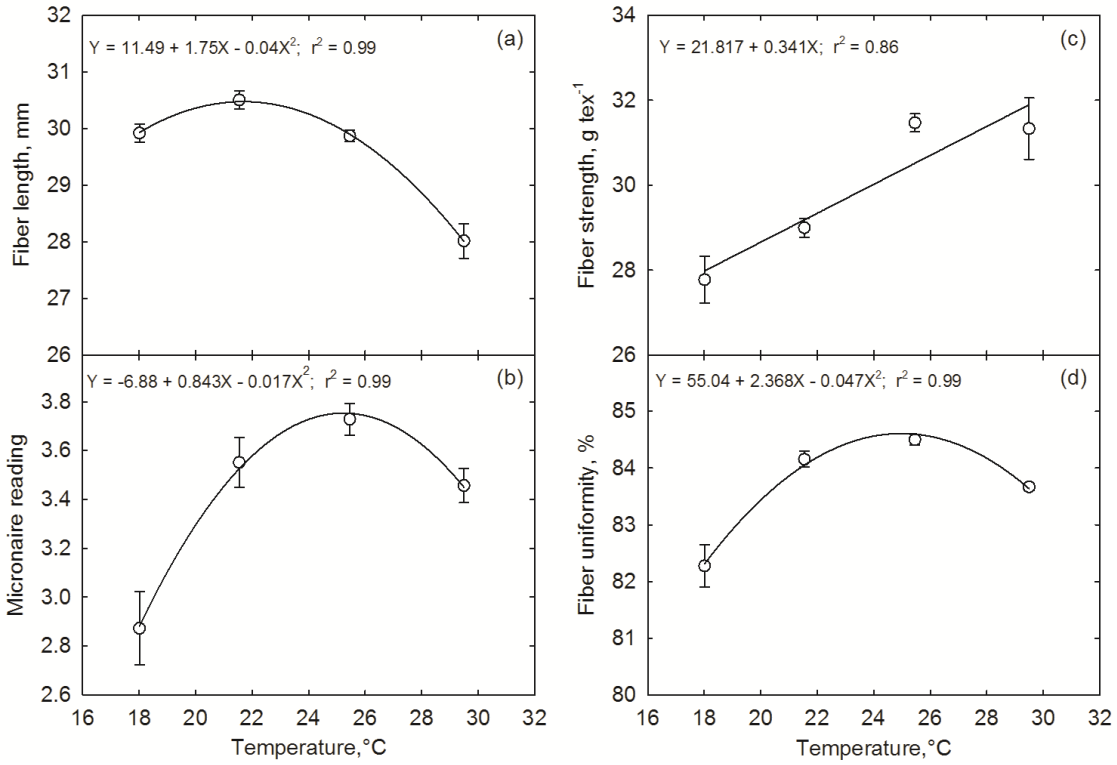


Figure 2.4 Temperature effects on (a) fiber length (b) micronaire reading (c) fiber strength and (d) fiber uniformity as a function of temperature measured with HVI.

The temperatures were averaged from flowering to open bolls. Lint samples were collected at final harvest in each treatment. The values are mean ± standard error of quality parameters

Short fiber content ($r^2$ = 0.99) and neps per gram ($r^2$ = 0.97) showed quadratic trends with temperature; declined from 18 to 25 °C and slightly increased at the highest temperature (Fig. 2.5a and 2.5c). The plants grown at low temperature showed higher short fiber content (7% by weight). The percent short fiber content is crucial in terms of waste component and also a part of fiber processing (Behery, 1993). An increase in short

fiber content is due to the effects of temperature on fiber elongation during the boll development period (Reddy et al., 1999). Also, the entanglement of fiber indicated by neps per gram was greater (17 no. $g^{-1}$) (Schleth and Peter, 2005) at low temperature was due to more amount of short fibers and motes which creates neps during ginning similar to results observed in other studies (Reddy et al., 1999; Bradow and Davidonis, 2010).

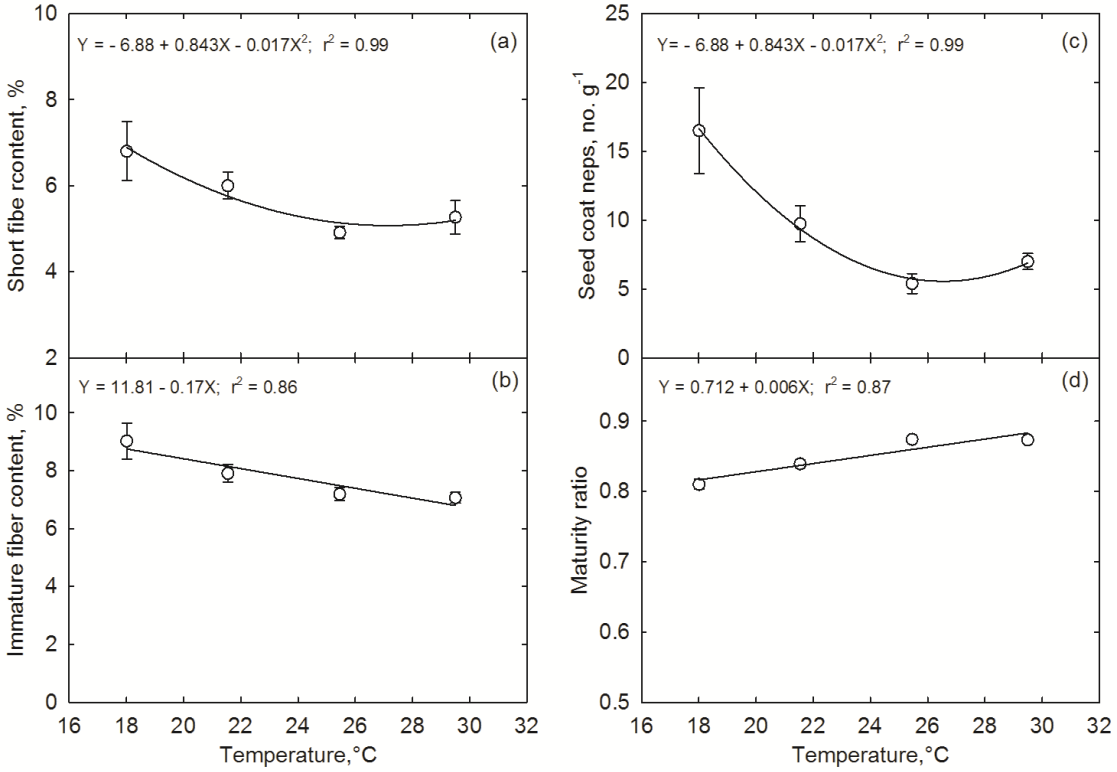


Figure 2.5 Temperature effects on (a) short fiber content (b) immature fiber content (c) seed coat neps per gram and (d) maturity ratio as a function of temperature measured with AFIS.

The temperatures were averaged from flowering to open bolls. Lint samples were collected at final harvest carried out at in each treatment. The values are mean ± standard error of quality parameters.

Fiber maturity is expressed in terms of maturity ratio which is a measure of degree of circularity along with immature fiber content. Immature fiber content is the

percentage of fibers with circularity less than 25 %. Immature fiber content declined linearly with temperature ($r^2$= 0.86, Fig. 2.5b) by 0.017% °C$^{-1}$. Maturity ratio, on the contrary, increased linearly from 18 to 30 °C ($r^2$ = 0.087, Fig. 2.5d). Fiber immaturity is mostly caused by lower temperature that limits the assimilation rate (Gipson and Joham, 1969; Pettigrew, 2008). Modern commercial cotton cultivars have sufficient potential to produce a thick secondary wall, but adverse temperature conditions result in more (9%) immature fibers (Haigler et al., 2005; Schleth and Peter, 2005). Also, the deformity in the fiber diameter leads to add more immature fiber content. A higher percentage of immature fiber content, in turn, reduces the fiber maturity ratio (0.82) in plants grown under low temperature conditions whereas fiber produced in high growing temperatures have higher (0.87) maturity ratio (Krieg, 2002; Schleth and Peter, 2005).

**Temperature indices for cotton fiber properties**

In order to develop models to study the current and projected changes in temperature and their interactions on fiber quality, first we need equations between temperature and fiber quality parameters under optimum water and nutrient conditions. In this study, we used the environmental productivity index concept developed by Reddy et al. (2003, 2008) to develop those functions. First, potential fiber quality values were estimated by dividing estimated maximum value by all the values to derive reduction factors or environmental productivity indices (Fig. 2.6) and the corresponding regression parameters and coefficients are presented in Table 2.3. These indices ranged from 0 when the temperature stress is totally limiting the fiber trait, to 1 when it did not limit that parameter, representing the fractional limitation due to temperature. This way, the effect

of temperature on fiber quality can be quantified without the interference of other environmental factors.

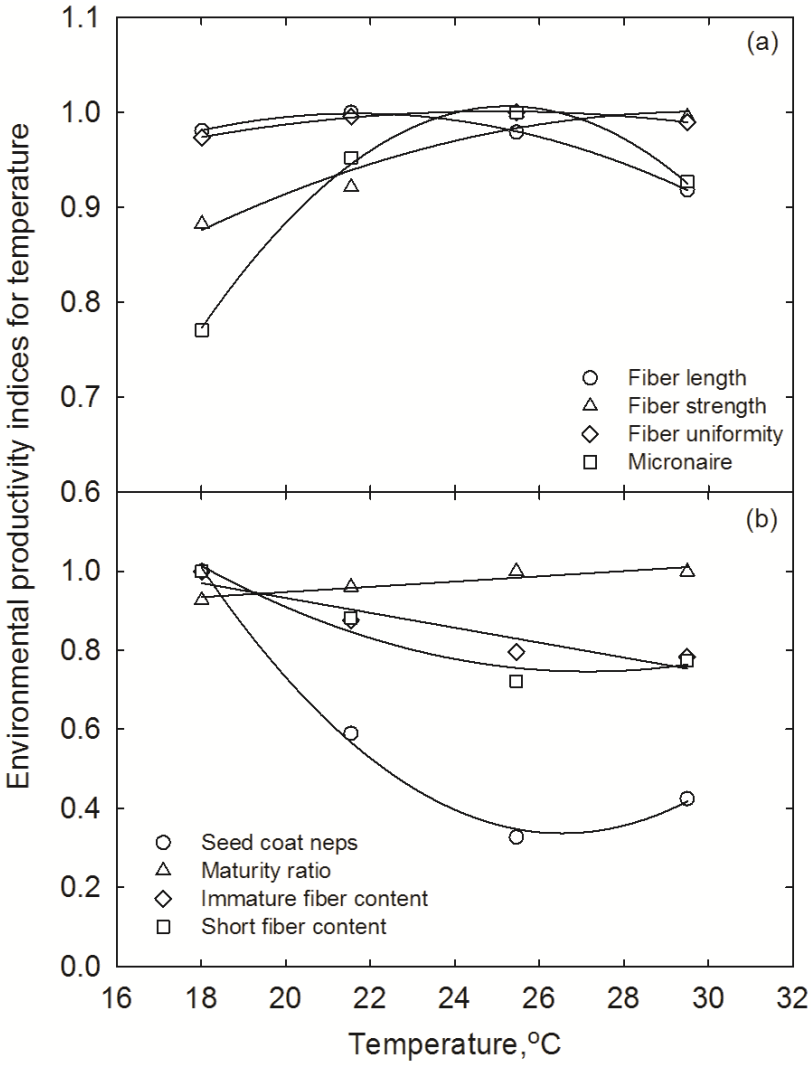


Figure 2.6 Temperature indices for various cotton fiber quality parameters.

Potential fiber quality values were estimated by dividing estimated maximum value by all the values to derive environmental productivity indices for temperature, which ranges from 0 when a given process is completely limiting the process and 1 when it does not limit that process.

This method also allowed us to look into fiber trait responses to temperature (Fig. 2.4). For example, among the important fiber traits, micronaire was most responsive to temperature followed by fiber strength. Fiber length and uniformity were relatively insensitive between 18 and 26 °C, but declined at high temperature (Fig. 2.6a). Similarly, indices were developed for other fiber quality parameters such as short fiber content, immature fiber fraction, seed coat neps, and fiber maturity ratio as a function temperature from the equations provided in Fig. 2.5. Seed coat neps were more responsive to increase in temperature followed by short fiber content and immature fiber content (Fig. 2.6b). The increments in immature fiber content were reflected in the maturity ratio.

Table 2.3 Regression parameters and coefficient of fiber quality parameters environmental productivity indices of cotton as affected by temperature.

| Fiber parameter | Regression parameters | | | Determination coefficient, $r^2$ |
|---|---|---|---|---|
| | yo | a | b | |
| Fiber length | 0.37 | 0.057 | -0.001 | 0.99 |
| Fiber strength | 0.21 | 0.053 | -0.0008 | 0.93 |
| Fiber uniformity | 0.65 | 0.028 | -0.0005 | 0.99 |
| Fiber micronaire | -1.84 | 0.226 | -0.004 | 0.99 |
| Seed coat neps | 6.83 | -0.49 | 0.009 | 0.99 |
| Maturity ratio | 0.81 | 0.007 | – | 0.87 |
| Immature fiber content | 1.30 | -0.019 | – | 0.87 |
| Short fiber content | 3.10 | -0.174 | 0.003 | 0.94 |

$y = yo + ax + bx^2$, where y is the fiber quality parameter and x is temperature.

## Summary

In this study, temperature effects on cotton growth, and development and fiber quality parameters were quantified under optimum water and nutrient conditions. Along with significant differences that occurred in the reproductive development, more pronounced differences were recorded for fiber properties. Plant biomass was greater

between 18 and 21 °C and declined at the two higher temperatures. Total boll, seedcotton and lint were not different between the two middle temperature treatments (21.5 and 25.5 °C), but lower at low and high temperature treatments. Bolls produced were significantly fewer at the highest (29.5 °) temperature compared to the other three temperature treatments. Even though boll maturation period declined with temperature, retained boll- and boll-component weights and seed numbers were not different between 18 and 25 °C, but declined at 29.5 °C. More numbers of open bolls were produced at the two moderate temperature treatments than at low and high temperatures.

Fiber parameters that are of interest to the textile industry were altered by temperature. Optimum temperature for fiber length was 22 °C and declined at the low and high temperatures. The decline in fiber length at high temperature was greater than at low temperature. Fiber strength increased linearly with temperature. Micronaire and fiber uniformity showed quadratic trends with temperature with optima closer to 25 °C. Similarly, short fiber content and seed coat neps exhibited quadratically declining trends with increasing in temperature, while immature fiber content declined linearly with temperature. The identified temperature-specific fiber quality indices can be incorporated in cotton simulation models to improve management practices under present and future enhanced temperature levels (Reddy et al., 2002b, Liang et al., 2012a, b). The resulting improved cotton models would be useful for optimizing yields by making appropriate production decisions and also assist in providing guidance to natural resource management and policy decisions including global climate change with respect to cotton production.

CHAPTER III

# REPRODUCTIVE AND FIBER QUALITY RESPONSES OF UPLAND COTTON TO MOISTURE DEFICIENCY


## Abstract

Among the abiotic stresses, water deficit during the cropping season is the most limiting factor of yield and affecting quality. However, limited quantitative information is available on water deficit effects on cotton reproductive potential and fiber quality for modeling. An experiment was conducted by seeding upland cotton cultivar, Texas Marker (TM)-1 using sunlit plant growth chambers and imposing water stress treatments of 100, 80, 60, and 40% of daily evapotranspiration of the control during flowering for plants grown at optimum temperature and nutrient supply. Plant growth and developmental rates were measured during early stages of water deficit treatments. Soil moisture content and midday leaf water potential (LWP) were measured twice weekly during the water stress period. Photosynthetic measurements, taken several times during the stress treatments, were correlated to midday leaf water potential. Flowers and bolls were tagged daily to estimate boll maturation period (BMP). Plant and boll-component dry weights were recorded at end of the experiment. Lint sample collected, grouped based on average LWP during BMP, were analyzed for fiber quality parameters. The stem elongation was more responsive to LWP than node addition rate whereas leaf photosynthesis declined with decrease in LWP. Seedcotton and seed weight, boll

numbers and total biomass declined significantly at severe water deficit treatment. Fiber length, strength, and uniformity decreased with decrease in LWP except for fiber micronaire which increased with decrease in LWP. More numbers of immature fibers were produced at moisture deficit regime resulting in reduced maturity ratio. Fiber strength was more responsive to changes in LWP followed by micronaire, length and uniformity. The functional relationships between LWP and fiber properties will be useful to develop fiber submodel under optimal temperature and nutrient conditions.

## Introduction

Water limiting conditions caused by climate variability influences the global and local food, forest and fiber production and productivity. Changes in climate are always associated with changes in the precipitation patterns (Giorgi and Lionello, 2008), as a result, drought affected areas are expanding and this trend is accelerating over time (Delmer, 2005). The projected increase in surface temperatures between 2 and 5$^{o}$C by end of this century (IPCC, 2001) will not only modify the rainfall distribution spatially but also increase the intensities of heat and drought in future climate (Giorgi and Lionello, 2008). Today, one third of the total world cultivated area suffers from inadequate supply of water (Massacci et al., 2008), and future world crop production will be substantially affected by any changes in climate that cause water supply depletion. Therefore, it will be important to understand crop growth and developmental responses to projected changes in climate, particularly water deficits as it is one of the most important abiotic stress factors that alter both quantity and quality of crop products.

Water stress is the condition when plant water and turgor potential declines enough at the extent it inhibits normal plant functions (Hsiao et al., 1973). Water is the

primary component of plants that is actively involved in several processes such as plant nutrient transport, cell reactions, cell expansion, and transpiration of growing crops (Hsiao et al., 1917; Gardner, 1984). As a result, small changes in available soil water content affects crop growth, development and physiological processes, and yield (Gardner and Gardner, 1983; Kramer and Turner, 1980). Cotton, being an indeterminate in growth in habit, is not an efficient water consumer and therefore the duration, intensity, and developmental stage at which water stress occurs are the key for efficient cotton production (Kramer, 1983; Dimitra and Oosterhuis, 2011). Early water stress affects canopy development and flowering whereas, mid and late-season water stress decreases boll retention and seed cotton yield (Guinn and Mauney, 1984). Krieg (1997) reported that the period from square initiation to first flower represents the most critical development period in terms of water supply affecting cotton growth and subsequently the yield and its components.

Changes in soil and plant water status modifies the growth and fruiting patterns in cotton (Oosterhuis, 1999) and limits the productivity by affecting fruit retention (Onder et al., 2010), square and boll shedding, lint yield (Pettigrew, 2004) and fiber quality (El-Zik and Thaxton, 1989). There have been many studies addressing several aspects of cotton growth, development and reproductive potential affected by water stress (Gerik et al., 1996; Grimes and Yamada, 1982; Grimes et al., 1969; Kimball et al., 1993). It has been reported that water deficit conditions stunted plant growth (Gerik et al., 1996), reduced leaf area expansion (Turner et al., 1986), decreased $CO_2$ assimilation rate, number of bolls and boll weight (Gerik et al., 1996; Pettigrew, 2004; Wang et al., 2007), and yield (Marani et al., 1985; Massacci et al., 2008). Several growth and developmental aspects of

upland cotton have been quantified using controlled environmental studies (Reddy et al., 1992a, b; 1993; 1997a, b) and many of those functions have been incorporated into cotton model GOSSYM to improve the functionality for field and policy arena applications (Staggenborg et al., 1996; Reddy et al., 2002a, b; Dorethy et al., 2003; Liang et al., 2012a, b). However, the existing cotton models, including GOSSYM, lack fiber components to be effectively used in the production environment to optimize fiber quality.

Fiber properties are mostly determined by internal and external cues perceived by cotton plant during fiber development that affects physiological, metabolic, and cellular activities (Allen and Aleman, 2011). Few studies have addressed the water stress effects on reproductive and fiber quality performance (Gerik et al., 1996; Basal et al., 2009; Onder et al., 2010). The early stage of fiber elongation that took place during 0-15 days after anthesis is crucial for several fiber quality parameters and water stress during this stage inhibits the fiber elongation (Mert, 2005) and reduces the fiber length and uniformity (Ritchie et al., 2004; Pace et al., 1999). Also, Johnson et al. (2002) reported that there was negative correlation between fiber strength and elongation with soil water deficit; whereas, Davidonis et al. (2004) reported that adequate soil water supply before and during boll development increased fiber maturity. However, quantitative information on how water deficit affects cotton reproductive performance and fiber quality parameters is inadequately addressed.

Cotton fiber is the world's most important natural textile fiber and is highly elongated single cell of seed epidermis (Basra, 1984). Fiber cell initiates by swelling above ovule surface and undergo temporal advancement of fiber elongation, cell wall

deposition, and maturity (Yong-Ling, 2007). The rate of progression during the fiber elongation process was affected by environment even though genetics play a major role (Haigler, 2010). Therefore, water limitation during boll developmental stages alters fiber developmental processes and properties. Although, efforts have been made to study fiber quality affected by plant water status in the field and semi-controlled environments (Basal et al., 2009; Dağdelen et al., 2009; Karademir et al., 2011; Pettigrew, 2008), these studies were not able to provide complete understanding of water deficit effects because of confounding effects from other abiotic stresses such as temperature and nutrients. Also, existing cotton simulation models are unable to predict the fiber quality parameters due to lack quantitative functional relationships between fiber quality parameters and changes in plant water status (Kelly et al., 2013). This is because of the difficulties of monitoring the dynamic properties of fiber growth and development and continuously and dynamically changing plant water status due to vagaries of weather during boll development and more importantly inadequate facilities to address these issues. . The objectives of this study were to investigate effects of water stress on cotton reproductive performance and fiber properties under optimum temperature and nutrient conditions and to develop functional algorithms which can be used to improve the functionality of cotton models for field applications.

## Materials and methods

### Experimental facility

The experiment was conducted in four sunlit, controlled environment chambers known as Soil-Plant-Atmosphere-Research (SPAR) units located at the R.R. Foil Plant Science Research Center, Mississippi State University (33$^{o}$ 28'N, 88$^{o}$ 47'W), MS. Each

SPAR chamber consists of a steel soil bin (1 m deep by 2 m long by 0.5 m wide) to accommodate the root system, a Plexiglas chamber (2.5 m tall by 2 m long by 1.5 m wide) to accommodate plant canopy and a heating and cooling system connected to air ducts that pass conditioned air to cause leaf flutter through the plant canopy. Variable density shade cloths, designed to simulate canopy spectral properties and placed around the edges of the plant canopy, were adjusted regularly to match canopy height and to eliminate the need for border plants. During this experiment, the incoming daily solar radiation outside of the SPAR units measured with a pyranometer (Model 4–8; The Eppley Laboratory Inc., Newport, RI, USA), ranged from 1.4 to 27.2 MJ $m^{-2}$ $d^{-1}$ with an average of 15.6 MJ $m^{-2}$ $d^{-1}$. The SPAR units supported by an environmental monitoring and control systems are networked to provide automatic acquisition and storage of the data, monitored every 10 s throughout the day and night. Many details of the operations and controls of SPAR chambers have been described by Reddy et al. (2001).

**Plant culture and moisture regimes control**

A genetic standard for many breeding and molecular studies of upland cotton (*Gossypium hirsutum* L.) cultivar Texas Marker (TM)-1 (Saha et al., 2008; Stelly et al., 2005; Wu et al., 2008) was seeded on June 16, 2009 in the SPAR units consisting fine sand as growing medium. Fifty percent of seedling emergence was observed five days later. Four rows with five plants per row were maintained in each chamber until harvest. Plants were fertigated with full-strength Hoagland nutrient solution (Hewitt, 1952) based on treatment-based daily measurement of evapotranspiration (Reddy et al., 2001) prior to treatment of water stress treatments and ET-based treatment during the tretment period.

Day/night temperatures of 30/22 °C and carbon dioxide concentration of 400 μmol $mol^{-1}$ were maintained throughout the experiment. Temperature control was achieved to the desired set points using chilled ethylene glycol supplied to the cooling system via several parallel solenoid values that were opened and closed depending on the cooling requirements and an electrical resistance heater which provided short pulses of heat and a fan circulated the air through the chamber (Reddy et al., 2001). Carbon dioxide concentration in each SPAR chamber was monitored and adjusted every 10 s throughout the day and maintained at 400 μmol $mol^{-1}$ during the daylight hours using a dedicated LI-6250 $CO_2$ analyzer (Li-COR, Inc., Lincoln, NE, USA). The seasonal data for daily mean temperature, daytime $CO_2$ concentration and relative humidity are presented in Table 3.1.

Table 3.1 The set treatments, percent of daily evapotranspiration (ET) imposed prior to flowering and measured chamber $CO_2$ concentration from a typical day, mean temperature and relative humidity during the experimental period for each treatment.

| Treatments | Measured variables | | |
|---|---|---|---|
| Evapotranspiration, (%) | $CO_2$ (μmol $mol^{-1}$) | Mean-T (°C) | Relative humidity (%) |
| 100 | †409 ± 2.1 | 25.5 | 45.8 ± 1.9 |
| 80 | 408 ± 3.1 | 25.4 | 44.8 ± 1.0 |
| 60 | 405 ± 4.1 | 25.6 | 45.2 ± 5.2 |
| 40 | 407 ± 2.7 | 25.8 | 36.4 ± 3.5 |

†Each value represents the mean ± SE for one typical day for $CO_2$, and 4 August to 15 October 2009 for temperature and relative humidity.

Four water stress treatments of 100, 80, 60 and 40 % of evapo-transpiration of the control (100% ET) were imposed from flowering to maturity stage of the crop. Evapotranspiration was estimated by collecting condensate from the cooling coils (Reddy

et al., 2001). A calibrated pressure transducer was used to estimate the amount ET on a 15-minute basis as described by Timlin et al. (2007). Based on evapotranspiration values recorded on previous day, the amount of water provided to each treatment were adjusted by making changes in the time and duration of irrigation provided.

## Measurements

### *Soil and water potential*

Soil moisture content and midday leaf water potential (LWP) was measured from first day of treatment to maturity to keep track of soil and plant water status in each water-stressed treatment. Three soil moisture probes (Decagon Devices Inc., Pullman, WA) inserted at 15 cm soil depth from the surface in each treatment, were used to monitor soil moisture content at 10-s basis and integrated by day are used in the analysis. Similarly, mid-day leaf water potential was estimated by using pressure chamber method as described by Turner (1988) and these measurements were made twice weekly during the treatment period. Top most fully expanded leaves from three plants were used to estimate leaf water potential in each treatment during the study.

### *Gas exchange measurements*

Net photosynthetic rates, stomatal conductance, and intercellular $CO_2$ concentration of the uppermost expanded main-stem leaves, which were the third or fourth leaf from main axis terminal, from three plants in each treatment were measured between 10:00 and 12:00 h using an open gas exchange system, LI-6400 portable photosynthesis system (LiCOR Inc., Lincoln, NE) at 7-day intervals. While measuring photosynthesis, the photosynthetically active radiation (PAR), provided by a 6400-02

LED light source, was set to 1500 μmol $m^{-2}$ $s^{-1}$, temperature inside the leaf cuvette was set to treatment daytime temperature (30 °C), relative humidity was adjusted to near ambient level (50%), and leaf chamber [$CO_2$] was set to 400 μmol $mol^{-1}$.

*Growth, biomass, and yield components*

Mainstem height was recorded from the cotyledonary node to the newest unfolded mainstem leaf from emergence to 21 days after water stress treatment at 4-day interval. The number of nodes on the mainstem was also recoded at the same interval. Flowers and open bolls were tagged daily throughout the experiment in all units. Cotton flowers are creamy-white in color on the day of anthesis and will turn into purple the day after, and thereby aiding the tagging of flowers. The day when the lint appears between the carpel walls is defined as open boll. Based on flowering and open boll dates, boll maturation period (BMP) for each boll was estimated in all treatments (Reddy et al., 1999). At the final harvest, total number of bolls produced and matured (opened) per plant were recorded. Also, stems, leaves, and reproductive structures were separated from each plant and total biomass per plant was calculated by adding dry weight of different plant parts. Each boll was separated into burr, seed, and lint and weights were recorded. Seedcotton and seed weight for each plant was calculated by adding the boll component's weight for given plant.

**Fiber quality analysis**

For each water stress treatment, based on flowering dates, open bolls were divided into different groups. Open bolls from the control were divided into 11 groups, whereas 80% ET, 60% ET, and 40% ET were divided into 10, 10 and 9 groups, respectively. The

bolls developed from flowers that were produced in the first three days of flowering constituted the first group and similarly the rest of groups of bolls were classified by successive interval of three days in each treatment. Overall, from all water stress treatments, 40 groups were obtained. Average midday LWP for each group was estimated by fitting regression equations for each treatment and running average of midday LWP over the boll maturation period for each group. All bolls from each group were analyzed for fiber quality parameters. Lint samples were assessed for quality using High Volume Instrumentation (HVI) by the Fiber and Biopolymer Research Institute at Texas Tech University, Lubbock, TX as described by Davidonis and Hinojosa (1994). Fiber properties measured on HVI were fiber length, strength, micronaire, elongation, and uniformity. Immature fiber content and maturity ratio were assessed by using advanced fiber information system (AFIS; Zellweger Uster Inc., Knoxville, TN, USA). The AFIS equipped maturity module which estimates immature and short fiber content, fiber fineness and maturity, with unmatched accuracy and speed as described by Schleth and Peter (2005) and Reddy et al. (2004).

**Data analysis**

The SPAR chambers are identical in design to provide uniform growth conditions and the treatments under study were finely controlled. All the measurements on 20 plants in each treatment were used as replicates for testing the significance of treatments, and standard errors of the mean are provided in the tables and figures. The data on growth, dry matter, and boll parameters were analyzed using general linear model PROC GLM in SAS and Fisher protected LSD tests at $P = 0.05$ (SAS Institute Inc., 2011). Regressions were fitted for midday leaf water potential and fiber quality parameters from all

treatments using SAS (SAS Institute Inc., 2011) and SigmaPlot 11.0 (Systat Software Inc., San Jose, CA).

## Results and discussion

### Soil and leaf water potential

Since leaf water relations and fiber growth and development are dynamic processes, it will be difficult to conduct meaningful experiments to develop functional algorithms for modeling. In this experiment, growing plants in nearly natural environment under optimum temperature, water and nutrient conditions up to few days to prior flowering and imposing various water deficit treatments once most of the reproductive structures (squares) are initiated permitted us to quantify cotton reproductive potential and fiber quality traits as affected by water stress conditions. Midday leaf water potential, a measure of atmosphere-plant-rooting zone soil water content, differed significantly among the treatments (Fig. 3.1). The midday leaf water potential declined during the first four weeks of treatments with ET-based irrigation treatments and stayed at those levels for the control, and two moderately stressed treatments (80 and 60% ET) and increased in the lowest treatment for the next 25-days and stayed similar for the rest of the treatment period (Fig. 3.1). On an average, the measured midday leaf water potentials, based on evapotranspiration irrigation, showed -1.71 MPa for the control treatment, and 5% (-1.79 MPa), 15% (-1.96 MPa) and 35% (-2.38 MPa) lower than the control for the 80, 60, and 40% ET treatments, respectively. Soil moisture content, measured at a depth of 15-cm, was positively and linearly correlated with measured midday leaf water potential ($r^2$ = 0.68, Fig. 3.2).

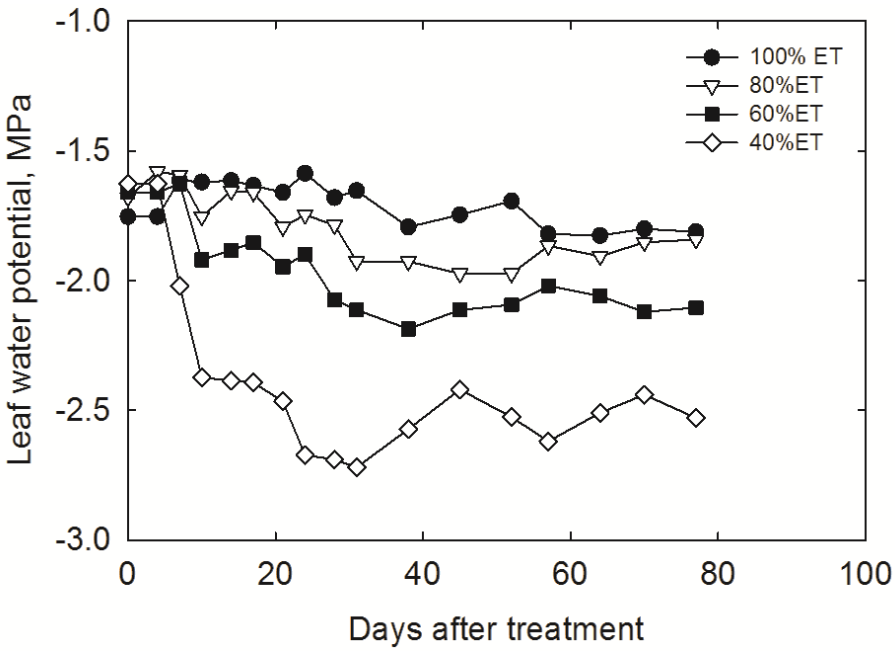


Figure 3.1 Temporal trends in cotton midday leaf water potential measured at noon time during the experimental period.

Each value is mean of three measurements taken from top-most recently fully expanded leaves from three different plants.

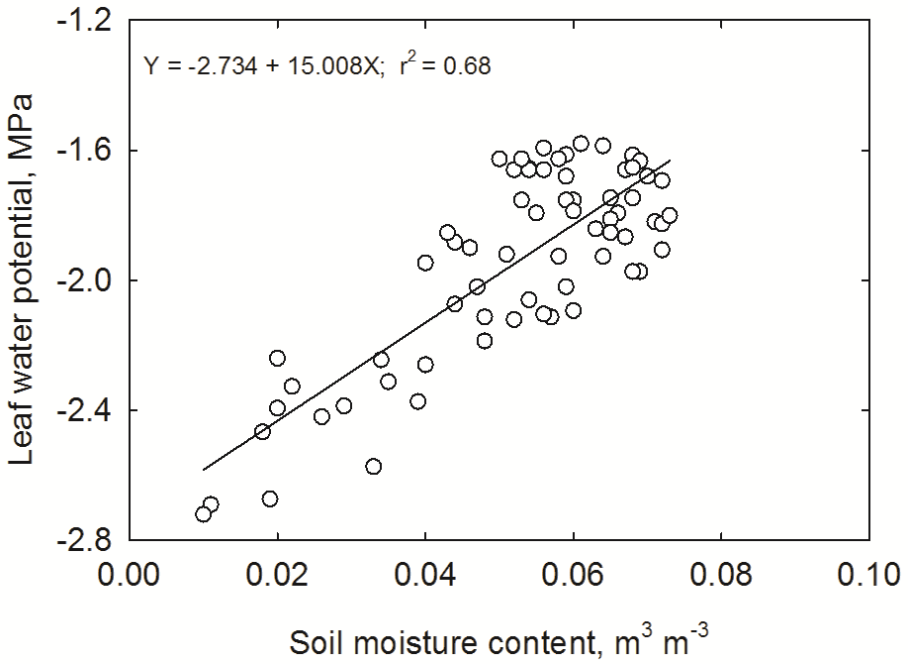


Figure 3.2 Relationship between soil moisture content and mid-day leaf water potential.

Measurements were taken starting from 0 days after treatment to harvesting maturity. Soil moisture content was measured at 15 cm depth soil column. Mid-day leaf water potential was estimated using pressure chamber method.

**Gas Exchange Processes**

Water limited condition in plants reflects the cycle of water availability and deficit. Photosynthesis inhibition along with leaf dehydration and stomatal closures mostly occurs in water deficit condition. Maximum photosynthesis (31 µmol $m^{-2}$ $s^{-1}$) rate was observed at -1.5 MPa midday leaf water potential, while at limited moisture regime (-2.6 MPa) there was 35% (20 µmol $m^{-2}$ $s^{-1}$) reduction in net photosynthesis rate. Stomatal conductance ($r^2$ = 0.53) and intercellular carbon dioxide concentration [Ci] ($r^2$ = 0.43) measured at fixed light level (1500 µmol $m^{-2}$ $s^{-1}$ PAR) linearly declined with midday lay water potential (Fig. 3.3).

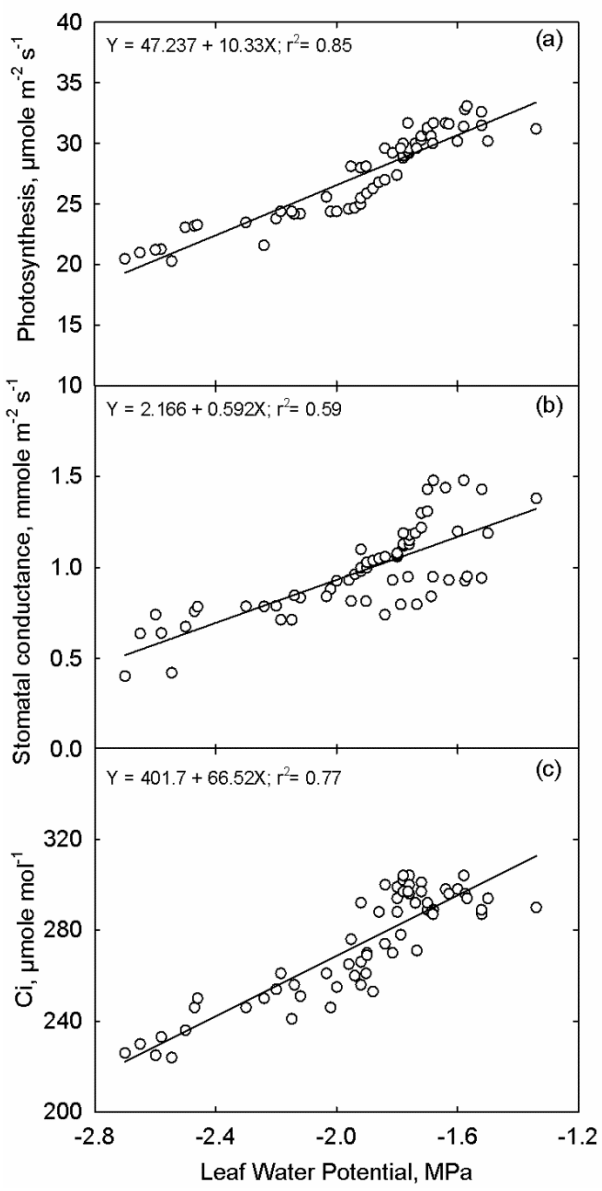


Figure 3.3 Relationship between cotton leaf mid-day leaf water potential and (a) photosynthesis rate (b) stomatal conductance (c) internal $CO_2$ concentration.

Parameters were measured on topmost fully expanded leaf (from 0 to 56 days after treatment at interval of seven days) with three samples per treatment by using Li-Cor-6400 measurement system calibrated at ambient $CO_2$ concentration (400 µmol $mol^{-1}$), 30 °C temperature and light level of 1500 µmoles $m^{-2}$ $s^{-1}$. Measurements were taken from 10:00 am to 1:30 pm during the treatment period.

Under drought stress condition, parallel response of $CO_2$ assimilation and stomatal conductance indicated that there will be restrictions in terms of $CO_2$ availability at the site of carboxylation (Carmo-Silva et al., 2012). The declining trend in stomatal conductance was steeper as compared to intercellular $CO_2$ concentration (Fig. 3.3). Under severe water stress condition, metabolic constraint like stomatal closure, mesophyll conductance became more prominent leading to inhibition of assimilation rate. Although Ci shows reduction to the level that limit carboxylation under severe water stress, the stomatal closure seems to be a major limiting factor for photosynthesis rate (Pinheiro and Chaves, 2011).

**Growth and yield attributes**

Stem elongation rates and leaf addition rates, measured during early stages of water deficit condition and during the active vegetative growth stage, showed linear and significant correlation and decline with midday leaf water potential (Fig. 3.4); stem extension rate being more sensitive (3.994 cm $plant^{-1}$ $MPa^{-1}$) than node addition rate (0.168 no. $plant^{-1}$ $MPa^{-1}$) with declining water deficits. Maximum stem elongation (3.9 cm $d^{-1}$) and node addition (0.168 nodes $d^{-1}$) rates were observed at -1.5 MPa midday leaf water potential (Fig. 3.4) and stem elongation ceased at -2.53 MPa. The reduction in stem elongation rate was due to water stress effects on cell elongation and division (Berlin et al., 1982; Boyer et al., 1980). Similar growth and developmental functional responses to midday LWP were reported in other studies in cotton (Marani et al., 1985) and other crops (Brown and Tanner, 1983; Hoogenboom et al., 1987). The reduced plant height and node numbers under water stress conditions restrict the overall vegetative growth of plant

which leads to reduction in leaf area and plant biomass and yield in cotton (Gerik et al., 1996; Pettigrew, 2004).

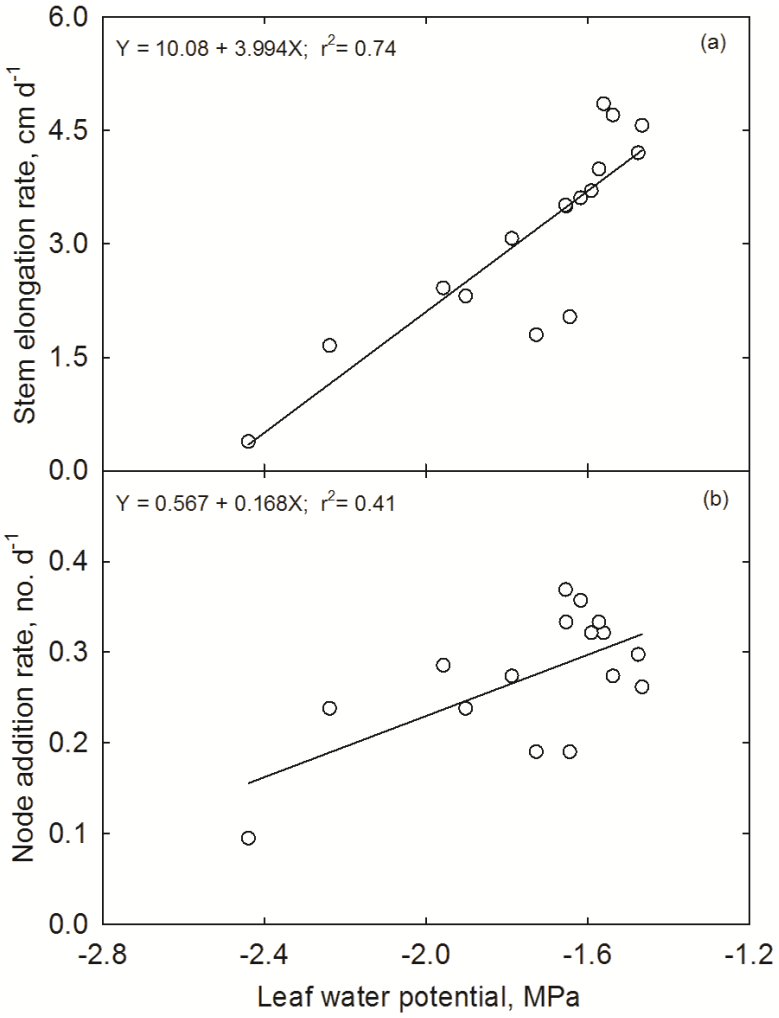


Figure 3.4 Relationship between cotton mid-day leaf water potential and (a) Stem elongation rate and (b) node addition rate.

Measurements were taken starting from 0 to 21 days after treatment with nine plants per treatment.

Plants grown under moderate (60% ET) and severe (40% ET) water stress conditions produced significantly lower amount of biomass ($P = 0.021$) per plant (Table 3.2). At optimum moisture regimes (100% ET) plants produced about 241 g plant$^{-1}$ of

biomass; whereas, moderate water stress (60% ET) and severe water stress (40% ET) showed reduction of 25 and 33 %, respectively (Table 3.2). Seedcotton weight per plant was decreased by 10% at moderate and 19% at severe water stress conditions whereas seed weight was declined by 11 and 19%, respectively (Table 3.2) at the same treatment levels. Reduced leaf area index under moisture deficit conditions lowers the canopy $CO_2$ assimilation rates which, in turn, results in shorter plants and fewer number of nodes and reproductive structures (Ennahli and Earl, 2005). Total boll numbers and open (mature) number of boll per plant were substantially lower ($P = 0.013$ and $P = 0.001$) in plants grown at severe (40% ET) moisture deficit condition (Table 3.2).

Table 3.2 Treatment means and least square difference (LSD) for all plant and boll biomass attributes studied.

| Plant Parameters | Water stress treatments, % evapotranspiration | | | | LSD |
|---|---|---|---|---|---|
| | 100 | 80 | 60 | 40 | |
| Total biomass, g plant$^{-1}$ | †241.4 a | 228.4 a | 180.1 b | 160.6 b | 40 |
| Total bolls, no. plant$^{-1}$ | 20.9 a | 18.8 a | 13.2 b | 11.8 b | 3.29 |
| Open bolls, no. plant$^{-1}$ | 13.2 a | 13.0 a | 11.6 ab | 10.5 bc | 1.79 |
| Seed cotton, g plant$^{-1}$ | 63.9 a | 62.1 a | 55.9 b | 51.7 b | 4.3 |
| Seed weight, g plant$^{-1}$ | 43.4 a | 42.2 a | 37.6 b | 35.1 b | 3.4 |
| Boll Components | | | | | |
| Boll weight, g boll$^{-1}$ | 6.31 | 6.46 | 6.44 | 6.42 | ns |
| Seed cotton weight, g boll$^{-1}$ | 4.69 a | 4.67 a | 4.60 ab | 4.53 b | 0.13 |
| Lint weight, g boll$^{-1}$ | 1.43 | 1.52 | 1.51 | 1.50 | ns |
| Seed weight, g boll$^{-1}$ | 3.22 a | 3.15 a | 3.09 a | 3.03 b | 0.20 |

†Values in each row followed by same letter are not significantly different ($P < 0.05$) according to Fisher's LSD. ns, not significant.
Plant attributes include plant height, main stem nodes, total dry weight while boll parameters include total bolls, open bolls and reproductive potential); boll components (Boll, seed cotton, lint and seed weight per boll). Final harvest was carried out at 80 % of boll opening in each treatment (20 plants per treatment).

Plants grown at optimum water condition produced 20 bolls per plant; however, only 11 bolls per plant were produced in water limited (40% ET) conditions (Table 3.2).

Plants grown at optimum water supply set more number of bolls per branch along with monopodial branches which contributed to more number of boll produced per plant. Under moisture deficit conditions, plants produced about 43% less bolls at nodes above 11 (Gerik et al., 1996; Pettigrew, 2004). Therefore, optimum water supply allowed plants to produce more number of bolls and showed significant reduction in boll numbers in plants grown under moisture deficit probably due to lower canopy photosynthesis.

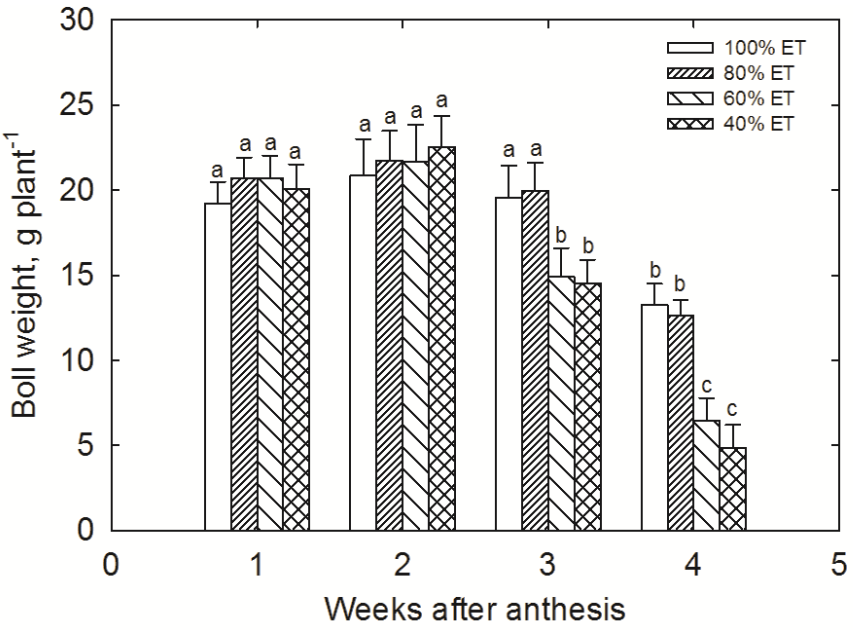


Figure 3.5 Water stress effects on cotton total boll weight per plant over time of anthesis.

Measurements were taken at final harvest carried out at 80 % of boll opening in each treatment (20 plants per treatment). Error bars indicates (±) standard error.

Seedcotton weight per boll was significantly decreased ($P = 0.016$) in severe (40% ET) moisture regimes, whereas seed weight per boll decreased by 7% in severe water stress condition. Boll and lint weight per boll did not show any significant difference across water stress treatments (Table 3.2). However, boll weight per plant over

time showed significant decline ($P = 0.003$) at later stage of treatments (Fig. 3.5). Seedcotton weight was negatively influenced by moisture deficit and individual boll weight was not affected by water stress which supports the findings reported by Pettigrew (2004). When water stress treatments imposed prior to flowering, water stress started developing gradually in cotton plants. The bolls that were developed in later part of anthesis showed significant reduction in individual boll number and weight in most water limiting condition (Basal et al., 2009).

**Fiber Properties**

Economically fiber is an important component of cotton plant and affects the profitability of the producers. Few studies have addressed and quantified water deficit and other management factor effects on fiber properties (Basal et al., 2009; Dağdelen et al., 2009; Karademir et al., 2011; Pettigrew, 2008). In general, fiber length, strength, and uniformity declined linearly whereas micronaire increased linearly with decrease in midday leaf water potential (Fig. 3.6). Longer fibers (33 mm) was observed at optimum water regime (-1.6 MPa), whereas fiber length substantially declined (< 28 mm) at leaf water potential, below -2.4MPa (Fig. 3.6a). A linear decline ($r^2 = 0.90$) in fiber length was about 8 mm $MPa^{-1}$ decrease in leaf water potential. Fiber uniformity declined linearly ($r^2 = 0.88$, Fig. 3.6d) with decrease in leaf water potential. A systematic imaging analysis conducted by Ruan et al. (2005) revealed that plasmodesmata initially open but closes after 5 days after anthesis (DAA) during peak period of elongation and reopen again at 16 days after anthesis. The closure of plasmodesmata during early stage of fiber elongation provides and maintains higher turgor pressure to drive elongation which was generated through influx of water by enhanced osmotically active solutes (Ruan et al.,

2005). Moisture deficit condition during early stages of fiber development inhibits the fiber length and subsequently the uniformity (Marani and Amirav, 1971; Hearn 1976) by affecting various mechanical and physiological process of cell expansion (Bradow and Davidonis, 2000; Pettigrew, 2004a; Ritchie et al., 2004).

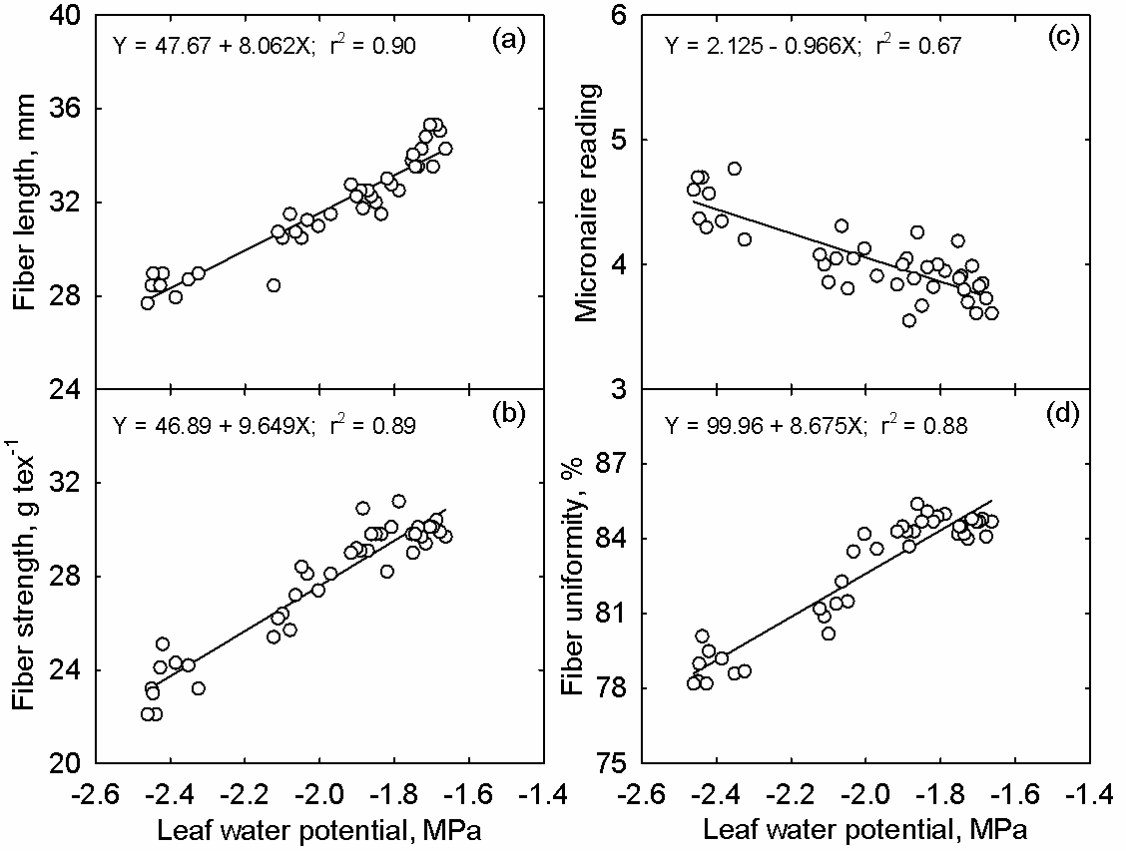


Figure 3.6 Water stress effects on (a) fiber length (b) fiber strength (c) micronaire reading and (d) fiber uniformity as a function of mid-day leaf water potential measured with HVI.

The leaf water potentials were averaged from flowering to open bolls. Lint samples were collected at final harvest carried out at 80 % of boll opening in each treatment.

Fiber strength declined linearly ($r^2$ = 0.89, Fig. 3.6b) with decrease in midday leaf water potential. Stronger fibers were produced (31 g $tex^{-1}$) under optimum water

conditions (-1.6 MPa) whereas, fiber strength weakened to 24 g $tex^{-1}$ that were produced in the severe moisture deficit regimes (below -2.3 MPa). Fiber micronaire readings exhibited linear increase ($r^2$ = 0.67, Fig. 3.6c) with decrease in leaf water potential. Micronaire values varied from 3.7 at -1.6 MPa to 4.5 at -2.5 MPa leaf water potential (Fig. 3.6c). The important process of secondary wall thickening after elongation provides strength to the cotton fibers (Seagull, 1993). Fiber elongation slows and terminates at around 20 DAA, which is accompanied by onset of intensive secondary cell wall cellulose synthesis (Basra and Malik, 1984). During this process, cellulose fibrils change the direction and concentration of metabolic sugars which increases the cellulose synthesis. Any changes in water and solute in the plasma membrane during secondary cell wall cellulose synthesis affect the fiber strength (Yong-Ling, 2007). Especially drastic reduction leaf water potential inhibits the cellulose synthesis which produces the weak fiber. Our findings of fiber strength decreased with increase in water deficit conditions supports those reported by Johnson et al. (2002) and Basal et al. (2009). Fiber perimeter and secondary wall cellulose enhances the secondary wall thickening which facilitates the spinning of yarn (Lord, 1955). This empirical relationship between cotton fiber processing properties and micronaire is used by mills (Chewning, 1995). The premium micronaire ranges between 3.7 and 4.2 (Bradow and Davidonis, 2000). Micronaire values were observed in discount range (4.5) at severe water deficit conditions. Previous studies showed inconsistency in the outcomes as micronaire was decreased (Pettigrew, 2004a) or increased (Bradow and Davidonis, 2000) as results of water stress.

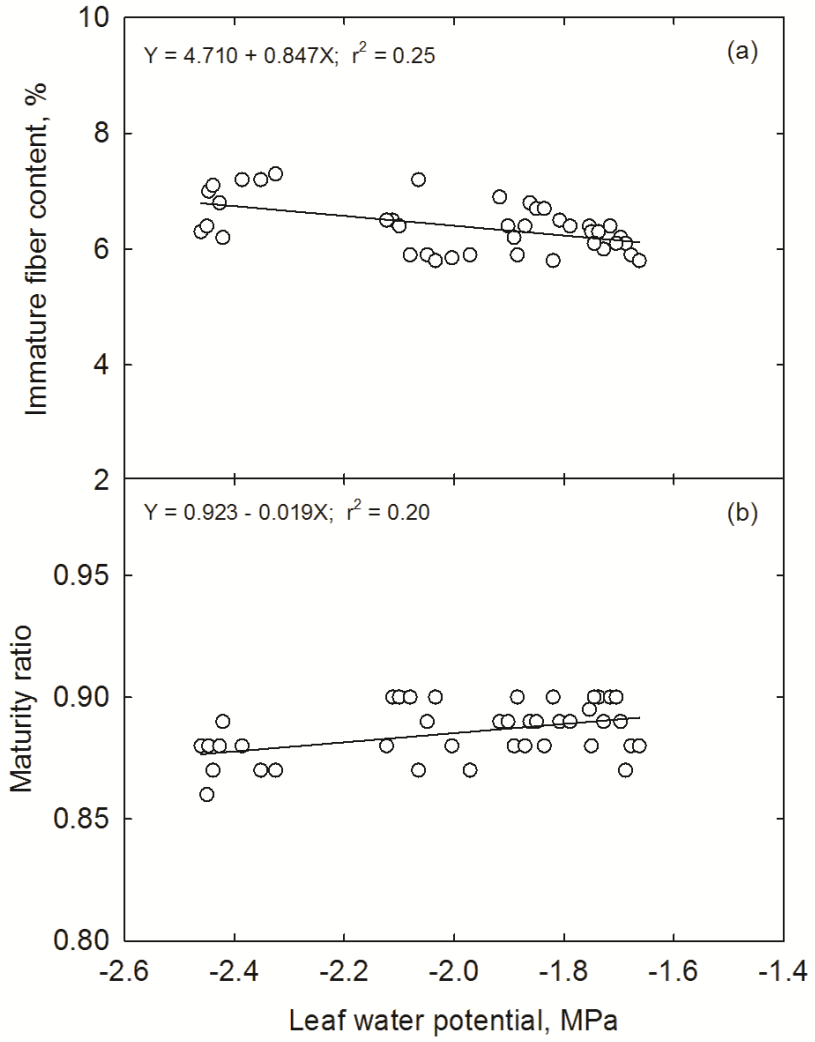


Figure 3.7 Water stress effects on (a) immature fiber content (b) fiber maturity ratio as a function of mid-day leaf water potential measured with HVI.

The leaf water potentials were averaged from flowering to open bolls. Lint samples were collected at final harvest carried out at 80% of boll opening in each treatment.

Fiber maturity is expressed in terms of maturity ratio which is a measure of degree of circularity along with immature fiber content. Although immature fiber content and maturity ratio showed poor correlation; immature fiber content inclined linearly with decrease in leaf water potential ($r^2$= 0.22, Fig. 3.7a), declined by 0.85% $MPa^{-1}$. Maturity ratio, on contrary, decreased linearly from well-watered to water-limiting conditions ($r^2$ =

0.19, Fig. 3.7b). Fiber maturity is a degree of secondary wall thickening relative to perimeter (Lord, 1981). Degree of thickening is the ratio of perimeter of the fiber wall cross section to area of circle of same perimeter. Immature fiber has very low dye affinity because of perimeter deformation and little or no secondary wall thickening. Water being crucial factor in secondary wall thickening inhibits fiber maturity ratio at mild to severe water stress conditions (Grimes and Yamada, 1982b; Ramey Jr., 1986).

**Water Stress Indices for Cotton Fiber Properties**

Quantitative relationships between cotton fiber quality parameters and plant water status are not available for use in developing models to study effects of water availability in current and projected precipitation patters due to climate change. Developing plant water status-specific fiber properties indices is the one way to quantify the effect of water stress on fiber quality. Potential fiber quality estimates are values which were obtained under optimum water and other environmental conditions. Water stress effects on fiber properties are quantified and modeled by accounting leaf water potential-specific reduction indices (Fig. 3.8) as described in methodology by Reddy et al. (2008). Corresponding regression parameters and coefficient are presented in Table 3.3.

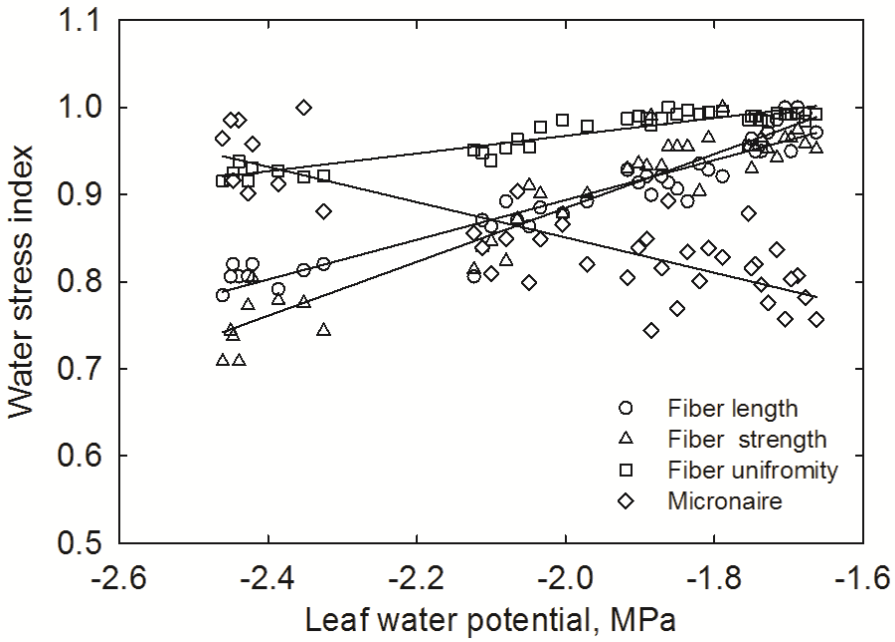


Figure 3.8 Water stress indices for various cotton fiber quality parameters.

Potential fiber quality values were estimated by dividing estimated maximum values by all the values to derive reduction factor and expressed in the fraction between 0 and 1.

Table 3.3 Regression parameters and coefficient of fiber quality parameters environmental productivity indices of cotton as affected by leaf water potential

| Fiber parameters | Regression Parameter | | Determination coefficient, $r^2$ |
|---|---|---|---|
| | yo | a | |
| Fiber length | 1.35 | 0.220 | 0.90 |
| Fiber strength | 1.50 | 0.309 | 0.89 |
| Fiber uniformity | 1.17 | 0.102 | 0.88 |
| Fiber micronaire | 0.44 | -0.203 | 0.67 |

$y = y_o + ax$, where y is the fiber quality parameter and x the leaf water potential.

The resulting indices ranging from 0 when given stress factor is completely limiting to 1 when it does not limit the given factor are presented in Fig. 3.8. The magnitude of the fraction represents the limitation due to water stress. Therefore, without any interference of other biotic and environmental factors, the effects of water stress on

fiber properties can be quantified. More importantly, this quantified information can be incorporated into a mechanistic model that responds to abiotic stress factors and could be used to predict cotton responses to weather/climatic parameters. The optimum leaf water potential for the fiber properties is -1.5 MPa. At severe water stress condition of about -2.4 MPa, there was reduction of about 25% in fiber strength estimates, whereas, micronaire values were reduced by 21% of potential estimates. This indicates that fiber strength was more responsive to leaf water potential than fiber length. Fiber micronaire is inversely proportional to leaf water potential. At severe water stressed condition fiber micronaire values of > 4.2 were observed which fell in the penalty range (Fig. 3.6c). The small amount of decrease (8%) in fiber uniformity indicates less dependence on water stress.

## Summary

This study evaluated cotton reproductive performance and fiber properties in relation to changes in water availability to plants. Along with significant differences that occurred in the reproductive development, more pronounced differences in fiber properties were of particular interest. Under different water stress regimes, cotton responded differently for plant biomass, boll size and boll maturation period. Many of these parameters declined under moderate and severe water stressed conditions. The primary gas exchange processes such as leaf photosynthesis and stomatal conductance were affected significantly under low moisture deficit regimes. Fiber parameters that are of interest to textile industry were altered by available plant water status. Fiber length was shortened under water stressed conditions, whereas, weaker fibers were produced with increase in moisture deficit. Fiber micronaire values fell in the base range (> 4.2) at

severe water limiting regimes. More short and immature fibers were produced when plants were grown under moisture deficit conditions. The identified plant water status-specific indices for fiber properties should be useful and can be incorporated into cotton simulation models to improve management practices under present and future climate change scenarios.

CHAPTER IV

# COTTON REPRODUCIVE AND FIBER QUALITY RESPONSES TO NITROGEN NUTRITION


## Abstract

Nutrient (N) stress in upland cotton affects growth, primary physiological processes, biomass, and fiber properties. An experiment was conducted by seeding upland cotton variety, TM-1, in sunlit plant growth chambers and imposing two nitrogen stress treatments (100 and 0% of optimum N level) at flowering for plants grown at optimum temperature and water supply. Flowers and bolls were tagged daily to estimate boll maturation period (BMP). Leaf samples were collected every four days from flowering to maturity to keep track of leaf N status. Plant height and mainstem nodes were measured/counted from emergence to 25 days after treatment (DAT) at 4-d interval, whereas, photosynthetic measurements were recorded weekly from 0 to 56 DAT. Plant and boll-component dry weights were recorded at end of the experiment. Lint samples were collected, grouped based on average leaf N concentration during boll maturation (BMP), for fiber quality analysis. At low N condition, total biomass declined by 23%. About 14 bolls per plant were produced in N deficient treatment compared to N sufficient (21). Leaf photosynthesis ($r^2 = 0.92$) and stomatal conductance ($r^2 = 0.86$) declined linearly with declining leaf N concentration. Fiber length and strength increased linearly with leaf N concentrations whereas fiber uniformity and micronaire declined linearly

with increasing leaf N. In relative terms, fiber micronaire was more responsive to changes in leaf N followed by strength, length and uniformity. The functional relationships between leaf nitrogen and fiber properties will be useful in developing a cotton fiber submodel under optimal temperature and water conditions.

## Introduction

Nitrogen (N) is one of the essential primary nutrients of plants and plays a vital role in agricultural production systems worldwide. Nitrogen is the key factor in biomass production and partitioning and the single most growth-limiting factor in production agriculture (Shah, 2008). It is needed in relatively larger amounts than other nutrients. Optimum amount and consistent supply of nitrogen are needed by cotton during growing season (Hou et al., 2007). Excessive or deficient N has detrimental effects on several plant processes of cotton plants (Gerik et al., 1998). Therefore, it is important to monitor the plant N status in order to make management changes to optimize yield and quality (Mackenzin and VanSchaik, 1963; Hou et al; 2007). Growth of the cotton plant depends upon leaf area development and leaf producing efficiency. Limited N supply decreases cell division, cell expansion, and leaf production (Chapin 1980; Evans, 1983) which restricts the growth and developmental processes. Prior studies showed a good correlation between leaf N content and leaf photosynthesis as major fraction of leaf nitrogen is associated with photosynthetic enzymes (Shiraiwa and Sinclair, 1993). Therefore, N deficiency in cotton causes reductions in yield by affecting stem elongation (Gardner and Tucker, 1967), leaf area development (Reddy et al., 1997; Lu et al., 2001), and photosynthetic and metabolic activities (Ciompi et al; 1996; Lu et al; 2001), reductions biomass and yield (Fritschi et al; 2003). In addition, lower than optimum N levels in the

leaf affects boll retention, fiber yield, and quality (Bradow and Davidonis, 2000; Reddy et al., 2004).

As N defficiency results in stunted growth and development (Jaynes et al., 2001), it is important to accurately detect plant N status. Leaf N concentration is an important indicator of plant N status (Gerik. 1994). About 75% of the leaf N is located in the chloroplast (Hak et al., 1993), so in $C_3$ plants like cotton, lowering N content results decrease in chlorophyll content (Reddy et al., 2002; Zhao et al., 2003) which affects the functionality of photosynthesis apparatus. It has been reported that cotton leaves accumulate about 44 g $kg^{-1}$ of N (Reddy et al., 2004) under well fertilized conditions. The strong relationship between N content of the leaves and photosynthesis is widely recognized and reported as well as that N deficiency decreases leaf area which lowers net photosynthesis rate (Wong, 1979; Radin and Boyer, 1982). Net photosynthesis and stomatal conductance were positively correlated with leaf N content and in cotton, the assimilation rate increased by 0.6 μmole $m^{-2}$ $s^{-1}$ per unit increase in N (Reddy et al., 1996) as rubisco activities declined.

The prime function of N is to initiate meristemtic activity (Crowther, 1938). Cotton requires larger amounts of N than of other elements as it is essential for growth facilitated by cell elongation and $CO_2$ assimilation (Chaplin, 1980). N availability during flowering decides the physiological stature of plant and reproductive development (Bourland et al., 1992). It has been argued that during reproductive growth, growing bolls have priority for plant assimilates and vegetative growth is suppressed (Jackson, 1990). Under N stress, vegetative growth is suppressed in all growth stages resulting in fewer bolls and higher boll shedding (Hearn, 1972). Also, studies conducted to evaluate effects

on fruiting structures have reported that N deficient cotton results in modified flowering patterns (Gerik et al., 1998) and reduced boll number and weights (Gerik et al., 1989).

Fiber is the primary and economically most important product of the cotton crop and is one of the prime sources for the textile industry (Ge, 2008). It is comprised of elongated and thickened single cell of seed epidermis whose development undergoes three distinct processes of elongation, secondary wall thickening, and maturation. Fiber achieves its maximum length in the early period of anthesis; by 15-20 days after anthesis, followed by cellulose deposition on secondary wall giving rise to strength and maturity (Davidonis et al., 2004). During the fiber development process, the stage at which the cotton plant is under nitrogen stress is crucial for fiber quality (Bradow and Davidonis, 2000). Additionally, the timing and intensity of N stress is equally important in impacting fiber quality (Ramey et al; 1986). Although several studies have focused on nitrogen nutrition effects on cotton reproductive performance and yield (Boquet et al., 1994; Pettigrew and Meredith, 1997; Bondada and Oosterhuis, 2000), few studies have extended to incorporate effects on fiber quality (Reddy et al., 2004; Read et al., 2006). It has been reported that N deficiency decreased fiber length (Rochester et al., 2001) and strength (Read et al., 2006), and increased the micronaire value (Reddy et al., 2004). A positive relationship between fiber strength and N fertility was reported by Fritschi et al. (2003), whereas, Boman and Westerman (1994) indicated no relationship between fiber strength and nitrogen.

Accurate prediction of growth, developmental and yield of cotton plants under a wide range of environmental conditions is important for management and decision making (Reddy et al., 2004). Several controlled environmental studies have been carried

out to quantify cotton growth and developmental aspects (Reddy et al 1992a, b; 1993; 1997a, b) and resulting derived mathematical functions were incorporated in to cotton simulation model, GOSSYM. This model was tested for various field and policy arenas (Dorethy et al., 2003; Liang et al., 2012a, b). However, the existing cotton models including GOSSYM model does not have a fiber quality submodel usable to effectively predict fiber properties in the production environment.

Despite several attempts to quantify the effect of nitrogen deficiency on fiber properties, conflicting results have been reported due to interactive effects of weather parameters, soil and genotypic variability in which the experiments were conducted (Reddy et al., 2004; Pettigrew et al., 1996; Jenkins et al., 1990; Jones and Wells, 1998). Therefore, studies are needed to completely isolate the effects of N deficiency on fiber properties. The objectives of this study were to evaluate the effects of nitrogen stress on cotton reproductive performance and fiber properties under optimum temperature and water conditions and to develop functional algorithms between leaf nitrogen and fiber parameters that are important to the ginning industry.

## Materials and methods

### Experimental facility

The experiment was conducted in two sunlit, controlled environment chambers known as Soil-Plant-Atmosphere-Research (SPAR) units located at the R.R. Foil Plant Science Research Center, Mississippi State University, Mississippi, USA. Each SPAR chamber consists of a steel soil bin (1 m deep by 2 m long by 0.5 m wide) to accommodate the root system, a Plexiglas chamber (2.5 m tall by 2 m long by 1.5 m wide) to accommodate plant canopy and a heating and cooling system connected to air

ducts that pass conditioned air to cause leaf flutter through the plant canopy. Variable density shade cloths, designed to simulate canopy spectral properties and placed around the edges of the plant canopy, were adjusted regularly to match canopy height and to eliminate the need for border plants. During this experiment, the incoming daily solar radiation (285 - 2800 nm) outside of the SPAR units measured with a pyranometer (Model 4–8; The Eppley Laboratory Inc., Newport, RI, USA), ranged from 1.4 to 27.2 MJ $m^{-2}$ $d^{-1}$ with average of 15.6 MJ $m^{-2}$ $d^{-1}$. The SPAR units supported by an environmental monitoring and control systems are networked to provide automatic acquisition and storage of the data, monitored every 10 s throughout the day and night. Many details of the operations and controls of SPAR chambers have been described by (Reddy et al., 2001).

**Nitrogen stress control and plant culture**

Two levels of nitrogen stress treatments of 100% and 0% N were imposed from flowering to maturity. Prior to N stress treatments, all chambers were well-watered with full strength Hoagland's nutrient solution (Hewitt, 1952). Plants were irrigated three times a day to in order to maintain optimum water supply throughout the experiment. For the two different N stress treatments, modified Hoagland's nutrient solution was stored in different tanks and pumped through plastic tubing to respective treatments by drip irrigation system. Day/night temperatures of 30/22 °C and carbon dioxide concentration of 400 µmol $mol^{-1}$ were maintained throughout the experiment. The temperature control was achieved to the desired set points using chilled ethylene glycol supplied to the cooling system via several parallel solenoid valves that were opened and closed depending on the cooling requirements and an electrical resistance heater which provided

short pulses of heat and a fan circulated the air through the chamber (Reddy et al., 2001). Carbon dioxide concentration in each SPAR chamber was monitored and adjusted every 10 s throughout the day and maintained at 400 μmol $mol^{-1}$ during the daylight hours using a dedicated LI-6250 $CO_2$ analyzer (Li-COR, Inc., Lincoln, NE, USA). The seasonal data for daily mean temperature and daytime $CO_2$ concentration are presented in Table 4.1.

Table 4.1 The set treatments, percent of N imposed prior to flowering and measured chamber $CO_2$ concentration from a typical day and mean temperature during the experimental period for each treatment.

| Treatments | Measured variables | |
|---|---|---|
| % N | $CO_2$ (μmol $mol^{-1}$) | Mean Temperature (°C) |
| 100 | †409 ± 2.1 | 25.5 |
| 0 | 408 ± 3.6 | 25.6 |

†Each value represents the mean ± SE for one typical day for $CO_2$, and 4 August to 15 October 2009 for temperature

A genetic standard for many breeding and molecular studies of upland cotton (*Gossypium hirsutum* L.) cultivar Texas Marker (TM)-1 (Saha et al., 2008; Stelly et al., 2005) was seeded on June 16, 2009 in the SPAR units utilizing fine sand as the rooting medium. Four rows with five plants per row were maintained in each chamber until harvest. Plants were harvested in each SPAR unit when the plants reached over 80% of the harvestable bolls opened.

**Measurements**

*Leaf nitrogen*

Three uppermost fully expanded leaves on mainstem from each N treatment were excised every 4 days from day of imposing treatment to physiological maturity. Leaf

samples were dried at 70 $^{o}$C for 72 hours and ground to pass 40 mesh screens. Leaf N was determined by standard micro-Kjeldahl method (Nelson and Sommers, 1972) and expressed in % N as well as grams per kilograms of N. As leaves were excised prior to analysis, the number of observations on given sampling dates were equivalent to the number of treatments. The main focus leaf N analysis was to determine temporal changes in leaf nitrogen under different level of nutrient stress and relate to reproductive performance and quality of lint produced in different fruiting zones, based on period of anthesis.

*Growth and biomass*

Mainstem height was recorded from the cotyledonary node to the newest unfolded mainstem leaf from emergence to 21 days after N stress treatment at 4-day interval. The number of nodes on the mainstem was also recoded at the same interval. Flowers and open bolls were tagged daily throughout the experiment in both treatments. Cotton flowers are creamy-white in color on the day of anthesis and will turn into purple the day after, and thereby aiding the tagging of flowers. The day when the lint appears between the carpel walls is defined as open boll. Based on flowering and open boll dates, boll maturation period (BMP) for each boll was estimated for each boll in both the treatments (Reddy et al., 1999). At the final harvest, total number of bolls produced and matured (opened) per plant were recorded. Also, stems, leaves, and reproductive structures were separated from each plant and total biomass per plant was calculated by adding dry weight of different plant parts. Each boll was separated into burr, seed and lint and weights were recorded. Seedcotton and seed weight for each plant was calculated by adding the boll component's weight for given plant.

*Photosynthesis and chlorophyll measurements*

Net photosynthetic rates and stomatal conductance of the uppermost, fully expanded mainstem leaves which were third or fourth from main axis terminal from three plants in each treatment were measured between 10:00 and 13:00 h using LI-6400 (LI-COR Inc., Lincoln, Nebraska, USA) with an integrated fluorescence chamber head (LI-6400-40 leaf chamber fluorometer). The measurements were taken at 1500 µmoles of photon $m^{-1}$ $s^{-1}$ photosynthetically active radiation, cuvette temperature set to daytime temperature of 30$^{o}$C and carbon dioxide concentration was maintained at 400 µmol $mol^{-1}$ and relative humidity was adjusted to ambient level (50%). Measurements were taken weekly from day of imposed treatments to physiological maturity.

Leaf pigment content and chlorophyll stability index (CSI) was measured by taking two sets of leaf samples collected from five fully-expanded leaves for each treatment during the same period. Five leaf discs, each 2.0 $cm^2$, from each sample were collected randomly and placed in vials containing 5 ml of dimethyl sulphoxide for chlorophyll (Chl) extraction. Absorbance of the extract was measured using a Bio-Rad ultraviolet/VIS spectrophotometer (Bio-Rad Laboratories, Hercules, CA, USA) at 470, 648, and 662 nm to calculate concentrations of Chl a, Chl b, and carotenoid content (Chapple et al., 1992). The chlorophyll stability index (CSI) was determined according to Sairam et al. (1997). Accordingly, another set of leaf discs, each 2.0 $cm^2$, was collected similarly from each cultivar and incubated at 56 °C in a temperature-controlled water bath for 30 min. The set of tubes was brought to 25 °C and the Chl content was measured from the heat-treated samples as described previously. The CSI was estimated as the ratio of Chl content in heated leaf (56°C) to that in fresh leaf expressed as a percentage.

**Fiber quality measurement**

For each nitrogen stress treatment, based on flowering dates, open bolls were divided into different groups. The bolls developed from the flowers that were produced in the first three days of flowering constituted the first group and similarly the rest groups of bolls were classified by successive interval of three days in each treatment. Overall, from both nitrogen stress treatments, 22 groups were obtained. Average leaf N concentration for each group was estimated by regression equations as days after N treatment and by running average of leaf N over boll maturation period for each group. All bolls from each group were analyzed for the fiber quality parameters. The lint samples were subjected for quality assessment by using High Volume Instrumentation (HVI) by the Fiber and Biopolymer Research Institute at Texas Tech University, Lubbock, TX as described by Davidonis and Hinojosa (1994). The HVI provides reports on five important quality characteristics describing the fiber length, strength, fineness, elongation, and uniformity.

**Data analysis**

The SPAR chambers were designed to be identical to provide even growth conditions and the treatments under study were finely controlled. All the measurements on 20 plants in each treatment were used as replicates for testing the significance of treatments, and standard errors of the mean are provided in the tables and figures. To test the significance of nitrogen stress on growth, dry matter and boll parameters were analyzed using general linear model PROC GLM in SAS and Fisher protected LSD tests at $P = 0.05$ (SAS Institute Inc., 2011). Regressions were fitted for leaf nitrogen content and fiber quality parameters from both treatments and 22 groups using SAS (SAS Institute Inc., 2011) and SigmaPlot 11.0 (Systat Software Inc., San Jose, CA).

## Results and Discussion

### Leaf nitrogen

The strategy of imposing N treatment few days before flowering worked well for achieving variability in leaf N and helped to derive its relationship to cotton reproductive and fiber parameters. Leaf N declined in both N treatments during the treatment period due to plant growth and N treatments (Fig. 4.1). The decline in N deficient treatment was steeper (*slope* = - 0.045 g N $kg^{-1}$; $r^2$ = 0.92) than for N- sufficient treatment (*slope* = - 0.024 g N $kg^{-1}$; $r^2$ = 0.91). At 72 days after treatment, leaf N contents were 35.9 g $kg^{-1}$ and 16.1 g $kg^{-1}$ in N-sufficient and N-deficient treatments, respectively. Under optimum conditions cotton plants accumulated 49 g $kg^{-1}$ of leaf N which is important indicator of plant nitrogen status (Bell et al., 2003) and whenever the plant nitrogen symptoms became visible, by the time various physiological processes were severely disrupted. Apart from growth and development, nitrogen is key component in cotton fiber developmental processes and has direct economic impact on fiber quality.

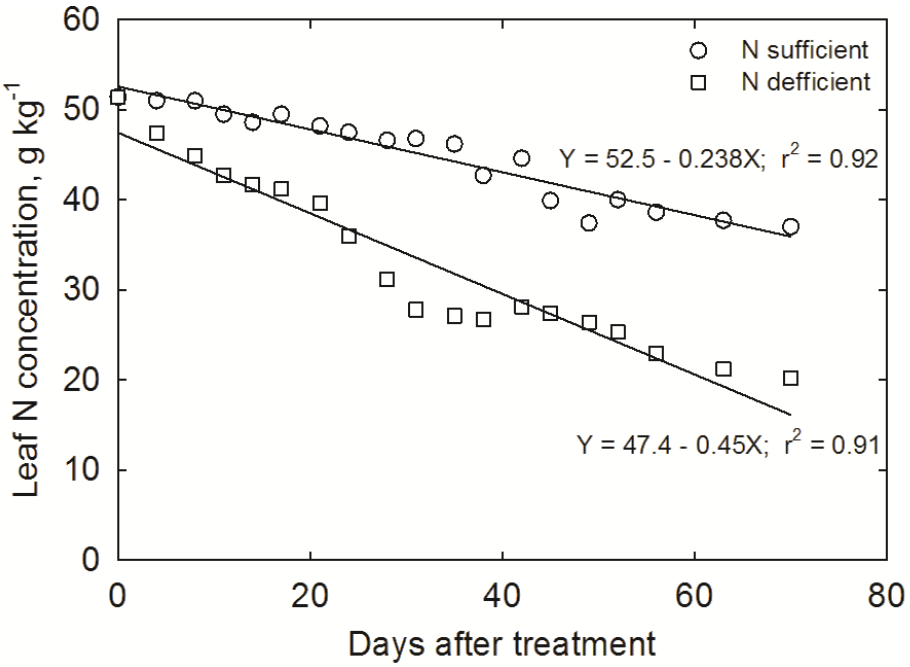


Figure 4.1 Daily average leaf nitrogen concentration plotted for two different nitrogen stress treatment (%).

Each nitrogen level was represented by lines in curves. Plants were harvested as they reached 80% open bolls.

**Leaf chlorophyll and Gas exchange processes**

Leaf N content altered cotton chlorophyll content and gas exchange processes. Photosynthesis was linearly decreased ($r^2$ = 0.92; Fig. 4.2) with decrease in leaf N content. Maximum photosynthesis of 32.7 µmol $m^{-2}$ $s^{-1}$ was observed at N content of 52 g $kg^{-1}$, whereas, at 25.2 g $kg^{-1}$ it was reduced by 41% (19.2 µmol $m^{-2}$ $s^{-1}$; Fig. 4.2). Photosynthesis decreased 0.48 µmol $m^{-2}$ $s^{-1}$ per unit decrease in leaf N content. The reduction in photosynthesis was due to decreased N content which is key component of photosynthetic enzymes and chlorophyll content (Chapin, 1980) which significantly declined in N-deficient plants ($P$ = 0.01; Fig. 4.3). Chlorophyll stability index, an

indicator of chloroplast membrane stability, was also significantly decreased ($P = 0.03$) in N-deficient condition (Fig. 4.3).

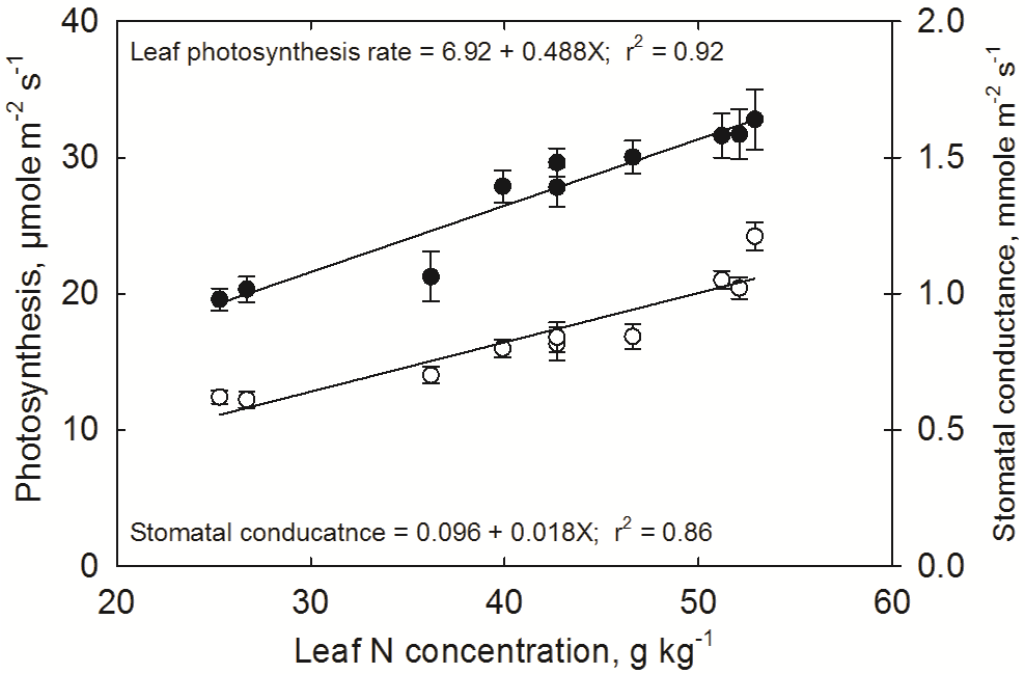


Figure 4.2 Relationship between leaf nitrogen concentration and leaf photosynthesis rate and stomatal conductance.

Parameter was measured on topmost fully expanded leaf (from 0 to 56 days after treatment at interval of seven days) with three samples per treatment by using Li-Cor-6400 measurement system calibrated at ambient $CO_2$ concentration (380 µmol $mol^{-1}$), 30°C temperature and light level of 1500 µmoles $m^{-2}$ $s^{-1}$. Measurements were taken from 10:00 am to 1:30 pm in clear sky condition.

Similar to photosynthesis, stomatal conductance declined ($r^2 = 0.86$; Fig. 4.2) with decrease in leaf N content. However, stomatal conductance decline (*slope* = 0.018; Fig. 4.2) was less steep compared to photosynthesis decline (*slope* = 0.48; Fig. 4.2) with leaf N concentration. As there was essentially no change in internal carbon dioxide concentration with decreased in leaf N and strong relationship between nitrogen and both RuBP carboxylase and chlorophyll (Evans, 1989), the decline in photosynthesis at low N

concentration is due to both greater stomatal resistance and less effective chloroplasts (Reddy et al., 1996). Our results are in agreement with prior reports of a close relationship between leaf chlorophyll and nitrogen content (Feibo et al., 1998; Zhao et al., 2005), and decline in leaf chlorophyll content (Wood et al., 1992) and photosynthesis rate (Reddy et al., 1996; Reddy et al., 1997; Lu et al., 2001) under N-deficient conditions.

**Plant growth and yield attributes**

Knowledge of the manner in which nitrogen affects vegetative and reproductive growth is the essential to understand N nutrition of cotton plants. Nitrogen deficient condition did not significantly affect the mainstem length, but mainstem node numbers were significantly decreased in with N stress ($P = 0.031$; Table 4.2). By the time the N-treatment has any significant effects, the cotton plants in this study achieved enough fruit load which competed with vegetative growth. Therefore, no significant differences were observed in this study between the N treatments as compared to many studies conducted during early stages of cotton development (Reddy et al., 1997). Mainstem length was accounted for by intermodal in elongation differences rather than mainstem node numbers (Gardner and Tucker, 1967). Plants grown under nitrogen deficient conditions produced significantly lower biomass ($P < 0.001$) per plant. The 100 N treatment plants produced 241 g plant$^{-1}$ of biomass; whereas in 0N treatment, biomass was reduced by 23% (Table 4.2). Reduction in biomass was due to reduction in leaf area (Fernáandez et al., 1996; Jackson and Gerik, 1990) and $CO_2$ assimilation rates (Ciompi et al., 1996; Reddy et al.,1997) due to insufficient N supply which, in turn, results in restricted reproductive growth.

Table 4.2 Treatment means and least square difference (LSD) for all plant and boll biomass attributes studied.

| Plant parameters | Nitrogen (%) | | LSD |
|---|---|---|---|
| | 100 | 0 | |
| Plant height, cm plant$^{-1}$ | †222 | 216 | ns |
| Mainstem nodes, no. plant$^{-1}$ | 21.2 a | 19.3 b | 0.8 |
| Total biomass, g plant$^{-1}$ | 241 a | 184 b | 40 |
| Total bolls, no. plant$^{-1}$ | 20.9 a | 14.5 b | 4.4 |
| Open bolls, no. plant$^{-1}$ | 13.2 | 12.5 | ns |
| Seed cotton weight, g plant$^{-1}$ | 63.9 a | 57.2 b | 4.7 |
| Seed weight, g plant$^{-1}$ | 40.4 a | 35.3 b | 3.7 |
| Boll components | | | |
| Boll weight, g boll$^{-1}$ | 6.31 | 6.38 | ns |
| Seed cotton weight, g boll$^{-1}$ | 4.69 | 4.65 | ns |
| Lint weight, g boll$^{-1}$ | 1.43 a | 1.59 b | 0.12 |
| Seed weight, g boll$^{-1}$ | 3.22 a | 3.06 b | 0.15 |

†Values in each row followed by same letter are not significantly different ($P < 0.05$) according to Fisher's LSD. ns, not significant.
Plant attributes include plant height, main stem nodes, total dry weight while boll parameters include total bolls, open bolls and reproductive potential); boll components (Boll, seed cotton, lint and seed weight per boll). Final harvest was carried out at 80 % of boll opening in each treatment (20 plants per treatment).

Total number of bolls produced per plant decreased ($P = 0.002$) under N-deficient condition. The 100N treatment produced about 20 bolls per plant where as the 0N treatment produced only 14 bolls per plant (Table 4.2). There was no significant decrease in open (matured) bolls in N-deficient treatment; but boll weight per plant in the 3$^{rd}$ and 4$^{th}$ week of anthesis significantly declined ($P = 0.021$) in 0N treatment (Fig. 4.4). By imposing the treatments few days before flowering, nitrogen content started depleting gradually in the cotton plants. Therefore, in later stages of anthesis, there was a significant reduction in boll number and individual boll weight (McMichael et al., 1984; Gerik et al., 1994). This is due to reduction in leaf area and canopy photosynthesis (Bondada et al., 1996; Bondada and Oosterhuis, 2001) under N deficient conditions.

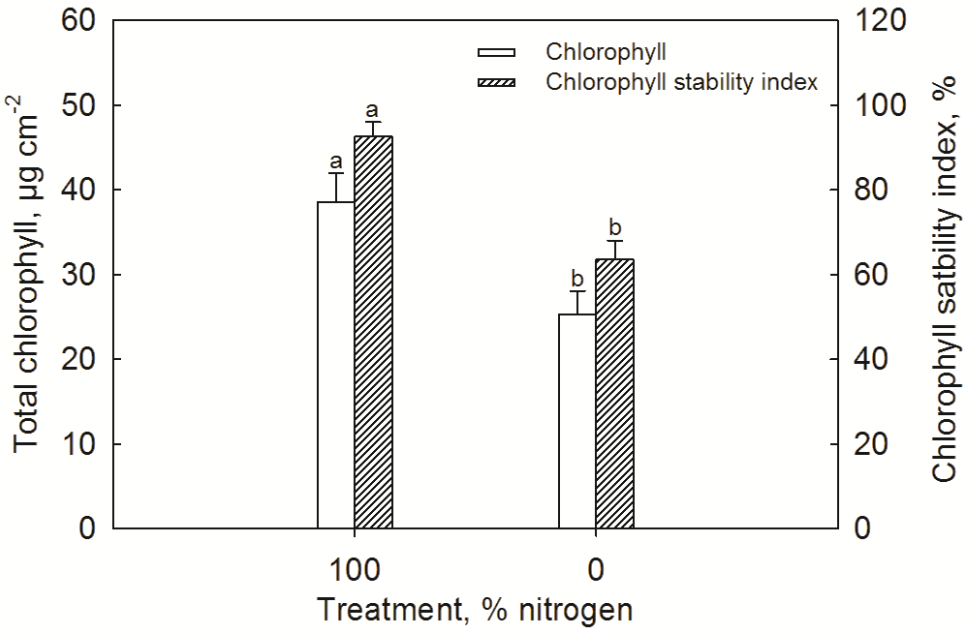


Figure 4.3 Nitrogen stress effects on total chlorophyll content and chlorophyll stability index.

Measurements were taken at 56 days after treatment on topmost fully expanded leaves from three plants and from each treatment. Error bars indicates (±) standard error.

Seedcotton and seed weights per plant significantly decreased in N-deficient treatment compared to N-sufficient treatment (Table 4.2). At 100N, plants produced 64 g of seedcotton and 43 g of seed per plant$^{-1}$, whereas a reduction of 10 (seedcotton) and 12% (seed weight) were recorded in 0N treatment. No significant differences in boll weights and seedcotton weight per boll were observed between the N treatments, however, N-deficient condition significantly ($P = 0.021$) increased the lint weight per boll whereas seed weight per boll significantly decreased ($P = 0.03$) in N-deficient treatment (Table 4.2). The decrease in seedcotton weight was due to reduction in seed weight per boll and retained boll numbers. The reduction in lint yield is due to fewer bolls retained whereas, increase in lint weight per boll under N stress condition as a result of better light

distribution within canopy due to low leaf area index and lower photosynthesis (Wullschleger and Oosterhuis, 1990; Reddy et al., 2004).

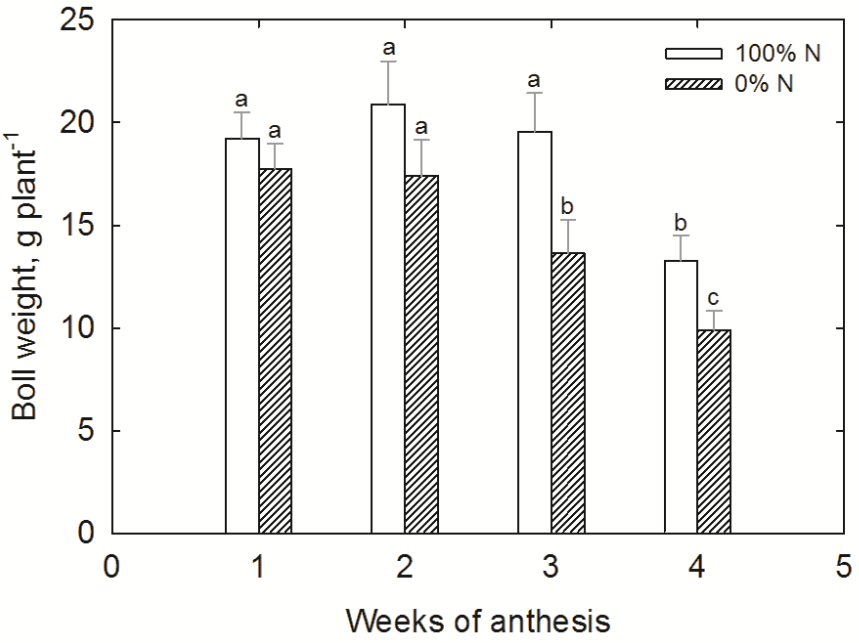


Figure 4.4 Nitrogen stress effects on cotton total boll weight per plant over time of anthesis.

Measurements were taken at final harvest carried out at 80 % of boll opening in each treatment (20 plants per treatment). Error bars indicates (±) standard error.

**Fiber properties**

Despite various studies on N effects on cotton growth and development, quantitative studies for fiber quality responses to N remain inadequate. In this study, we did find the fiber quality trends with respect to leaf N and boll maturation period. In general, fiber length, and strength showed linear decline whereas, fiber micronaire and uniformity was linearly inclined with decrease in leaf N concentration. Fiber quality is mainly determined by fiber cell elongation, primary and secondary cell wall deposition

during maturation. It will be reasonable to use leaf N concentration to evaluate the effect of N nutrition on fiber quality formation (Wang et al., 2012).

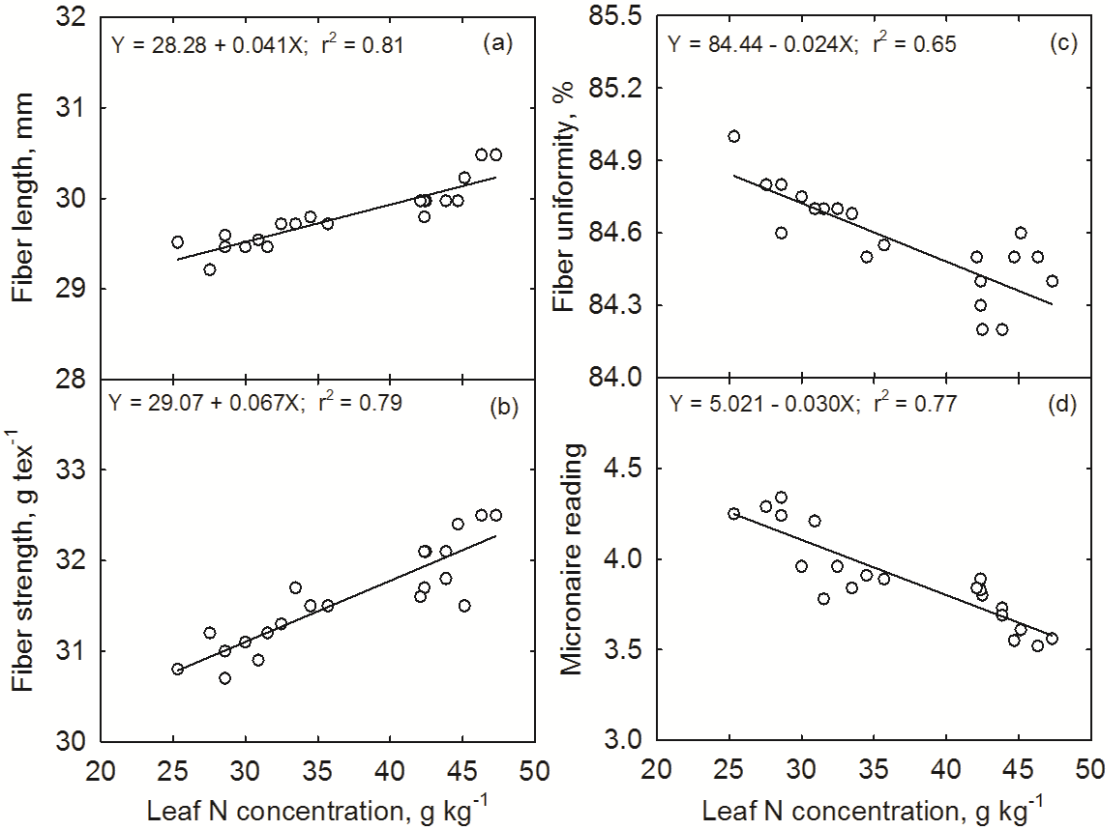


Figure 4.5 Nitrogen stress effects on (a) fiber length (b) fiber strength (c) micronaire reading and (d) fiber uniformity as a function of leaf nitrogen concentration measured with HVI.

The leaf N concentration was averaged from flowering to open bolls. Lint samples were collected at final harvest carried out at 80 % of boll opening in each treatment.

Fiber length declined linearly with declining leaf N concentration ($r^2$ = 0.81, Fig. 4.5a), with the longest fibers (30.4 mm) recorded at optimum nitrogen (45 g $kg^{-1}$). The decline in fiber length was 0.41 mm per 10 g $kg^{-1}$ decline of leaf N concentration. At leaf nitrogen concentration of 25 g $kg^{-1}$, fiber length was reduced to 29.1 mm. However, the despite the decrease, fiber length was still in the range of longer fibers (29 – 34 mm) that

is acceptable for the mills (Bradow and Davidonis, 2000). Although, fiber uniformity linearly increased ($r^2$ = 0.65, Fig. 4.5c) with decrease in leaf nitrogen, the changes in the uniformity were not significant and within the range that is not being penalized by mill industry (83 to 85%) (USDA, 2005). In a given single seed, fiber length varies as longer fiber occurs at chalazal end of the seed whereas, short fiber occurs at the micropyle end. This variation was converted into percent of total number of fiber by HVI fiber length data and expressed in terms of mean, upper half mean length, and uniformity ratio (Behery, 1993). The elongation period in fiber development process is the critical formation period for fiber length (Thaker et al., 1989; Braden and Smith, 2004). The results obtained by Reddy et al. (2004) that fiber length is negatively correlated with increased nitrogen stress during boll maturation period is in accordance with the results obtained in this study. Also, Gerik et al. (1998) concluded that, fiber grown under N stress conditions (Leaf N 25 g $kg^{-1}$) shortened fiber length and any decline in the upper half mean length affected the fiber uniformity.

Fiber strength declined ($r^2$ = 0.79, Fig. 4.5b) with decrease in leaf N. Fiber strength was recorded at 32.3 g $tex^{-1}$ when produced under optimum N conditions (45 g $kg^{-1}$), whereas, at leaf N concentration of 25 g $kg^{-1}$, fiber strength decreased to 30.5 g $tex^{-1}$. In spite of this decrease in fiber strength with N concentration, it remained in the range of strong fiber (29 and above g $tex^{-1}$) (USDA, 2005). Fiber micronaire readings measured with HVI instrument, however, exhibited linear increase ($r^2$ = 0.77, Fig. 4.5d) with decrease in leaf nitrogen concentration. The micronaire reading of 4.3 (base range) was reported a leaf N concentration of 25 g $kg^{-1}$. The acceptable upland micronaire premium range is 3.7 to 4.2 while base range is 4.3 to 4.9. Any values below 3.5 and above 4.9 will

suffer a price penalty (Bradow and Davidonis, 2000). The boll age of 24 days there is stage shift for sucrose metabolism in cotton fiber regulated by nitrogen (Ma et al., 2008). Nitrogen deficient condition during 20-40 days post-anthesis affects the fiber strength (Bradow and Davidonis, 2000; Ramey Jr, 1986). An outside pot experiment conducted by Read et al. (2006) found a reduction in fiber strength at 0% N treatment which is in conformity with the results obtained from this study. Micronaire, a measure of fiber maturity and fineness is an indirect measurement of air permeability and a very important fiber quality parameter (Lord and Heap, 1988; Moore, 1996). Results similar to this study were recorded by studies conducted by Bauer and Roof and Reddy et al. (2004). Leaf N is mostly related to the translocation capacity of photosynthate and carbohydrate to boll (Sun et al., 2007). The reduction in micronaire and maturity may be related lowered photosynthesis under N-stressed conditions (Bauer et al., 2000). A number of studies have revealed a linear correlation between micronaire and canopy photosynthesis during boll developmental stages (Pettigrew, 2001; Bauer et al., 2000).

**Nitrogen deficiency indices for cotton fiber properties**

Quantitative relationships between cotton fiber quality properties as a function of leaf nitrogen status are not available for developing a submodel for fiber quality in many cotton models. Developing leaf N concentration-specific fiber properties will help to quantify the effect of nitrogen stress on fiber quality. Potential fiber quality estimates are values which were obtained at optimum temperature, water and other environmental conditions. Nitrogen deficiency effects on fiber properties are quantified and modeled by accounting leaf nitrogen-specific reduction indices (Fig.4.6) adopting the protocols

developed by Reddy et al. (2008). Corresponding regression parameters and coefficients are presented in Table 4.3.

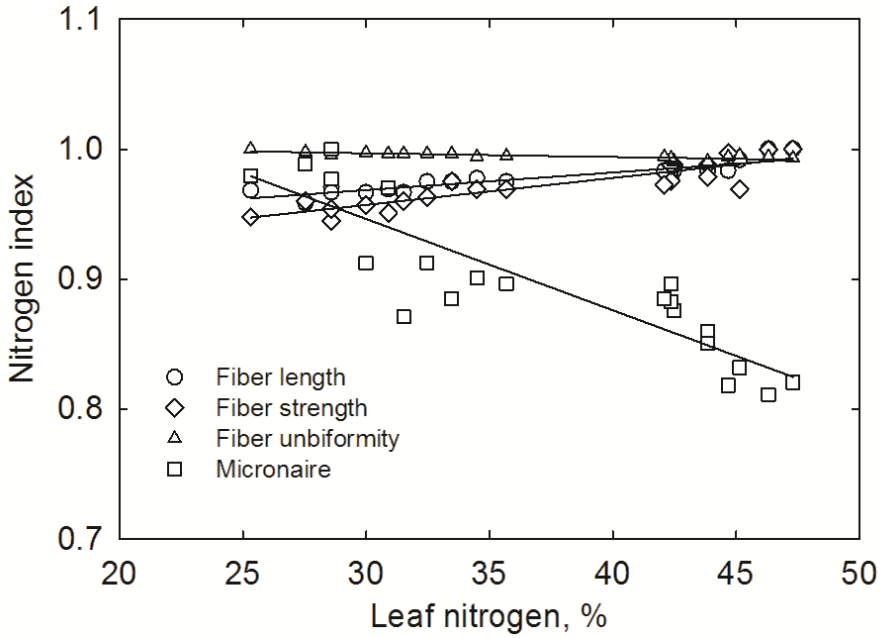


Figure 4.6 Nitrogen stress indices for various cotton fiber quality parameters

Potential fiber quality values were estimated by dividing estimated maximum values by all the values to derive reduction factor and expressed in the fraction between 0 and 1.

Table 4.3 Regression parameters and coefficient of fiber quality parameters environmental productivity indices of cotton as affected by nitrogen stress

| Fiber Parameters | Regression Parameter | | Determination coefficient, $r^2$ |
|---|---|---|---|
| | yo | a | |
| Fiber length | 0.928 | 0.001 | 0.81 |
| Fiber strength | 0.895 | 0.021 | 0.79 |
| Fiber uniformity | 1.005 | -0.003 | 0.65 |
| Fiber micronaire | 1.157 | -0.07 | 0.77 |

y = yo + ax, where y is the fiber quality parameter and x the leaf nitrogen content

The resulting indices, were ranged from 0, when given stress factor is completely limiting to 1, when it does not limit the given fiber traits. Therefore, without any interference of other biotic or environmental factors, the effects of nitrogen stress on fiber properties can be quantified and can be incorporated into a mechanistic model as sub-model. At leaf nitrogen concentration of about 25 g $kg^{-1}$, there was reduction of 6% in fiber strength estimates, whereas, fiber length was reduced by 4% of potential estimates. Fiber micronaire is inversely proportional to leaf nitrogen status, but at high N stress condition, fiber micronaire values remain above 4.2 (Fig. 4.5d). The small amount of increase (2%) in fiber uniformity indicates less dependence on leaf N status.

## Summary

This study evaluated cotton reproductive performance and fiber properties in relation to changes in leaf nitrogen. Our results show that nitrogen defficiency reduced the node numbers and plant biomass. Retained bolls and boll components were substantially decreased in plants grown under limited N condition. The primary gas exchange processes such as leaf photosynthesis and stomatal conductance were also affected significantly under low nitrogen regime. Photosynthesis was more responsive to changes in leaf N compared to stomatal conductance. The decline in leaf N concentration was reflected in decreasing trends in fiber length strength, whereas, fiber micronaire values fell in the base range (> 4.2) at nitrogen limiting condition. Changes in leaf N did not affect the fiber uniformity. The identified plant leaf N status-specific indices for fiber properties should be useful and can be incorporated in cotton simulation models to improve management practices dealing with nitrogen nutrition insufficiency.

# CHAPTER V

# REPRODUCTIVE PERFORMANCE AND FIBER QUALITY RESPONCES OF COTTON TO POTASSIUM NUTRITION


## Abstract

Potassium (K) stress in upland cotton affects growth, primary metabolic processes, biomass, and fiber properties. Two experiments were conducted in an outdoor pot facility by imposing four potassium stress treatments (100, 40, 20 and 0% of optimum K level) prior to flowering in years 2010 and 2011. Upland cotton cultivar TM-1 was seeded in the pots comprised of fine sand as rooting medium. Flowers and bolls were tagged daily to estimate boll maturation period (BMP). Leaf samples were collected every four days from flowering to maturity to track leaf K status. Plant height and node numbers were recorded from emergence to 21 days after treatment. Photosynthesis measurements were taken weekly from day of treatment imposition to physiological maturity at an interval of seven days. Stem, leaf, and boll dry weights, and boll numbers were recorded at the end of the experiments. From each boll, the lint samples were collected, grouped based on average leaf potassium concentration during BMP and fiber quality parameters were recorded. At high K deficient (0K) condition, total biomass declined by 27 and 28% in year 2010 and 2011, respectively. Significantly lower numbers of bolls were retained per plant at 0K stress during both years. Leaf photosynthesis ($r^2$ = 0.92) and stomatal conductance declined ($r^2$ = 0.80) with decline in

leaf K concentration. Fiber length, strength, micronaire and uniformity linearly declined with decrease in leaf K content. Weaker fiber with medium length was produced under K deficient condition, whereas, micronaire values were in the discount range. Fiber uniformity did not decline significantly with decrease in leaf K. The identified plant leaf K status-specific relationships for fiber properties can be used to improve management practices under potassium deficiency and to develop mathematical equations for modeling.

## Introduction

Cotton is one of the most economically important fiber crops and optimum yield and lint quality of cotton depend upon availability of nutritional elements as well as environmental conditions. Availability of major nutrients such as nitrogen, phosphorous and potassium (K) plays an important role in cotton production (Morrow and Krieg, 1990; Pettigrew, 2003). Being an important nutritional element, cotton growth, development and yield is dependent on availability of K during the growing season (Oosterhius, 1996). Cotton is more sensitive to K deficiencies than other crops (Cope, 1981) because of its less dense root system (Gerik et al., 1987).

Although K is not important constituent of many plant components, it plays a vital role in growth and metabolism. Potassium acts as osmoticum to balance the turgor pressure (Kaiser, 1982), regulate opening and closing of stomata (Humble and Raschke, 1971) and balances the exchange of anions (Streeter and Barta, 1984). It is a key element in enzyme activation (Evans and Sorger, 1966) and physiological functions of the cells. It also influences the transportation of photoassimilates from leaves to other plant parts (Ashley and Goodson, 1972; Pettigrew, 1997) and restricts fruit production to a greater

extent (Kerbey and Adams, 1985). As K is involved in carbohydrate translocation and transpiration, K deficiency substantially inhibits cotton vegetative and reproductive growth (Pettigrew and Meredith Jr, 1997; Kerby and Adams, 1985). Potassium deficiency decreases photosynthesis via its impact on reducing leaf area (Huber, 1985), $CO_2$ fixation (Ozbun et al., 1965), and stomatal conductance (Reschke, 1975) along with increasing mesophyll resistance (Peoples and Koch, 1979). Therefore, it will be useful to study the relationships between K deficiency and various plant growth and developmental processes.

Several studies have focused on potassium nutrition effects on yield, and fruiting efficiency (Boquet and Breitenbeck, 2000; Pettigrew and Meredith Jr, 1997). These efforts were also extended to study effects on fiber quality (Read et al., 2006; Bradow and Davidonis, 2000). Potassium deficiency led to decreased leaf chlorophyll content and poor development of leaf anatomy (Zhao et al., 2001). As a result there was a restriction on transport of photosynthate which leads to accumulation of sugars in leaf tissues (Pettigrew, 1999; Bednarz and Oosterhuis, 1999). Potassium deficiency during the early blooming period decreased vegetative growth (Kerby and Adams 1985) and plant biomass (Cassman et al 1989). Only a small portion of total soil K is soluble and in an exchangeable forms readily available to plants (Reddy et al., 1994). Therefore, the peak blooming period in cotton has a strong association with nutrient uptake (Boquet and Breitenbeck, 2000). Potassium demand increases during boll development (Gormus, 2002), particularly in high-fruiting and genetically-modified recent cultivars. As cotton plants produce bolls continuously, this stage of development is crucial for any study of the influence of K deficiency on seedcotton, seed and lint quantity and quality (Bradow

and Davidonis, 2000; Boquet and Moser, 2003). Also, the timing and intensity of K stress are important factors in predicting its effect of on fiber quality (Ramey Jr, 1986; Mullins and Burmaester, 1991).

Fiber development initiates from the outer seed coat and undergoes the process of elongation and secondary wall deposition followed by maturation and drying (Davidonis et al., 2004). Potassium is the key element in primary osmotica which increases turgor pressure during elongation of fiber which takes place from 0 to 20 days after anthesis (Ramey, Jr., 1986), thus K deficiency during this process decreases fiber length (Pettigrew, 1996). Apart from fiber length, the importance of micronaire and strength has increased relative to other parameters (Deussen, 1986). Studies carried out to evaluate K nutrition on eight cotton genotypes by Pettigrew and Meredith (1997) reported a reduction in fiber length and micronaire. Fiber maturity is determined by the degree of secondary wall deposition whereas micronaire is a measure of maturity and fineness. Ample supply of carbohydrates provided by canopy photosynthesis to growing bolls is linearly correlated with micronaire (Bauer et al., 2000). Cotton plants continuously produce bolls, so at given day an individual boll may be at fiber elongation stage, while others may be in cell wall thickening or maturation phase (Davidonis et al., 2004; Ramey, 1986). Therefore, the onset and intensity of K deficiency is very important to understand its effects on fiber development.

Although various studies have demonstrated the effect of K deficiency on vegetative growth and yield (Pettigrew and Meredith, 2000; Minton and Ebelhar, 1991; Reddy and Zhao, 2005), few studies have addressed the effect on lint quality (Read et al., 2006; Bradow and Davidonis, 2000). There is a demand for enhancing the overall

profitability of cotton by optimizing lint quality without sacrificing the production quantity by using various improved agronomic practices. So there is still opportunity to improve direct cultural inputs during growing season to minimize effect of K stress on cotton reproductive performance and fiber properties. The objectives of this study were to evaluate the effects of potassium stress on cotton growth and reproductive performance and to study relationships between leaf potassium and fiber parameters.

## Materials and methods

### Experimental facility

The experiments were conducted in an out-door pot culture facility located at the R. R. Foil Plant Science Research Center, Mississippi State University, Mississippi State, MS, USA (33° 28'N,88° 47'W) during the years of 2010 and 2011. The pots were 0.65 m in height and 0.15 m in diameter with a small hole at the bottom to drain excess water. The study comprised of 320 pots with 80 pots per treatment and four replications of 20 pots each. The pots were oriented in east-west direction with 1-m spacing between rows. A drip irrigation system was laid out to irrigate the plants. The average temperatures during the treatment period were 27.2 and 26.9 $^{o}$C in year 2010 and 2011, respectively.

### Potassium stress control and plant culture

Four levels of potassium stress treatments of 100, 40, 20 and 0% of optimum K were imposed from flowering to crop maturity. Four different Hoagland's nutrient solution (Hewitt, 1952) of varied K in accordance with treatments were prepared, stored in different tanks, and pumped through plastic lines to respective plants by the drip irrigation system (Reddy and Zhao, 2005). Prior to K stress treatments, all plants were

well-watered with full-strength Hoagland's nutrient solution. Plants were irrigated three times a day to maintain optimum water supply throughout the experiment. Upland cotton (*Gossypium hirsutum* L.) cultivar Texas Marker (TM)-1, a genetic standard for many breeding and molecular studies (Stelly et al., 2005; Saha et al., 2008) was seeded May 11 in 2010 and May 04 in 2011 in the pot facilities consisting of fine sand as growing medium similar to many experiments conducted in the facility (Read et al., 2006). Fifty percent of emergence was observed five days after seeding. Plants were harvested in each treatment when the plants reached over 80% of the harvestable bolls opened.

**Measurements**

*Leaf Potassium*

In both years, three uppermost fully expanded leaves on mainstem from each K treatment were excised every 4 days from day of imposed treatment to physiological maturity. Leaf samples were dried at 70 $^{o}$C and for 72 hours and ground to pass 40 mesh screens. Leaf K was determined in the Soil Testing laboratory, Mississippi State University, according to the methods of Donohue and Aho (1992) by using inductively coupled plasma optical emission spectroscopy and expressed in grams per kilogram of K. As leaves were excised prior to analysis, the number of observation on given sampling dates were equivalent to number of treatments. The main focus leaf K analysis was to determine temporal changes in leaf potassium under different levels of nutrient stress and relate to reproductive performance and quality of lint produced in different fruiting zones, based on period of anthesis.

*Growth, biomass, and yield components*

Plant height from the cotyledonary node to the newest unfolded mainstem leaf was recorded from emergence to 25 days after potassium treatment at 5-day intervals. Similarly, the number of nodes on the mainstem was recorded at the same intervals. The plants were harvested when 80% of plants reached harvestable bolls opened. Flowers and open bolls were tagged daily throughout the experiment in all treatments. The day when the lint appears between the carpel walls is defined as open boll. Based on these dates, boll maturation period for each boll was estimated in all units (Reddy et al., 1999). The total number of bolls produced and mature (opened) bolls were recorded at the final harvest in all treatments. Stems, leaves, and reproductive structures were separated from each plant. Total biomass per plant was calculated by the adding dry weight of the different plant parts. Also, bolls were separated into burr, seed and lint and their respective weights were recorded.

*Gas exchange processes*

Net photosynthetic rates and stomatal conductance of the uppermost, fully expanded leaves from four plants, one from each replication, in each treatment were measured between 10:00 and 13:00 h using LI-6400 (LI-COR Inc., Lincoln, Nebraska, USA) with an integrated fluorescence chamber head (LI-6400-40 leaf chamber fluorometer). The measurements were taken at 1500 μmole of photon $m^{-2}$ $s^{-1}$ photosynthetically active radiation, cuvette air temperature set to 30ºC and $CO_2$ concentration was maintained at 380 μmol $mol^{-1}$. Measurements were taken at 0, 14, 28, 42 and 56 days after treatment.

*Chlorophyll content and cell membrane thermostability*

Leaf chlorophyll content in all potassium treatments were measured 42 DAT by taking one set of leaf samples collected from five fully expanded leaves for each treatment period. Five leaf discs, each with 2.0 $cm^2$, from each sample were collected randomly and placed in vials containing 5 mL of dimethyl sulphoxide for chlorophyll (Chl) extraction. Absorbance of the extract was measured using a Bio-Rad ultraviolet/VIS spectrophotometer (Bio-Rad Laboratories, Hercules, CA) at 470, 648, and 664 nm to calculate concentrations of Chl a, Chl b, and carotenoid content (Chapple et al., 1992) and expressed in $\mu g\ cm^{-2}$.

The leaf cell membrane thermostability (CMT) in potassium treatments was assessed on 42 DAT according to the procedure described by Martineau et al. (1979) with minor modification. In brief, a sample for assay consisted of a paired set namely; control (C) set and treatment (T) set, of five leaf disks each 1.3 $cm^{-2}$, cut from five fully expanded $3^{rd}$ or $4^{th}$ leaf from mainstem apex randomly selected leaves. Samples were replicated three times each. Prior to assay, the paired set of leaf disks were placed in two separate test tubes and washed thoroughly with four changes of deionized water, 10 mL each time, to remove electrolytes adhering to the cut surface of the leaf disks. After the final wash, both sets of test tubes were filled with 10 mL of deionized water and sealed with aluminum foil to minimize the evaporation of water. The T-set of the test tubes were incubated for 20 minutes at 50°C in a temperature controlled-water bath, whilst the C-set of test tubes were left at room temperature (approx. 25 °C). Then, both sets of test tubes were incubated at 10 °C for 24 h. Initial conductance readings of both sets (CEC1 and TEC1) using an electrical conductivity meter (Corning Checkmate II: Corning Inc., New

York, NY, USA) were made after bringing test tubes to room temperature. After which, tubes were again sealed with aluminum foil and autoclaved at 120 °C and 0.15 MPa for 20 min to completely kill the leaf tissue. Autoclaved tubes were cooled to room temperature, contents mixed thoroughly and a final conductance (CEC2 and TEC2) was recorded. The CMT was calculated by using equation (5.1).

$$CMT(\%) = \frac{1-(\mathrm{TEC1}/\mathrm{TEC2})}{1-(\mathrm{CEC1}/\mathrm{CEC2})} \times 100 \qquad (5.1)$$

where, TEC and CEC are the measure of conductance in treated and controlled test tubes, respectively, at initial = 1 and final = 2 conductance measurements.

**Fiber properties**

In year 2011, for each potassium stress treatment, based on flowering dates, open bolls were divided into eight different groups. The bolls developed from the flowers that were produced in the first four days of flowering constituted the first group and similarly the rest groups of bolls were classified by successive interval of four days in each treatment. Overall from all potassium stress treatments, 32 groups were obtained. Average leaf K concentration for each group was estimated by running average of leaf K over boll maturation period for each group. All bolls from each group were analyzed for the fiber quality parameters. The lint samples were subjected for quality assessment by using High Volume Instrumentation (HVI) by the Fiber and Biopolymer Research Institute at Texas Tech University, Lubbock, TX as described by Davidonis and Hinojosa (1994). The HVI provides reports on five important quality characteristics describing the fiber length, strength, fineness, elongation, uniformity.

**Data analysis**

The outside pot facility was designed identically in order to provide even growth conditions, with controlled potassium fertigation. 20 plants per treatments were used for testing the significance of treatments, and standard errors of the mean are provided in the tables and figures. To test the significance of potassium stress on growth, dry matter and boll parameters were analyzed using general linear model PROC GLM in SAS and Fisher protected LSD tests at $P = 0.05$ (SAS Institute Inc., 2011). Regressions were fitted for leaf potassium content and fiber quality parameters from all treatments using SAS (SAS Institute Inc., 2011) and SigmaPlot 11.0 (Systat Software Inc., San Jose, CA) to understand the relationships and to provide mathematical equations for fiber quality as a function of leaf K.

## Results and Discussion

**Leaf potassium**

Monitoring and understanding of K requirement during crop growth are essential to study its effects and in making improved management decisions. Potassium concentration of uppermost fully expanded mainstem leaves differed among four levels of potassium treatments in the years, 2010 and 2011 (Fig. 5.1). Symptoms of K deficiency including yellowing and premature leaf drop were observed in 20 and 0K treatments predominantly in older leaves in both years. Whenever cotton leaf K concentration falls below 15 g $kg^{-1}$ during early bloom, the plant becomes deficient in K (Kerby and Adams, 1985). The 20K treatment resulted in lowered leaf K, 11 and 11.5 g $kg^{-1}$ in year 2010 and 2011, respectively (Fig. 5.1). The Severe K stress treatment, 0K, resulted in leaf K concentration dropping below 5 g $kg^{-1}$ at 60 days after treatment in both

years of experiment, whereas in the control and 40K treatments, the concentration of K in the leaves was above critical level and no visual K deficiency symptoms were observed.

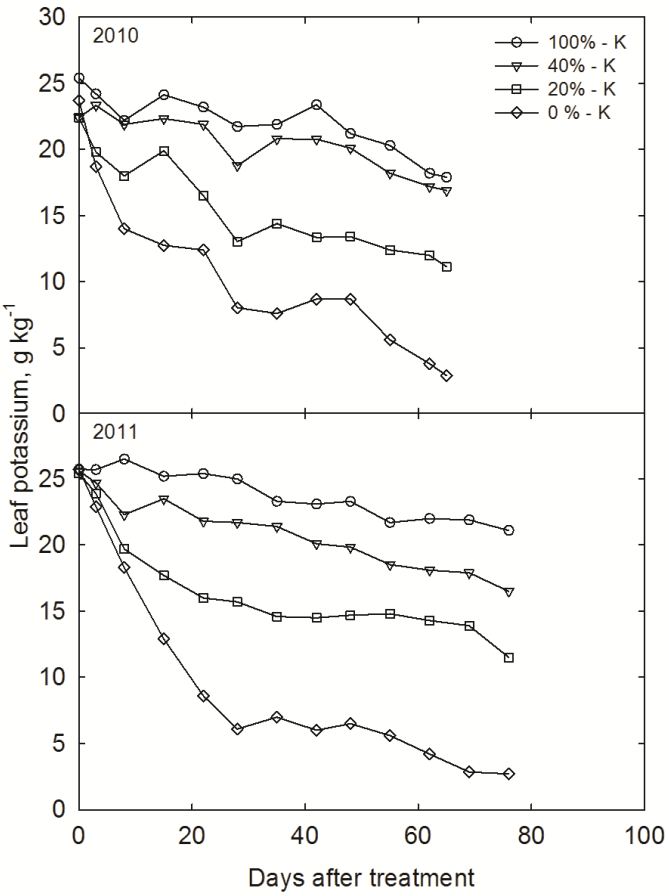


Figure 5.1 Daily average leaf potassium concentration plotted for four different potassium stress treatment (%) for year 2010 and 2011.

Each potassium level was represented by lines in curves.

It has been reported that the critical leaf K concentration affecting cotton yield was 8.5 g $kg^{-1}$ during peak flowering, whereas, Pettit (1994) reported the critical concentration to be 15 g $kg^{-1}$. An experiment conducted in an indoor facility by Oosterhuis (1996) argued it to be 6.7 to 9.5 g $kg^{-1}$during squaring which influences

growth and physiology. This study clearly indicated the critical K level achieved to study its effects on growth, reproductive performance and fiber quality.

**Leaf chlorophyll, membrane thermostability and gas exchange processes**

Leaf chlorophyll content expressed in μg $cm^{-2}$ significantly differed (*P =0.02*; Fig. 5.2a) among K treatments in years, 2010 and 2011. The 40 and 20K treatment plants had comparable chlorophyll content to those of control plants, but the plants receiving 0K had 14% and 16% lower chlorophyll in year 2010 and 2011, respectively (Fig. 5.2a). This is because the K deficient plant leaves were filled with more starch granules and fewer grana as compared to K sufficient plants (Zhao et al., 2001) and disrupting the chloroplast. Similar results were recorded in a K-deficient maize experiment conducted by Hall et al. (1972), and Huber (1984) working with soybean and by Oosterhuis (1995) in cotton, respectively.

There were significant reductions of 25 and 21% in year 2010 and 2011, respectively, in cell membrane thermostability (CMTS) of potassium deficient plants (0K) compared to control (Fig. 5.2b). It has been suggested that osmotic potential in leaf tissues may influence CMTS because of the close relationship between water relations and nutrient concentrations in cell sap and leaf tissues (Premchandra et al., 1990). Potassium acts as osmoticum to balance turgor pressure (Kaiser, 1982) and potassium-mediated osmotic changes were reported in the plants (Blum, 1989). Therefore, K deficiency influences the relative water content of leaves and subsequently increases injury to the cell membranes.

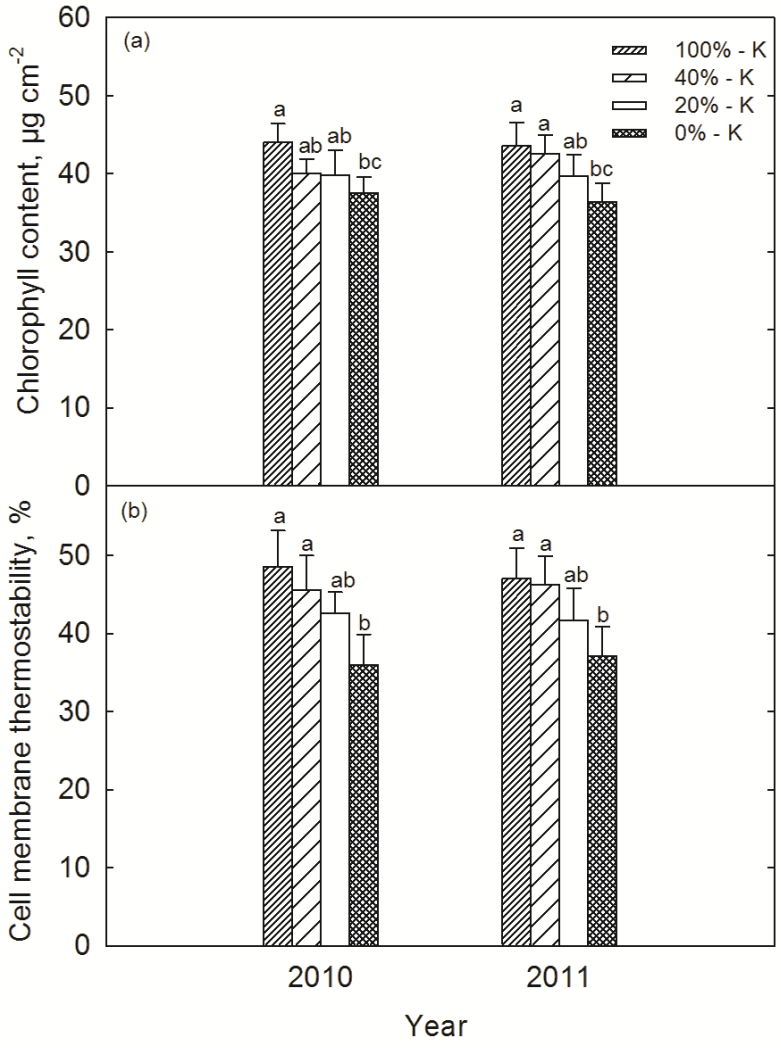


Figure 5.2 Potassium stress effects on total chlorophyll content and cell membrane thermostability.

Measurements were taken at 42 days after treatment on topmost fully expanded leaves from three plants and from each treatment. Error bars indicates (±) standard error.

Photosynthesis decreased linearly ($r^2$ = 0.84; Fig. 5.3) with decrease in leaf K content. Maximum photosynthesis of 32.8 µmol $m^{-2}$ $s^{-1}$ was observed at K content of 25.7 g $kg^{-1}$, whereas, at 6 g $kg^{-1}$ , it was lower by 28% (Fig. 5.3). The rate of decline in photosynthesis was 0.31 µmol $m^{-2}$ $s^{-1}$ per unit decrease in leaf K content. Stomatal conductance also declined linearly ($r^2$ = 0.80; Fig. 5.3) with decrease in leaf K content.

However, stomatal conductance (*slope* = 0.015; Fig. 5.3) decline was less steep compared to the decline in photosynthesis (*slope* = 0.45; Fig. 5.3). There was essentially no change in internal carbon dioxide with decreased leaf K. The strong relationship between potassium and both RuBP carboxylase activity (Peoples and Koch, 1979) and chlorophyll content (Zhao et al., 2001) indicates the central role of K concentration in maintenance of photosynthesis and related processes. Therefore, the decline in photosynthesis at low K concentration may due to both greater stomatal resistance and less effective chloroplast activity (Cakmak, 2005; Zhao et al., 2001). Our results are in agreement with prior reports of a close relationship between leaf chlorophyll and potassium content, declining in both leaf chlorophyll content (Reddy and Zhao, 2005; Zhao et al., 2001; Longstreth and Nobel, 1980) and photosynthesis rate (Reddy and Zhao, 2005; Cakmak, 2005; Bednarz et al., 1998) under K deficient conditions.

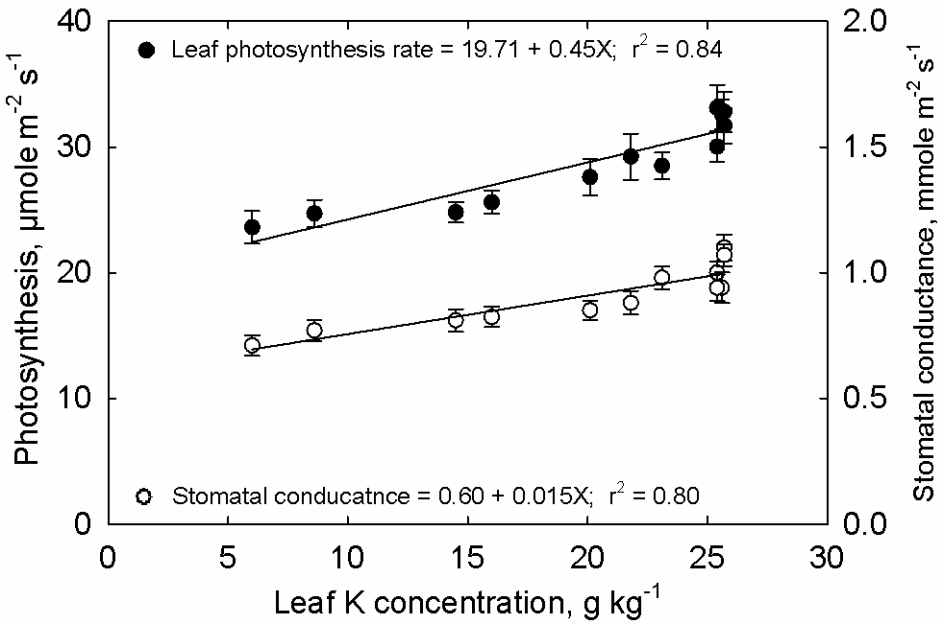


Figure 5.3 Relationship between leaf potassium concentration and leaf photosynthesis rate and stomatal conductance.

Parameter was measured on topmost fully expanded leaf (from 0 to 56 days after treatment at interval of seven days) with three samples per treatment by using Li-Cor-6400 measurement system calibrated at ambient $CO_2$ concentration (380 µmol $mol^{-1}$), 30 °C temperature and light level of 1500 µmoles $m^{-2}$ $s^{-1}$. Measurements were taken from 10:00 am to 1:30 pm in clear sky condition.

**Growth and yield attributes**

Knowledge of the manner in which potassium affects vegetative and reproductive growth is essential to understand K nutrition of cotton plants. Plant height increased as plants aged in both years and significantly differed among K treatments (Fig. 5.4). Potassium deficiency caused significant decrease in plant height with maximum decrease for both years at 0K treatments. After 25 days after treatment, plants grown under control (100K) were 144 cm (year 2010) and 151 cm (year 2011). In comparison to the control, K treatments of 40, 20, and 0K, plant height decreased by 2, 10, and 20% for year 2010, and, 2, 9, ad 19% for year 2011, respectively. Similarly, adding nodes on the mainstem

increased as plants aged in both years (Fig. 5.4) and differed significantly among K treatments. In year 2010 and 2011, at 25 days after treatment, there was reduction of 13 and 12% in K deficient treatment (0K), respectively, as compared to the control. Cotton plants require large amount of K for optimum growth and yield (Kerbey and Adams, 1985; Oosterhuis, 1994) and potassium is an important constituent in transportation of photo-assimilates from leaves to other plant parts (Ashley and Goodson, 1972). So the decline in mainstem length and node numbers may due to restrictive carbohydrate translocation and plant water relations (Pettigrew and Meredith Jr, 1997).

Plants grown under potassium deficient conditions produced significantly lower biomass ($P < 0.001$) per plant. In year 2010 and 2011, control treatment plants produced 226 and 237 g plant$^{-1}$ of biomass, respectively, whereas in 0K treatments, biomass production was reduced by 27 and 28%, respectively (Fig. 5.5). Reduction in biomass may be due to reduced leaf area and $CO_2$ assimilation rates (Reddy and Zhao, 2005) which subsequently restrict reproductive growth. The retained boll numbers per plant decreased ($P = 0.002$; Fig. 5.6) in plants grown under K deficient conditions. The control treatment retained 13 and 14 bolls per plant in year 2010 and 2011, respectively; however, only 9 and 10 bolls per plant were retained in the 0K treatment (Fig. 5.6). It has been reported that K deficiency during boll development caused the greatest decrease in fruit numbers and dry mass (Zhao et al., 2001) thus leading to reduced retained fruiting structures and plant biomass.

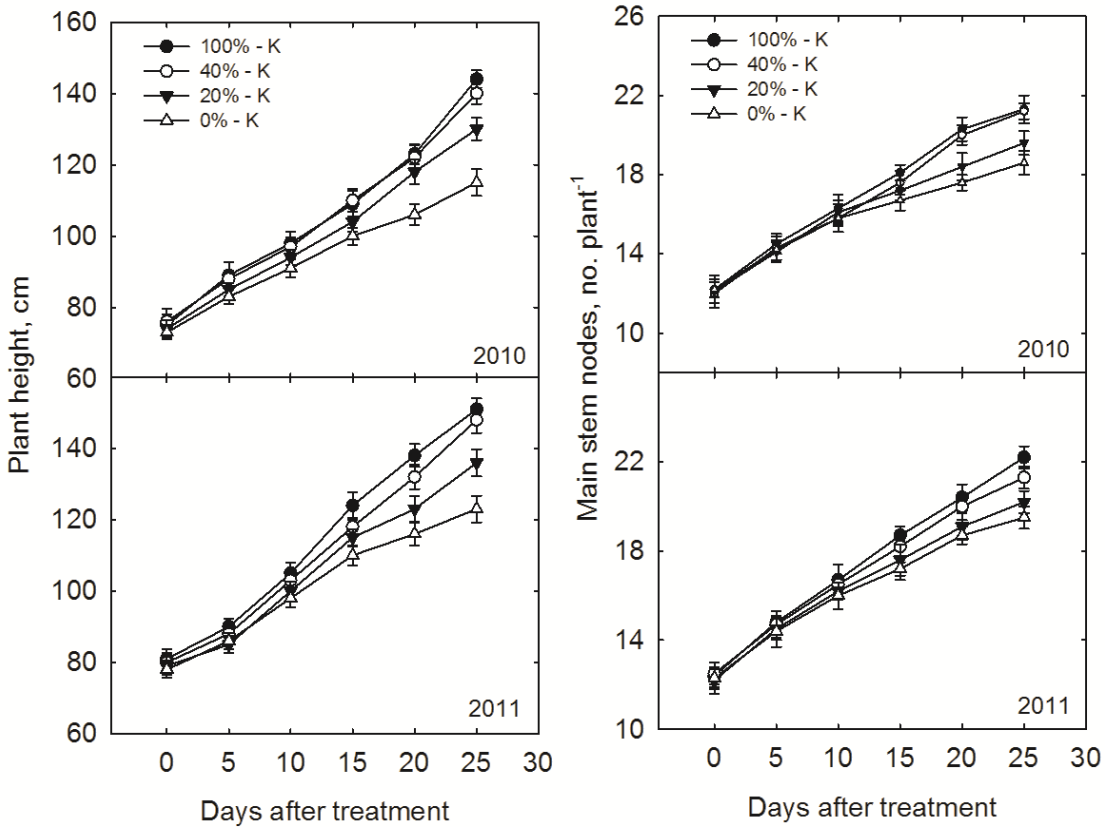


Figure 5.4 Changes in the plant height and main stem nodes of cotton as affected by potassium treatments for year 2010 and 2011.

Each data point is mean of nine individual plants and with standard errors.

Seedcotton, lint, and seed weights per plant were not significantly affected by K treatment in the first and second flowering groups in both years whereas in the third and fourth flowering group the weights were significantly affected in K deficient plants (Table 5.1). In flowering group four, 20 and 0K treatments resulted in significantly decreased seedcotton ($P = 0.021$ & $P = 0.013$), lint ($P = 0.01$ & $P = 0.03$) and seed weight ($P = 0.02$ & $P = 0.03$) per plant in year 2010 and 2011 (Table 5.1). For 100K, 56 and 63 g per plant of total seedcotton was produced while a reduction of 25 and 30% compared to the control were recorded for 0N in years 2010 and 2011, respectively.

Table 5.1 Seed cotton, seed and lint weight per plant affected by K fertilization rates across year 2010 and 2011

| Potassium treatment | Group 1 | | Group 2 | | Group 3 | | Group 4 | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2010 (2-8 July) | 2011 (3-9 July) | 2010 (9-15 July) | 2011 (10-16 July) | 2010 (16-22 July) | 2011 (17-24 July) | 2010 (23-30 July) | 2011 (15-31 July) | 2010 | 2011 |
| Seedcotton weight (g plant$^{-1}$) | | | | | | | | | | |
| Control | 16.1 | 17.0 | 15.3 | 17.6 | 13.3a | 15.2a | 11.6a | 13.0 | 56.3a | 62.8a |
| 40% K | 14.9 | 15.7 | 14.8 | 17.4 | 12.0a | 13.9a | 9.3a | 10.4a | 51.0a | 57.5a |
| 20% K | 15.6 | 15.9 | 14.3 | 15.4 | 10.8ab | 11.8ab | 4.9b | 5.6b | 45.5b | 48.7b |
| 0% K | 15.5 | 15.1 | 13.3 | 14.6 | 9.3bc | 10.4bc | 4.0b | 3.8c | 42.2b | 43.9b |
| LSD (0.05) | ns | ns | ns | ns | 2.1 | 2.8 | 2.5 | 1.6 | 5.4 | 6.1 |
| Lint weight (g plant$^{-1}$) | | | | | | | | | | |
| Control | 6.1 | 6.5 | 5.8 | 6.7 | 5.1a | 5.8a | 4.4a | 4.9a | 21.4a | 23.9a |
| 40% K | 5.9 | 6.3 | 5.9 | 7.0 | 4.8ab | 5.6ab | 3.7a | 4.2a | 20.4ab | 23.0ab |
| 20% K | 6.5 | 6.7 | 6.0 | 6.4 | 4.5ab | 5.0ab | 2.1b | 2.4b | 19.1ab | 20.5ab |
| 0% K | 6.4 | 6.2 | 5.4 | 6.0 | 3.8bc | 4.3bc | 1.6b | 1.6c | 17.3bc | 18.0bc |
| LSD (0.05) | ns | ns | ns | ns | 0.9 | 1.1 | 0.9 | 0.8 | 2.0 | 2.6 |
| Seed weight (g plant$^{-1}$) | | | | | | | | | | |
| Control | 10.0 | 10.5 | 9.5 | 10.9 | 8.2a | 9.4a | 7.2a | 8.1a | 34.8a | 38.9a |
| 40% K | 8.9 | 9.4 | 8.9 | 10.4 | 7.2ab | 8.4ab | 5.6a | 6.3a | 30.5ab | 34.5a |
| 20% K | 9.0 | 9.2 | 8.3 | 8.9 | 6.2ab | 6.8ab | 2.8b | 3.3b | 26.3ab | 28.3b |
| 0% K | 9.2 | 8.9 | 7.8 | 8.6 | 5.5bc | 6.2bc | 2.4b | 2.3b | 24.8bc | 25.9b |
| LSD (0.05) | ns | ns | ns | ns | 1.6 | 1.4 | 1.5 | 1.1 | 4.5 | 4.3 |

Measurements were recorded at 80 % of boll opening in each treatment.
†Within columns, mean followed by same letter are not significantly different at 0.05 level of probability. ns, not significant.

In year 2010, lint and seed weight per plant were reduced by 19 and 28% in 0K treatments, respectively, whereas, reductions of 24 and 33%, respectively, were recorded in year 2011 (Table 5.1). The decrease in seedcotton weight was due to reduction in seed and lint weight per boll and retained bolls (Read et al., 2006). By imposing the treatments a few days before flowering, potassium content started depleting gradually in the cotton plants (Fig. 5.1). Therefore, for the bolls developed in later stages of anthesis, a significant reduction in boll number and individual boll weight occurred (McMichael et al., 1984; Read et al., 2006). This may be due to restricted translocation of assimilates to

growing bolls due to reduction in leaf area and canopy photosynthesis (Reddy and Zhao., 2005) under K deficient condition.

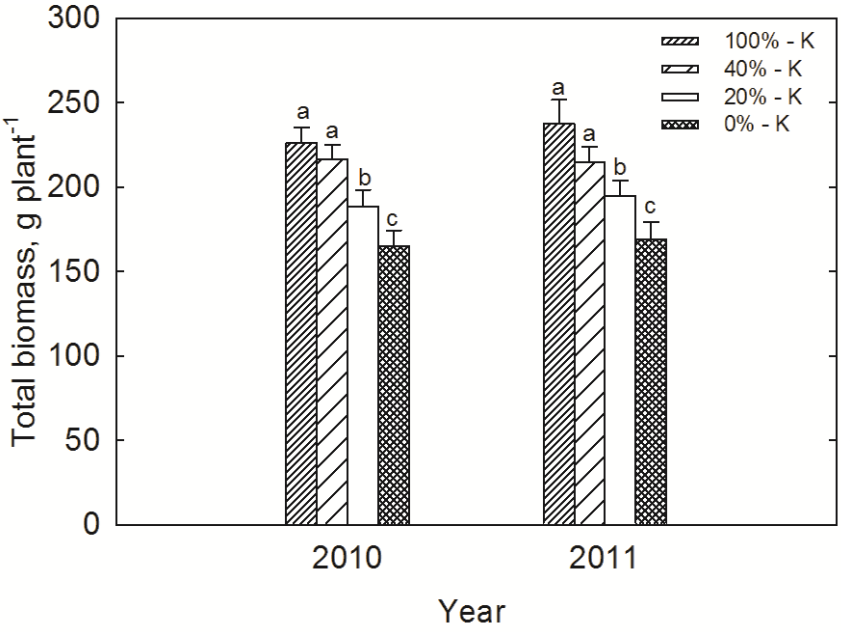


Figure 5.5 Effect of K stress on total biomass per plant. Plants were harvested at 80% of boll opening in each treatment

Values represents mean of 24 plants in each treatment.

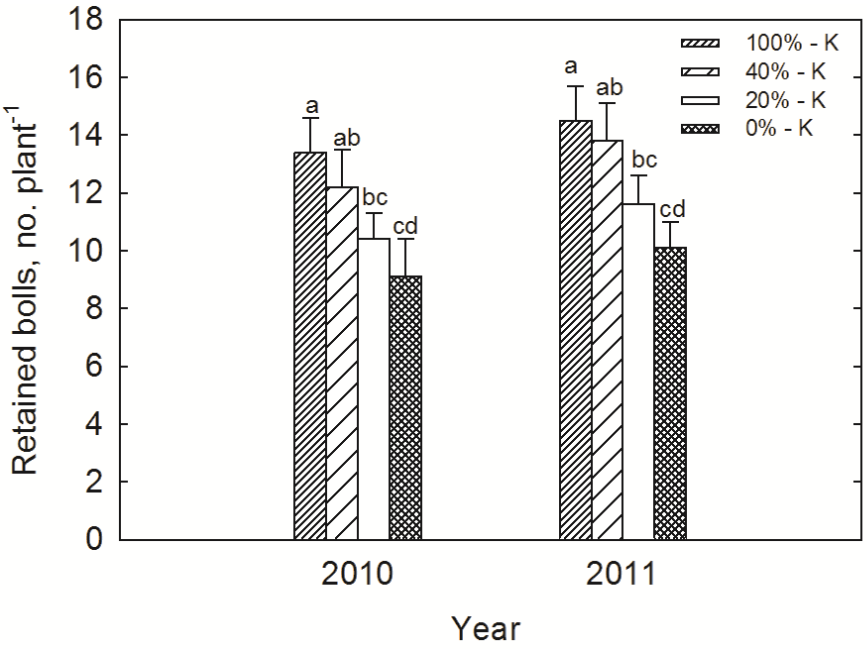


Figure 5.6 Effect of K stress on retained bolls per plant. Plants were harvested at 80% of boll opening in each treatment

Values represents mean of 24 plants in each treatment.

**Fiber properties**

This study determined the fiber quality trends with respect to leaf K averaged over the boll maturation period and the period of anthesis. Fiber quality is mainly determined by fiber cell elongation, primary and secondary cell wall deposition and maturation. It will be reasonable to use leaf K concentration to evaluate the effect of K nutrition on fiber quality (Cassman et al., 1990). In general, fiber length, strength, micronaire, and uniformity linearly declined with decrease in leaf K content.

Fiber length declined linearly with leaf K concentration ($r^2$ = 0.49, Fig. 5.7a), and the longest fibers (28.9 mm) were recorded at optimum potassium (25 g $kg^{-1}$). The decline in fiber length was 0.03 mm per unit of leaf K concentration. At leaf potassium concentration of 4.6 g $kg^{-1}$, fiber length was reduced to 27.8 mm. In spite of this decrease

in fiber length, the recorded values still remained in the range of medium length fiber (24-28 mm) (Bradow and Davidonis, 2000). Although, fiber uniformity decreased linearly ($r^2$ = 0.29, Fig. 5.7c) with decrease in leaf potassium, the changes in the uniformity were not significant and the uniformity remained within the range that is not penalized by mill industry (83 to 85%) (USDA, 2005).

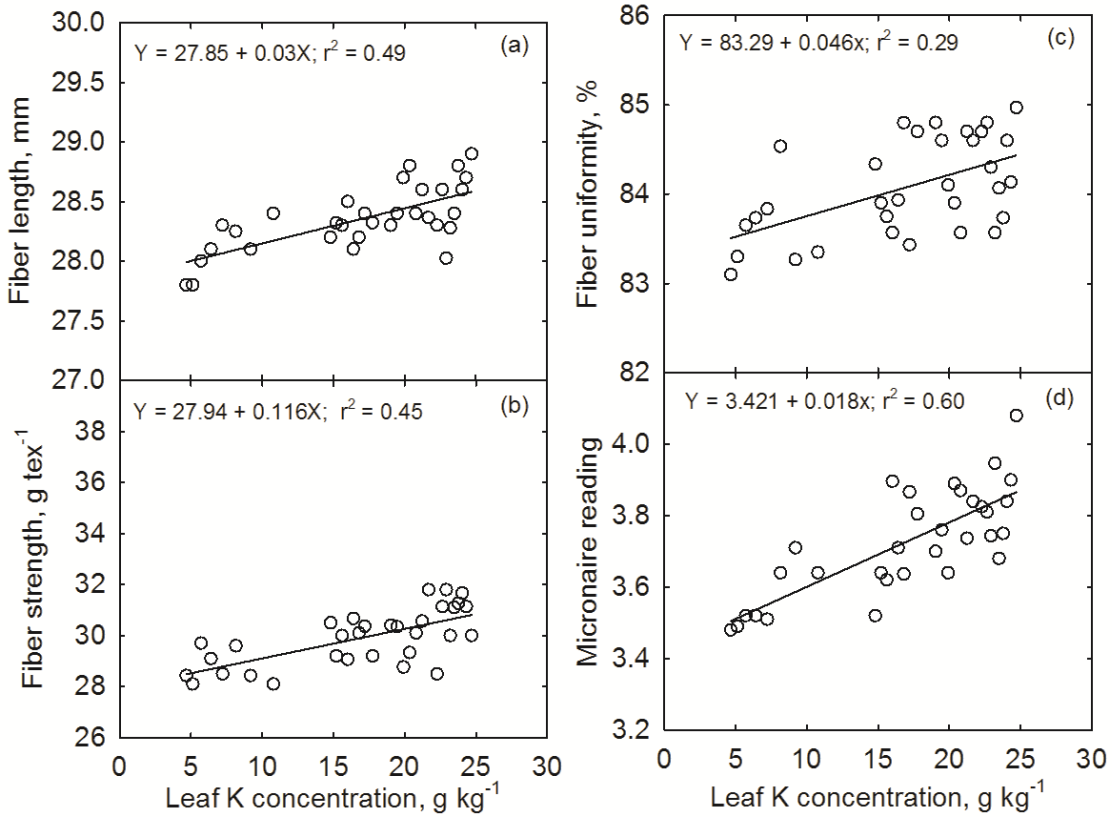


Figure 5.7 Potassium stress effects on (a) fiber length (b) fiber strength (c) uniformity and (d) fiber micronaire as a function of leaf potassium concentration measured with HVI.

The leaf K concentration was averaged from flowering to open bolls. Lint samples were collected at final harvest carried out at 80 % of boll opening in each treatment.

The elongation period in the fiber development process is critical for fiber length (Thaker et al., 1989; Braden and Smith, 2004) and potassium plays an imporatant role in

uptake of sucrose in the plasma membrane during the elongation period (Ruan, 2007). The results obtained by Read et al. (2006) that fiber length decreases with potassium stress were in accordance with the results obtained in this study. Although there is significant decline in fiber length with increase in K deficiency, the uniformity was not significantly affected. This is because very few bolls were retained in the later part of anthesis under K deficient conditions, upper half mean length was unaffected, and uniformity values remained in the high range. These results are in accordance with those reported by Gormus (1998) and Pettigrew (2003) that fiber uniformity ratio remained unaffected under K stress treatments.

Fiber strength declined ($r^2 = 0.45$, Fig. 5.7b) with decrease in leaf K. Fiber strength was recorded to be 30.0 g $tex^{-1}$ when produced under optimum K conditions (25 g $kg^{-1}$), whereas, leaf K concentration of 4.6 g $kg^{-1}$ , resulted in fiber strength decreasing to 28.3 g $tex^{-1}$. This decrease in fiber strength, at critical leaf K deficient concentration, pushed the values to average strength fiber (26-29 g $tex^{-1}$) (USDA, 2005). A field experiment conducted by Gormus (2006) found a reduction in fiber strength at 0% K treatment, which is in conformance with the results obtained from this study. Fiber micronaire readings as measured with the HVI instrument, however, exhibited a linear decrease ($r^2 = 0.60$, Fig. 5.7d) with decreased leaf K concentration. The micronaire reading of 3.48 (discount range) was reported at leaf K concentration of 4.6 g $kg^{-1}$. The acceptable upland micronaire premium range is 3.7 to 4.2 while base range is 4.3 to 4.9 and any value below 3.5 and above 4.9 will suffer a price penalty (Bradow and Davidonis, 2000). More than 24 days after anthesis is considered to be stage shift for sucrose metabolism in cotton fiber (Ma et al., 2008. Micronaire, a measure of fiber

maturity and fineness is an indirect measurement of air permeability (Lord and Heap, 1988; Moore, 1996) was recorded in the discount range which was in accordence with results obtained by Read et al. (2006) and Cassaman et al. (1990). Potassium is involved in carbohydrates translocation and plant water relations mostly related to translocation capacity of photosynthate and carbohydrates to bolls (Pettigrew, 1997). The amount of canopy photosynthesis which occurred between 15 to 45 days after flowering is linearly related with micronaire and maturity (Bauer et al., 2000). Therefore potassium, due to its important role in fiber development processes, affected the fiber properties.

## Summary

This study evaluated cotton reproductive performance and fiber properties in relation to changes in potassium. Our results show that potassium deficiency reduced the mainstem length, node numbers and total plant biomass. Retained bolls and boll components were substantially decreased in plants grown under limited K conditions. The primary gas exchange processes such as leaf photosynthesis and stomatal conductance declined significantly under potassium deficiency. Photosynthesis was more responsive to change in leaf K than was stomatal conductance. The decline in leaf K concentration reflected in shortened fiber length and weakened fiber strength, whereas, fiber micronaire values fell into the discount range (< 3.5). Changes in leaf K did not significantly affect fiber uniformity. The identified plant leaf K status-specific indices for fiber properties can be used to improve management practices under potassium deficiency and to develop a fiber model responsive to changes in leaf K levels in production environment.

CHAPTER VI

# FIBER QUALITY MODULE


## Abstract

Crop simulation models are valuable tools that scientists could use in testing hypotheses and to identify areas where knowledge is void, indicating the need for future research activities. In addition, models are being used as decision support systems at the farm-level and in policy arena to optimize resource management. The cotton simulation model, GOSSYM, is a mechanistic process level model which simulates cotton growth, development and yield and has been used for over 20 years as an on-farm decision support tool by cotton producers and consultants resulting in increased profits. In cotton, fiber development processes are major determinants of lint quality which is an economically important component of cotton yield. Fiber properties are substantially affected by temperature, water and nutrient conditions during the growing season. In this study, functional algorithms between fiber quality parameters and several abiotic stress effects (temperature, water stress, and nutrients, nitrogen and potassium) were quantified and presented a protocol on how to model fiber quality.


## Introduction

Over the last three decades, crop simulation modelling has become a major research tool in production agriculture for resource management. Information needed for

making agricultural management decision at all levels is increasing due to increased demands for agricultural products and increased pressures on land, water, and other natural resources (Jones et al., 2003). A systems approach provides a framework in which research is conducted to understand how the system and its components function. This understanding is then integrated into models that allow one to predict the behavior of the system for given conditions (Fleisher, 2003). In crop growth simulation models, current knowledge of plant growth and development from various disciplines, such as crop physiology, phenology, soil science and agronomy is integrated in a coherent, quantitative and process oriented manner (Reddy et al., 2007). These models offer great potential for numerous improvements in crop production efficiency and crop management, and also assist in policy decision.

Cotton has been produced in over 76 countries covering more than 32 million ha across a wide range of environmental conditions. It is the world's leading textile fiber plant and plays an important part in global as well as domestic agriculture and employment sectors (Singh et al., 2007). Similar to other agricultural commodities, fluctuations in supply and demand forces of the marketplace influence the value of cotton lint (Moore, 1996). Due to increase in demand for quality fiber along with economic competition on the domestic and international markets, fiber quality has become a value determinant equal in importance to fiber yield (Ethridge, 1996; Hudson et al., 1996). Therefore, the quality of fibers ginned from the cotton seeds decides the end use and economic value of a cotton crop which determines the profit returned to both the producers and processors. As processing, performance, and marketing of textile properties are directly affected by fiber quality (Bradow and Davidonis, 2000) and

introduction of new weaving technology in textile are prompting farmers to produce high quality cotton fibers (Landes et al., 2005). In production agriculture, every season is unique. Each year is unique in the timing of rain, temperature regimes, etc., and when the uniqueness is climate/weather is combined with individuality of cultural practices and cultivars traits, the farm manager has more variables to consider than human mind can reasonably think and organize information. They need tools such as crop simulation models to help make their decisions.

There are several cotton simulations that are being used at various levels to assist farm decisions. Among them, the GOSSYM cotton summation model is the most extensively and commonly used model in commercial agriculture to assist in soil, water, and nitrogen management leading to minimized risk and maximized profits (Baker et al., 1983; Reddy et al., 1997, 2002). For more than two decades, GOSSYM has been used in both tactical and strategic farm management to increase profit, manage resources and learn more about how cotton responds to environmental factors. Use of the model has also helped in complying with governmental regulations (Boone, 1997). Continuous efforts have been made by teams of researchers to improve predictability and applicability of GOSSYM across a wide range of climatic and soil conditions (Reddy et al., 2002). However, the improved model GOSSYM along with other cotton models in market do not have fiber components to be effectively used in a production environment to optimize fiber quality. The objective of this study was to develop functional algorithms between various stresses and fiber quality parameters that are important to ginners.

## History

GOSSYM, the cotton simulation model is a result of comprehensive research efforts by multidisciplinary teams at Mississippi State University, Clemson University and the USDA-ARS Crop Simulation Research Unit. GOSSYM is comprehensive and widely used in commercial agriculture to aid in making crop management decisions. The model formulation, development, and application of GOSSYM have been well documented (Baker et al., 1983; McKinion et al., 1989; Baker and Landivar, 1991; Boone et al., 1995; Hodges et al., 1998; Reddy et al., 1997, 2002). It is a mass-balance dynamic model that simulates carbon, nitrogen and water processes along with the basic biological and physical processes involved in the growth and development in the plant and soil root zone throughout the cotton life cycle (Baker et al., 1983; Boone et al., 1995). The model predicts crop growth, phenology, and yield by taking into account responses to environmental stresses, primarily from temperature, water, and nitrogen. These stresses are determined by climate variables such as solar radiation, temperature, rainfall, soil properties, and cultural practices including irrigation, fertilization and other growth regulators and crop termination chemicals.

Process-oriented crop growth models are composed of mathematical equations which represent processes in crop growth and development, simulate plant carbon balance, soil-plant-water balance, soil-plant-nitrogen, and energy balance (Boote et al., 1998). There are numerous process-oriented crop growth models are available which include CERES-Maize (Jones and Kiniry, 1986), CROPGRO-Soybean (Boote et al., 1998), and GOSSYM (Baker et al. 1983). Model uses have been grouped into the general categories of research knowledge synthesis, decision management, and policy exploration

by Boote et al. (1996). Presently, crop growth models have been used for determining optimum management schemes for fertilization, irrigation, cultural inputs, and testing hypotheses about causes for variability in fields (Hearn and Bange, 2002; Hebbar et al., 2008; Liang et al., 2012).

GOSSYM model has been used routinely in commercial cotton production to optimize resources as the model has continuously validated using numerous comprehensive datasets. The validation tests consist of checking model prediction against actual phenological events such as time of first square, first bloom, and first open boll. In addition it has capability to predict plant height, node numbers, leaf area index, stem, leaf, and fruit weight over time and seedcotton yield (Boone, 1997). Over the last three decades, GOSSYM has been actively used in field and policy arenas applications (Fye, 1984; Whisler et al., 1993; Reddy et al., 1990; Staggenborg et al., 1996; Reddy et al., 2002a, b; Dorethy et al., 2003; Liang et al., 2012a, b). However, the cotton model, GOSSYM, lack a fiber quality module to be effectively used to simulate and optimize fiber quality.

## Concept and methodology

This module is built to estimate fiber properties as affected by various environmental factors. Cotton fiber is the world's most important natural textile fiber and is the highly elongated single cell of seed epidermis (Basra, 1984). Its development undergoes three distinct processes of elongation, secondary cell wall thickening, and maturation. Fiber achieves its maximum length in the early period of anthesis, 15-20 days after anthesis, followed by cellulose deposition on secondary cell wall thickening giving rise to strength and maturity (Davidonis et al., 2004). The rate of progression during these

processes is continuously affected by environment (Haigler, 2010) and varies considerably among the cultivars, therefore temperature, water limiting conditions, and nutrient defficiency during boll development stages alters fiber developmental processes.

**Potential fiber quality**

The functional relationships between fiber quality parameters and temperature, water stress and nitrogen are presented in previous chapters. One way to quantify several weather and management factor effects on fiber quality is to develop stress-specific growth indices as proposed by Reddy at al. (2008). Potential fiber quality, defined as rate/amount of an individual parameter that takes place under optimum water and nutrient conditions under a wide range of temperatures. Fiber length, micronaire, and uniformity exhibited quadratic relationships, whereas, fiber strength increased linearly with increase in temperature. Optimum temperature for fiber length was 22°C and with declines at the low and high temperatures, whereas, fiber micronaire and uniformity have temperature optima closer to 25 °C. The mathematical equations (6.1 to 6.4) relating potential fiber quality parameters to temperature (Fig. 2.4) are given as follows:

$$FLp = 11.49 + 1.75x - 0.04x^2 \quad (6.1)$$

$$FSp = 21.81 - 0.34x \quad (6.2)$$

$$FMp = -6.88 + 0.84x - 0.017x^2 \quad (6.3)$$

$$FUp = 55.04 + 2.36x - 0.047x^2 \quad (6.4)$$

where, $FL_P$ is the potential fiber length expressed in mm, $FS_P$ is the fiber strength expressed in g $tex^{-1}$, $FM_P$ is the fiber micronaire value, $FU_P$ is fiber uniformity expressed in % and x is the average temperature ($^oC$) over the boll maturation period (BMP).

**Developing water and nitrogen stress indices.**

Once potential fiber quality is estimated as a function of temperature under optimum water and nutrient conditions, then stress (water and nitrogen)-specific reduction factors or indices were estimated to account for limiting conditions.

*Water limiting condition*

Water stress effects on fiber properties are presented chapter III. Since the cotton model, GOSSYM, estimates leaf water potential based soil-plant atmosphere continuum, developing functional algorithms as a function of midday leaf water potential was carried out first as described in chapter III. To account water stress effects on fiber quality, midday leaf water potential-dependent indices for fiber quality traits were calculated and corresponding regression parameters and coefficients are presented in the following equations (6.5 to 6.8) and in Table 3.3.

$$(CFL)ws = 1.35 + 0.22x \quad (6.5)$$

$$(CFS)ws = 1.50 + 0.309x \quad (6.6)$$

$$(CFM)ws = 1.17 + 0.102x \quad (6.7)$$

$$(CFU)ws = 0.44 - 0.203x \quad (6.8)$$

where, $(CFL)_{WS}$ is the coefficient of reduction in fiber length due to water stress

$(CFS)_{WS}$ is the coefficient of reduction in fiber strength due to water stress

$(CFM)_{WS}$ is the coefficient of reduction in fiber micronaire due to water stress

$(CFU)_{WS}$ is the coefficient of reduction in fiber uniformity due to water stress

x is the average leaf water potential (MPa) over boll maturation period (BMP).

All the indices ranging from 0, when the midday leaf potential is totally limiting the particular fiber trait, to 1, when it does not limit that parameter, represents the fractional limitation due to midday leaf water potential.

*Nitrogen limiting condition*

Since GOSSYM model calculates leaf nitrogen based on plant growth and root zone soil nitrogen and uptake, functional relationships between leaf nitrogen and fiber quality traits were calculated and presented in chapter IV. Similar to water stress effects, nitrogen-specific fiber quality functional algorithm are calculated and the resulting regression parameters indices and coefficients are presented in the following equations (6.9 to 6.12) and coefficients are presented in Table 4.3.

$$(CFL)ns = 0.928 + 0.001x \quad (6.9)$$

$$(CFS)ns = 0.895 + 0.002x \quad (6.10)$$

$$(CFM)ns = 1.00 - 0.0003x \quad (6.11)$$

$$(CFU)ns = 1.15 - 0.007x \quad (6.12)$$

where, $(CFL)_{NS}$ is the coefficient of reduction in fiber length due to nitrogen stress

$(CFS)_{NS}$ is the coefficient of reduction in fiber strength due to nitrogen stress

$(CFM)_{NS}$ is the coefficient of reduction in fiber micronaire due to nitrogen stress

$(CFU)_{NS}$ is the coefficient of reduction in fiber uniformity due to nitrogen stress

x is the average leaf nitrogen (g $kg^{-1}$) over boll maturation period (BMP).

**Overall fiber quality**

Overall fiber properties were calculated by taking into account the reduction by water and nitrogen stress and given by following equations (6.13 to 6.16):

$$Fiber\ Length = FLp * (CFL)ws * (CFL)ns \quad (6.13)$$

$$Fiber\ Strength = FSp * (CFS)ws * (CFS)ns \quad (6.14)$$

$$Fiber\ Micronaire = FMp * (CFM)ws * (CFM)ns \quad (6.15)$$

$$Fiber\ Uniformity = FUp * (CFU)ws * (CFU)ns \quad (6.16)$$

The standalone program for fiber properties was developed in perl and presented in Appendix-A.

## Summary

The data presented in this study should be useful for building a fiber quality subroutine in GOSSYM and other cotton models. Accurate prediction of fiber length, strength, micronaire, and uniformity would be estimated by taking as inputs such as temperature, leaf water potential and leaf nitrogen content from the existing GOSSYM model. The module has been developed to be capable of simulation of fiber properties and its output will be useful in improving management decisions. The cotton model with fiber quality sub-model will be useful to manage yield and fiber quality under varying weather, cultural and management conditions and also help assist in climate change and policy arena by integrating the climate data with weather, cultural and management practices.

# CHAPTER VII

# GENERAL SUMMARY AND CONCLUSIONS

Abiotic stresses affect several growth and developmental processes and can cause extensive losses to yield and product quality. Inspite of several studies on stress effects on cotton, quantitative relationships between plant processes, particularly fiber quality, and abiotic stresses are not fully addressed so for. Four experiments were conducted using sunlit controlled environment chambers and pot-culture facilities to quantify cotton growth, development and fiber quality responses to several abiotic stresses. The objectives this investigation were to study temperature, water, and nutrients (nitrogen and potassium) stresses on cotton growth and reproductive performance, and fiber quantify responses to those stresses, and to develop mathematical functional algorithms between abiotic stresses and fiber properties for modeling. Temperature (Experiment I), water stress (Experiment II), and nitrogen stress (Experiment III) studies were conducted in the sunlit plant growth chambers know as Soil-Plant-Atmosphere-Research (SPAR) units. Potassium stress (Experiment IV) was conducted in outdoor pot-culture facility. In all experiments, cotton cultivar, Texas Marker-1 (TM-1), a genetic (molecular and breeding) standard, was used. In addition, the study provided modeling methodologies on abiotic stress effects on cotton fiber quality parameters, which can be readily incorporated into many current cotton models for their improved performance on quality.

Among plants grown in low and high temperature conditions, there were significant reduction in retained bolls, plant biomass, seedcotton, seed and lint weights. However, these reductions were less under low temperature as compared to high temperature condition. The significant increase in boll maturation period (days) with decrease in temperature appeared to be one of the indications of dependency of cotton boll development on temperature. The decline in fiber length at high temperatures was greater than that at low temperature with optimum closer to 22 $^{o}$C, whereas, fiber strength increased linearly with increase in temperature. Fiber micronaire and uniformity showed quadratic trends with temperature with optima greater than that observed for fiber length. Short fiber content declined quadratically, however, immature fiber content decreased with increase in temperature. The estimated temperature indices for fiber properties indicated that fiber micronaire and strength were more responsive to low temperature whereas, fiber length and uniformity were more sensitive to high temperature.

Drought-induced reduction in leaf photosynthesis, stomatal conductance, and internal carbon dioxide concentration confirmed the cotton plant sensitivity to plant water status. This study also revealed that stomatal regulation is the major limitation for photosynthesis under drought condition in cotton and that severe drought can cause additional non-stomatal limitation to photosynthesis. Severe water stress condition significantly decreased stem elongation and node addition rates. Moderate and severe drought stresses substantially decreased the total plant biomass by limiting $CO_2$ assimilation, vegetative growth and reducing retained boll numbers and sizes. Under water deficit conditions, fiber length was shortened and weaker strength fibers were produced. Fiber micronaire values fell in the base range under water stress because more

short and immature fibers were produced under this condition. The estimated water stress-specific relative indices for fiber properties indicted more responsiveness of fiber strength and micronaire to water limiting conditions compared to length. Fiber uniformity was the least responsive to water stress among all quality parameters indicating its lower dependence on plant water condition.

The exposure of plants to nitrogen stress clearly indicated a negative impact on cotton growth and gas exchange processes, as well as yield components. Nitrogen stress substantially decreased cotton dry matter production and reproductive performance by inhibiting mainstem height, node numbers, reducing retained boll numbers and weights. Reductions in the primary gas exchange processes such as leaf photosynthesis and stomatal conductance under nitrogen limiting condition suggests the importance of maintenance of sufficient nitrogen during both vegetative and reproductive growth of cotton. The decline in leaf nitrogen concentration was reflected in declining trends in fiber length and strength. Fiber micronaire values were in base range under nitrogen limiting condition, however, the decline in the leaf nitrogen did not affect the fiber uniformity. Among all fiber quality parameters, fiber micronaire was most responsive to nitrogen defficiency followed by strength, length, and uniformity.

Potassium is an important component in plant growth and metabolism. Severe K deficiency reduced the mainstem length and node numbers. Leaf photosynthesis was more responsive to change in leaf K concentration compared to stomatal conductance. Retained bolls, boll component weights, and total plant biomass substantially decreased in plants grown under limited K conditions. The decline in leaf K concentration results in reduction in fiber length and strength. Fiber micronaire values were found to be in the

discount price range due to K defficiency during boll development, while fiber uniformity remained unaffected.

In conclusion, the current study showed that cotton growth, reproductive performance, and fiber properties were responsive to all studied abiotic factors, temperature, water, and two major nutrients, nitrogen and potassium. Evaluating and quantifying the effect on cotton cultivar TM-1 under various stress conditions revealed that inhibition of basic plant metabolic and physiological processes which led to stunted growth, biomass and ultimately reduced overall reproductive performance of cotton. Fiber properties exhibited an overall sensitivity to all stress conditions studied. However, relative responses to individual fiber quality parameter differed depending upon the type, time and severity of each stress. The quantified relationships developed among stress factors and lint quality based on their responses will be useful in improving management decisions. The data presented can also be used to build a fiber quality subroutine in GOSSYM and other cotton models. Accurate prediction of fiber, length, strength, micronaire, and uniformity would be estimated by taking input as temperature, leaf water potential and leaf nitrogen content from the existing GOSSYM model. The developed module will be useful to improve crop management decisions.

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# APPENDIX A

# FIBER QUALITY PROGRAM

```
my @TEMPLIST = ();
my @NITROLIST = ();
my @LWPLIST = ();

#Calculations for fiber Length
$tempt_Length=temperatureLEN(\@TEMPLIST);
$EPI_nitro_Length=nitrogenLEN(\@NITROLIST);
$EPI_lwp_Length=waterLEN(\@LWPLIST);
$fiber_Length= $tempt_Length * $EPI_nitro_Length * $EPI_lwp_Length;

#Calculations for fiber Strength
$tempt_Strength=temperatureSTR(\@TEMPLIST);
$EPI_nitro_Strength=nitrogenSTR(\@NITROLIST);
$EPI_lwp_Strength=waterSTR(\@LWPLIST);
$fiber_Strength= $tempt_Strength * $EPI_nitro_Strength * $EPI_lwp_Strength;

#Calculations for fiber Uniformity
$tempt_Uniformity=temperatureUNI(\@TEMPLIST);
$EPI_nitro_Uniformity=nitrogenUNI(\@NITROLIST);
$EPI_lwp_Uniformity=waterUNI(\@LWPLIST);
$fiber_Uniformity= $tempt_Uniformity * $EPI_nitro_Uniformity * $EPI_lwp_Uniformity;

#Calculations for fiber Micronaire
$tempt_Micronaire=temperatureMIC(\@TEMPLIST);
$EPI_nitro_Micronaire=nitrogenMIC(\@NITROLIST);
$EPI_lwp_Micronaire=waterMIC(\@LWPLIST);
$fiber_Micronaire= $tempt_Micronaire * $EPI_nitro_Micronaire * $EPI_lwp_Micronaire;

#Average papameter output
open (OUTFILE, ">lint quality.txt");
print OUTFILE "The average TEMPERATURE is : $totalTPlen 0C \n";
print OUTFILE "The average NITROGEN is : $totalNTlen g N per Kg \n";
print OUTFILE "The average LEAF WATER POTENTIAL is : $totalWTlen MPa \n \n";

#Fiber quality output
#print OUTFILE "The POTENTIAL Fiber LENGHT of given lint sample is : $tempt_Length \n";
print OUTFILE "The Fiber LENGHT of lint sample is : $fiber_Length \n";
#print OUTFILE "The POTENTIAL Fiber STRENGTH of given lint sample is : $tempt_Strength \n";
print OUTFILE "The Fiber STRENGTH of lint sample is : $fiber_Strength \n";
#print OUTFILE "The POTENTIAL Fiber UNIFORMITY of given lint sample is : $tempt_Uniformity
\n";
print OUTFILE "The Fiber UNIFORMITY of lint sample is : $fiber_Uniformity \n";
#print OUTFILE "The POTENTIAL Fiber MICRONAIRE of given lint sample is : $tempt_Micronaire
\n";
print OUTFILE "The Fiber MICRONAIRE of lint sample is : $fiber_Micronaire \n";
```

```
#subroutine for temperature LENGTH
sub temperatureLEN{
$TEMPMEM = shift;
@TEMPLIST = @{$TEMPMEM};
print "Enter the TEMPERATURE file:\n";
chomp($filename =<STDIN>);
open (INFILE, $filename) or die ("Cannot open $filename\n");
chomp(@temp=<INFILE>);
foreach (@temp){
totalTL += $_;
     }

$totalTPlen= $totalTL / scalar @temp;
$EPItemp_len=(11.49+1.75*$totalTPlen-0.04*$totalTPlen*$totalTPlen);
return $EPItemp_len;
}

#subroutine for EPI nitrogen and LENGTH

sub nitrogenLEN{
$NITROMEM = shift;
@NITROPLIST = @{$NITROMEM};
print "Enter the NITROGEN file:\n";
chomp($filename =<STDIN>);
open (INFILE, $filename) or die ("Cannot open $filename\n");
chomp(@nitro=<INFILE>);
foreach(@nitro){
$totalNL += $_;
                        }

$totalNTlen= $totalNL / scalar @nitro;
$EPInitro_len=(0.928+0.001*$totalNTlen);
return $EPInitro_len;
}

#subroutine for EPI LWP and LENGTH

sub waterLEN{
$LWPMEM = shift;
@LWPLIST = @{$LWPMEM};
print "Enter the LEAF WATER POTENTIAL file:\n";
chomp($filename =<STDIN>);
open (INFILE, $filename) or die ("Cannot open $filename\n");
chomp(@lwp=<INFILE>);
foreach (@lwp){
$totalWL += $_;
                        }
```

```
$totalWTlen= $totalWL / scalar @lwp;
$EPIlwp_len=(1.35+0.220*$totalWTlen);
return $EPIlwp_len;
}

#subroutine for temperature STRENGTH
sub temperatureSTR{
$TEMPMEM = shift;
@TEMPLIST = @{$TEMPMEM};
foreach (@temp){
$totalTS += $_;
                        }

$totalTPstr= $totalTS / scalar @temp;
$EPItemp_str=(21.81+0.341*$totalTPstr);
return $EPItemp_str;
}

#subroutine for EPI nitrogen and STRENGTH

sub nitrogenSTR{
$NITROMEM = shift;
@NITROPLIST = @{$NITROMEM};
foreach (@nitro){
$totalNS += $_;
                        }
$totalNTstr= $totalNS / scalar @nitro;
$EPInitro_str=(0.895+0.002*$totalNTstr);
return $EPInitro_str;
}

#subroutine for EPI LWP and STRENGTH

sub waterSTR{
$LWPMEM = shift;
@LWPLIST = @{$LWPMEM};
foreach (@lwp){
$totalWS += $_;
            }

$totalWTstr= $totalWS / scalar @lwp;
$EPIlwp_str=(1.50+0.309*$totalWTstr);
return $EPIlwp_str;
}
```

```
#subroutine for temperature UNIFORMITY
sub temperatureUNI{
$TEMPMEM = shift;
@TEMPLIST = @{$TEMPMEM};
foreach (@temp){
$totalTU += $_;
                }

$totalTPuni= $totalTU / scalar @temp;
$EPItemp_uni=(55.04+2.368*$totalTPuni-0.047*$totalTPuni*$totalTPuni);
return $EPItemp_uni;
}

#subroutine for EPI nitrogen and UNIFORMITY

sub nitrogenUNI{
$NITROMEM = shift;
@NITROPLIST = @{$NITROMEM};
foreach (@nitro){
$totalNU += $_;
     }

$totalNTuni= $totalNU / scalar @nitro;
$EPInitro_uni=(1.005-0.0003*$totalNTuni);
return $EPInitro_uni;
}

#subroutine for EPI LWP and UNIFORMITY

sub waterUNI{
$LWPMEM = shift;
@LWPLIST = @{$LWPMEM};
foreach (@lwp){
$totalWU += $_;
     }

$totalWTuni= $totalWU / scalar @lwp;
$EPIlwp_uni=(1.17+0.102*$totalWTuni);
return $EPIlwp_uni;
}

#subroutine for temperature MICRONAIRE
sub temperatureMIC{
$TEMPMEM = shift;
@TEMPLIST = @{$TEMPMEM};
foreach (@temp){
$totalTM += $_;
```

```
                }

$totalTPmic= $totalTM / scalar @temp;
$EPItemp_mic=(-6.88+0.843*$totalTPmic-0.017*$totalTPmic*$totalTPmic);
return $EPItemp_mic;
}

#subroutine for EPI nitrogen and MICRONAIRE

sub nitrogenMIC{
$NITROMEM = shift;
@NITROPLIST = @{$NITROMEM};
foreach (@nitro){
$totalNM += $_;
                        }

$totalNTmic= $totalNM / scalar @nitro;
$EPInitro_mic=(1.157-0.007*$totalNTmic);
return $EPInitro_mic;
}#subroutine for EPI LWP and MICRONAIRE
sub waterMIC{$LWPMEM = shift;
@LWPLIST = @{$LWPMEM};
foreach (@lwp){
$totalWM += $_;
    }

$totalWTmic= $totalWM / scalar @lwp;
$EPIlwp_mic=(0.44-0.203*$totalWTmic);
return $EPIlwp_mic;
}

close (INFILE);
close (OUTFILE);
```