# EFFECTS OF 1-METHYLCYCLOPROPENE (1-MCP) ON GROWTH, YIELD, AND PHYSIOLOGICAL PARAMETERS OF FIELD GROWN COTTON

(*Gossypium hirsutum* L.)

A Dissertation

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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December 2015

Major Subject: Agronomy

# ABSTRACT

Cotton (*Gossypium hirsutum* L.) crops usually experience some type of environmental stress during the season. Soil moisture deficits along with high temperatures pose the biggest constraints for crop productivity. Although usually hard to distinguish between drought and high temperature stress effects, it is important to develop means to help mitigate the negative impacts of such stresses on crop productivity. The 1-methylcyclopropene (1-MCP) is an ethylene antagonist that acts by binding to ethylene receptors, thus delaying and/or diminishing its effects on plants. Recently 1-MCP became the focus of several studies due to its potential to mitigate negative impacts of abiotic stresses. The main objective of this research was to assess the impact of 1-MCP on field grown cotton. The secondary objective was to investigate the association of canopy temperature (CT), canopy temperature depression (CTD), stress degree day (SDD), thermal stress index (TSI), and crop water stress index (CWSI) with crop yield. Field studies were conducted at the Texas A&M University Field Laboratory in Burleson County, TX from 2012 to 2014. Plots were arranged in a randomized complete block design and replicated four times. Treatments consisted of 1-MCP application (25 g a.i. $ha^{-1}$) triggered by canopy temperature (28 °C) and forecasted ambient temperatures (35 and 27.8 °C). For the secondary objective treatments were two irrigation levels, namely, dryland and irrigated.

Results indicated that 1-MCP had little to no effect on the physiology and morphology of cotton at different stages of crop development. Daily plant canopy temperature, net photosynthesis, transpiration, and photosystem II quantum yield were affected by 1-MCP treatment when plants were irrigated, but not under dryland conditions. Effects of 1-MCP applications during different seasons were inconsistent. Ultimately, 1-MCP treatment effects were not enough to increase final seedcotton yield under the conditions tested. Negative relationships between yield and CT ($r^2$ = 0.66), yield and TSI ($r^2$ = 0.70), and yield and CWSI ($r^2$ = 0.58) were found. CTD and SDD showed great distinction between the humid (2012 and 2014) and dry (2013) years, and to a lesser extent, this was also apparent for CWSI. Evidence suggests that CTD, SDD, and CWSI models should be interpreted with caution, particularly in locations where great inter-annual weather variability occurs.

# DEDICATION

This manuscript is dedicated to the loving memory of Dr. J. Tom Cothren, outstanding professor and advisor, but above all; an unforgettable friend.

“In life, it’s not where you go;
It’s who you travel with.”
(Charles Schulz)

# ACKNOWLEDGEMENTS

First of all I would like to thank GOD for blessing me with the strength and peace of mind necessary to complete this project. Sincere thanks my advisor Dr. James L. Heilman for his mentorship, trust, and valuable support. Drs. Vladimir da Costa, Carlos Fernandez, Gaylon Morgan, and Nithya Rajan are also acknowledged for their support and guidance. Great appreciation is also extended to Dr. Juan A. Landivar for his friendship, support, and for encouraging me to pursue my graduate degree in the USA. I would also like to gratefully acknowledge Henrique Carvalho, Landon Crotwell, Pedro Fávero, Steven Garcia, Dustin Kelley, Clayton and Dr. Katie Lewis, Jordan Maldonado, Jonathan Moreno, Hunter Teel, and Zachary Zemanek not only for their assistance in collecting the data required for this study, but most importantly, for their friendship. Special thanks go to Cotton Incorporated, United States Department of Agriculture, and AgroFresh for generously supporting this project, and to the Texas A&M University Dept. of Soil & Crop Sciences for partial financial support through a teaching assistantship. My deepest thanks go to Dr. J. Tom Cothren for the opportunity, guidance, trust, and example. Memories shared with him (and his Cotton Physiology group at Texas A&M University) will never be forgotten. To all my friends who have contributed directly or indirectly to my academic training: my sincere thanks. Words cannot describe my gratitude to my family (Edson, Régia, Guilherme, Milena, Zion, and Andrea) and family-in-law (Nilmar, Ednamar, Paula e Murilo) whose unconditional love, trust, and support throughout my study made it possible to complete this degree.

Primeiramente gostaria de agradecer a DEUS por me abençoar com a força e paz necessárias para completar este projeto. Sincero agradecimento ao meu orientador Dr. James L. Heilman pelas orientações, confiança e valioso suporte. Drs. Vladimir da Costa, Carlos Fernandez, Gaylon Morgan, e Nithya Rajan também são reconhecidos pelo suporte e pelas orientações. Gostaria também de estender minha gratidão ao Dr. Juan A. Landivar, pela amizade e suporte, e por me encorajar a perseguir minha pós graduação nos Estados Unidos. Reconhecimento também é estendido ao Henrique Carvalho, Landon Crotwell, Pedro Fávero, Steven Garcia, Dustin Kelley, Clayton e Dr. Katie Lewis, Jordan Maldonado, Jonathan Moreno, Hunter Teel, e Zachary Zemanek não só pela ajuda na coleta dos dados necessários para este estudo, mas mais impotante, pela amizade. Agradecimento especial vai para a Cotton Incorporated, United States Department of Agriculture e AgroFresh por generosamente apoiar este projeto, e para o Dept. of Soil and Crop Sciences na Texas A&M University pela ajuda financeira parcial através de uma bolsa de estudos. Meu profundo agradecimento vai para o Dr. J. Tom Cothren pela oportunidade, orientação, e exemplo. Memórias compartilhadas com ele (e seu grupo de Fisiologia de Algodão na Texas A&M University) nunca serão esquecidas. A todos os amigos que direta ou indiretamente contribuíram para minha formação acadêmica: meus sinceros agradecimentos. Palavras não são suficientes para descrever minha gratidão a minha família (Edson, Régia, Guilherme, Milena, Zion e Andrea), sogros (Nilmar e Ednamar) e cunhada(o) (Paula e Murilo). Seu amor, confiança e suporte incondicionais durante o meu estudo fizeram com que fosse possível completar este grau.

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# CHAPTER I

# INTRODUCTION AND LITERATURE REVIEW

Cotton (*Gossypium hirsutum* L.) grown all over the U.S. Cotton Belt and other parts of the world usually experience some type of environmental stress. Because of constraints by unfavorable environmental factors, plants often have limitations expressing their full genetic potential for growth and yield (Boyer, 1982). With the ever-growing world population, it seems inevitable that it comes accompanied by an increase in greenhouse gases emissions, ultimately leading to changes in global climate patterns, such as increases in temperatures and changes in rainfall patterns (Allan and Soden, 2008; Karl and Trenberth, 2003).

Several studies have indicated the possibility of greater intra- and inter-annual variability of rainfall patterns with fewer but more intense events with extended drier periods in between (Allan and Soden, 2008; Easterling et al., 2000; Groisman and Knight, 2008; Karl and Trenberth, 2003). Furthermore, there is mounting evidence that wet environments are likely to become wetter, while dry environments will become drier (Chou et al., 2007; Xuebin et al., 2007). For the United States specifically, models also predict an increase in temperature ranging from 3 to 5 °C on average, in the next 100 years, assuming that the growth of world greenhouse gases emissions continues (MacCracken et al., 2003). Exact and detailed knowledge of how these changes in climate patterns will affect plants and ecosystems is lacking. How agriculture will adapt to such changes is also largely unknown. Among abiotic stresses, drought and high temperature are perhaps the two most common in cotton, and both often occur concomitantly. High temperature is likely the most constant and difficult to manage, assuming of course, that irrigation water is available to supplement rainfall within a growing season. Since these two types of stresses are so intimately interrelated for warm-season crops, it is often difficult to separate between their different effects under natural conditions. According to Idso et al. (1977), moisture and temperature are the two primary factors determining crop productivity. Although researchers have studied the effects of temperature extremes (e.g. heat shock and chilling injury) in different plants, according to Burke et al. (1993) such extreme temperatures are not necessary for a plant to experience thermal stress.

High temperature stress may be defined as any temperature outside of the upper bound of the thermal kinetic window (TKW). The TKW represents the temperature range in which the apparent Michaelis-Menten constant ($K_m$) remains within 200% of the minimum value for optimum enzyme function. It appears that the term TKW was first coined by Mahan et al. (1987). Leonor Michaelis and Maud Leonora Menten developed the Michaelis-Menten ($K_m$) constant a little over a century ago. Their original paper "*Die Kinetik der Invertinwirkung*" in German was published in 1913, and showed that the rate at which an enzyme-catalyzed reaction occurs is proportional to the concentration of the enzyme-substrate complex. More recently the original publication was translated to English by Johnson and Goody (2011).

Major reductions in yield due to heat stress may occur in certain geographical areas if temperatures deviate as little as one or two degrees from the plant optimum temperature (Carmo-Silva et al., 2012). The first study on cotton's TKW during the late 1900s reported an optimum temperature range between 23.5 and 32 °C (Burke et al., 1988), and it was based on glyoxylate reductase for nicotinamide adenine dinucleotide (NADH). The most recent report on cotton shows that its ideal temperature is centered around 28 ± 3 °C (Burke and Wanjura, 2010), where important physiological, developmental, and biochemical processes are at peak performance. However, it is important to note that ambient temperatures above 31 °C during the season are not that uncommon in most cotton growing areas. Burke et al.'s (1988) study on cotton utilizing a 50° field-of-view infrared thermometer (IRT) showed that plants were within their TKW for less than 30% of the season. The results led researchers to conclude that around 70% of the growing season is still available for increasing crop production (i.e. changes in management practices and/or genetics). Temperatures such as 30/20 °C day/night have already been implicated in causing fruit shedding in cotton (Reddy et al., 1991b). Some fruit shedding may be normally expected during the plant reproductive stage. However, loss of such structures may be increased with the onset of severe stress, ultimately leading to a negative impact on the final crop yield (Pettigrew, 2004).

Most plants have the ability of leaf cooling through the loss of water to the atmosphere (transpiration). However, during the first half of the 20th century there was still disagreement among plant physiologists as to the effectiveness and true importance of transpiration in the cooling of plant leaves. While some researchers believed that the cooling effect was generally small and had little impact in helping plants avoid excess heat (Clum, 1926; Curtis, 1926; Curtis, 1938), others thought the effects of transpiration on cooling were significant (Clements, 1934; Shull, 1919; Wallace and Clum, 1938). In the present day there is a general agreement regarding the importance of transpiration in leaf cooling, and several researchers including Reicosky et al. (1985), Upchurch et al. (1988), Lu et al. (1994), and Burke et al. (1989) have shown that cotton possesses a substantial cooling ability.

Different hormones, such as cytokinins, abscisic acid, gibberellins, auxins, and ethylene, regulate growth in plants. Among the various known plant hormones, ethylene possesses the simplest molecular structure ($C_2H_4$). It was first identified as the active component of coal gas sometime during the nineteenth century, when it was observed that trees growing near street lamps showed greater defoliation when compared to other trees (Taiz and Zeiger, 2002). Later in 1934, ethylene was proved to be a naturally occurring product of plant metabolism (Gane, 1934), which led to its classification as a plant hormone.

Today, ethylene is known to be produced by almost all plant parts, from roots to stems, to leaves and flowers, and to be biologically active even in trace amounts. It is involved in a number of developmental and physiological processes in plants, including seed germination (Gniazdowska et al., 2010; Linkies and Leubner-Metzger, 2012), seedcoat development (Mohapatra and Mohapatra, 2006), production of volatile compounds (Dexter et al., 2007; Underwood et al., 2005), growth (De Grauwe et al., 2005; Foo et al., 2006; Malloch and Osborne, 1975), fruit ripening (Bapat et al., 2010; Goodenough, 1986), stress response (Fluhr and Mattoo, 1996; Pierik et al., 2007; Sharp and LeNoble, 2002), and abscission of vegetative and reproductive structures (Abeles and Leather, 1971; Jones et al., 1995; Morgan et al., 1992; Orzaez et al., 1999; Reid and Wu, 1992; Steffens and Sauter, 2005). Ethylene effects are different depending upon the plant and tissue, however, it is known to affect plant growth at all developmental stages.

Ethylene synthesis involves a multistep enzymatic pathway which converts methionine (ethylene biological precursor) to ethylene (Fluhr and Mattoo, 1996). It is produced from methionine via *S*-adenosylmethionine (SAM) and 1-aminocyclopropane-1-carboxilic acid (ACC) (Sisler and Yang, 1984). SAM is converted to ACC by the enzyme ACC-synthase (ACCS), and ACC is then oxidized by ACC-oxidase (ACCO) to form ethylene. During the final step of the process, catalyzed by ACCO, carbon dioxide ($CO_2$) and hydrogen cyanide (HCN) are also produced (Chaves and de Mello-Farias, 2006). The rate-limiting enzyme in the ethylene biosynthesis cycle (also known as Yang cycle) is ACCS (Ecker, 1995). While tissues producing insignificant amounts of ethylene have been found to have a low ACCS activity (Chae et al., 2003), both ACCS and ACCO activities may be induced upon stress (Morgan and Drew, 1997).

For ethylene to act, it is necessary that it binds to a receptor which has a high affinity and specificity for ethylene (Sisler and Yang, 1984). These receptors are thought to contain a metal, and although $Cu^+$ has been suggested as a possible candidate (Thompson et al., 1983), direct evidence is said to be lacking (Sisler and Yang, 1984). At the cellular level, these receptors are located in great amounts in the endoplasmatic reticulum, but in smaller amounts, they may also be found in the plasmalemma (Bleecker, 1999; Chen et al., 2002; Evans et al., 1982).

In the past couple of decades, a lot of attention has been given to anti-stress compounds such as silver thiosulfate (STS), aminoethoxyvinylglycine (AVG), aminooxyacetic acid (AOA), and 1-methylcyclopropene (1-MCP), which either inhibit ethylene synthesis, or block its receptors in the plant. Fairly recently, 1-MCP has been the focus of several studies due to its potential benefits in helping alleviate negative impacts of stress-induced ethylene production. This compound is known to have approximately a 10-fold higher affinity for ethylene receptors in the plant when compared to ethylene itself. Although effects seem to be transient and variable depending upon the plant and plant part treated, by competing for these receptors 1-MCP prevents ethylene binding to treated tissues, thus delaying and/or diminishing its effects in plants (Sisler and Serek, 1997). Since its introduction 1-MCP has been widely used in the fruit, vegetable and ornamental flower markets in order to delay ripening and senescence during shipping and storage of various products, ultimately leading to an increase in their shelf life.

The background work that led to the discovery of 1-MCP as an ethylene inhibitor came from the laboratories of Edward Sisler and Sylvia Blankenship at North Carolina State University and jointly Sisler and Blankenship hold the patent for use of cyclopropenes as ethylene inhibitors (Sisler and Blankenship, 1996). Cyclopropenes are a breakdown product of diazocyclopentadiene (DACP), another known ethylene inhibitor (Blankenship and Dole, 2003). The first 1-MCP product approved by the United States Environmental Protection Agency (EPA) for commercial use was sold under the trade name “EthylBloc” in 1999 for ornamental crops; however, it wasn’t until

2002 that the 1-MCP based product “SmartFresh” was cleared by the U.S. Government for use in edible crops (Blankenship, 2003). During the same year that 1-MCP was first approved by the EPA, Sisler et al. (1999) studied 3-Methylcyclopropene, an alternative to 1-MCP that was also proven effective in inhibiting ethylene responses. The same authors concluded, however, that 1-MCP required substantially lower concentrations, about 2.5 and 10 times were needed in banana and flowers, respectively, for the same level of protection. The exact reason for this behavior is unclear. While the effectiveness of 1-MCP to counteract negative ethylene effects has been proven in some applications, much of its success in the fruit, vegetable, and ornamental flower markets has to do with the fact that these products are often stored and transported under tightly controlled environments (i.e. temperature, relative humidity, oxygen and carbon dioxide levels, among others).

It seems clear that changes in global climate patterns are very likely to impact agriculture in several different geographic locations. To tackle the food security and crop productivity concerns, a better understanding of the negative impacts caused by climate change and the effects of compounds with the potential to help alleviate stress such as 1-MCP are still needed. Technology has evolved very rapidly in the past few decades, enabling its deployment in agricultural settings in a relatively cost-effective fashion. With the improvements in data acquisition equipment and now widespread use of the Internet, farmers are able to monitor various parameters of their crops in real time, without the need of physically being in the field. Infrared thermometers (IRT’s) are used to monitor plant canopy temperature; sensors are relatively inexpensive and could provide valuable information about the efficiency of different irrigation regimes while also providing a possible stress index value. Furthermore, compounds that have the potential to counteract the negative effects of stress-induced ethylene could prove very useful in agriculture. Although ethylene antagonists such as 1-MCP have been widely used in some markets and its efficiency proven under controlled environments, the utility of said compound in a field setting however, still requires a lot of attention from the scientific community.

The main objective was to assess the effects of 1-MCP applications on yield of cotton grown in differing watering conditions under field conditions. The specific objectives were: i) identify a trigger (best time) for 1-MCP application in cotton based on forecasted ambient temperatures; and ii) characterize physiological and morphological effects of 1-MCP application in cotton plants. Secondary objectives were to calculate multiple canopy temperature-based stress indices, compare their association with the final yield of field-grown cotton and assess the correlation between two yield components (number of bolls plant$^{-1}$ and fruit retention) with the stress indices.

# CHAPTER II

# EFFECTS OF 1-METHYLCYCLOPROPENE (1-MCP) ON YIELD, PHYSIOLOGICAL AND MORPHOLOGICAL CHARACTERISTICS OF COTTON

## OVERVIEW

Cotton (*Gossypium hirsutum* L.) is the lead cash crop in Texas, and its productivity is usually challenged by stressful environmental conditions such as high temperatures and sub-optimal water supply. The objective of this investigation was to assess the impact of 1-methylcyclopropene (1-MCP) applications triggered by canopy temperature and forecasted ambient temperatures on field grown cotton plants. Yield, physiological and morphological responses to 1-MCP applications were investigated in field studies conducted during the summers of 2012-2014 at the Texas A&M University Field Laboratory in Burleson County, TX. During all three growing seasons, more than 65% of the days reached temperatures above 28 °C, which indicated great potential for high temperature stress. Daily plant canopy temperature, net photosynthesis, transpiration, and photosystem II quantum yield were affected by 1-MCP treatment when plants were irrigated, but not under dryland conditions. Positive effects of 1-MCP were found for fruit retention in 2013 and 2014 for both irrigated and dryland studies while a negative impact was found in the 2012 irrigated study. At harvest, 1-MCP applications had no effect (positive or negative) on final seedcotton yield or fiber quality parameters. Applications of 1-MCP affected both physiological and morphological characteristics; however, it did not improve crop yield.

# INTRODUCTION

Plants living under natural conditions are often unable to express their full genetic potential due to unfavorable environmental conditions. According to Boyer (1982), atmospheric and/or soil moisture deficits along with high radiation and temperatures pose the biggest constraints for plant survival and crop productivity. Due to their intimate relationship, it is difficult to distinguish between drought and high temperature stress effects. It is important, however, to develop means to help mitigate the negative impacts of such stresses on crop productivity.

The hormone ethylene is a naturally occurring product of plant development (Gane, 1934), and widely known for its involvement in multiple physiological and developmental processes (Bapat et al., 2010; De Grauwe et al., 2005; Foo et al., 2006; Gniazdowska et al., 2010; Linkies and Leubner-Metzger, 2012; Mohapatra and Mohapatra, 2006; Steffens and Sauter, 2005). Although its effects may be different depending upon the plant and plant tissue, ethylene is known to affect plant growth at all developmental stages. More important for the scope of this project, however, is ethylene’s involvement in plant stress response (Fluhr and Mattoo, 1996; Pierik et al., 2007; Sharp and LeNoble, 2002), especially those related to the abscission of vegetative and reproductive structures (Abeles and Leather, 1971; Jones et al., 1995; Morgan et al., 1992; Reid and Wu, 1992), and the potential of some ethylene inhibitors to help protect stress-induced yield losses. The compound 1-methylcyclopropene (1-MCP) is an ethylene antagonist that works by binding to ethylene receptors in the plant, preventing and/or delaying the negative effects promoted by stress-induced ethylene (Sisler and

Serek, 1997). Under controlled environments, it has been widely and effectively used in the fruits, vegetables, and ornamental flowers market to delay senescence and fruit ripening, thus significantly extending the shelf-life of various products (Hofman et al., 2001; Jiang et al., 2001; Ku and Wills, 1999; Wills and Ku, 2002).

Theoretically, under field conditions 1-MCP has the potential to mitigate the negative impacts of stress and positively influence cotton yield. Results from limited literature available, however, are contradictory. Kawakami et al. (2010a) and de Brito et al. (2013) conducted field trials in Arkansas (USA) and Goiás (Brazil), respectively, and both concluded that 1-MCP increased cotton yield under field conditions. Kawakami et al. (2010a) attributed the increase in yield to decreased levels of stress (higher maximum quantum efficiency of Photosystem II + decreased glutathione reductase activity) and increased boll weight, while de Brito et al. (2013) provided no such explanation. On the other hand, in Texas, da Costa et al. (2011) utilized ethephon (synthetic ethylene) as a source of stress applied one day after 1-MCP treatment, and reported that although 1-MCP improved growth and yield components (mainly in the upper canopy), no improvement in yield was found with either one of the rates tested (25 and 50 g a.i. ha$^{-1}$). In another field study conducted in Texas, Chen et al. (2014) reported that 1-MCP treatment delivered to plants at 10 g a.i. ha$^{-1}$ decreased membrane damage, increased chlorophyll content and photosynthetic efficiency of subtending leaves (of tagged bolls), but that all these positive responses did not translate into higher yields.

The primary objective of the study was to assess the effects of 1-MCP applications triggered by different temperature thresholds, as a means to help alleviate the negative impacts of high temperature stress on yield of field grown cotton plants. To achieve this, several physiological and morphological parameters were monitored and analyzed at three very distinct crop stages.

## MATERIALS AND METHODS

### Cultural practices

Two field trials (irrigated and dryland) were conducted at the Texas A&M AgriLife Field Laboratory in Burleson County (30°33'01.67" N, 96°26'07.07" W), approximately 8 miles west of College Station, TX, on a Weswood silt loam soil (fine-silty, mixed, superactive, thermic, Udifluventic Haplustepts), during the summers of 2012 - 2014. The study area was equipped with a sub-surface drip irrigation system installed at a depth of 45.7 cm, with emitters spaced 45.7 cm apart. Drip lines were spaced at 1.02 m apart and were located at the center of each row (i.e. directly under the cotton plants). For the irrigated studies, the water delivery was arbitrarily set at 80% evapotranspiration replacement ($ET_r$). Amounts were adjusted based on crop stage following guidelines by Fisher and Udeigwe (2012).

Management practices such as fertility, disease prevention, weed and insect control followed the guidelines provided by the Texas A&M AgriLife Extension service for the region. Cotton (*G. hirsutum* L. cv. Phytogen 499 WRF) seeds were sown on April 10 in 2012 and April 09 in 2013 and 2014, at a rate of 108,000 seeds $ha^{-1}$ in northwest to southeast oriented rows, spaced 1.02-m apart. Plant growth regulator applications consisted of a combination of cyclanilide (1-(2,4-dichlorophenylaminocarbonyl)-

cyclopropane carboxylic acid; 0.003 kg a.i. $ha^{-1}$) and mepiquat chloride (N,N-dimethylpiperidinium chloride; 0.012 kg a.i. $ha^{-1}$), which were applied as needed during the growing season. Harvest aids were applied when cotton plants exhibited approximately 60-70% open bolls, and consisted of a combination of thidiazuron (*N*-phenyl-*N*-1,2,3-thidiazol-5-ylurea; 0.056 kg a.i. $ha^{-1}$), ethephon (2-chloroethyl phosphonic acid; 1.106 kg a.i. $ha^{-1}$), and cyclanilide (1-(2,4-dichlorophenylaminocarbonyl)-cyclopropane carboxylic acid; 0.069 kg a.i. $ha^{-1}$).

### Treatments and experimental design

The studies were arranged in a randomized complete block design. Plots were four rows wide, 9.73-m in length with a 3-m alley in between, and the four treatments (including an untreated control) were replicated four times. Treatments were sprayed using a four-row compressed air small-plot sprayer with hollow cone nozzle tips spaced at 51 cm delivering 102.9 L $ha^{-1}$, and consisted of 1-methylcyclopropene (1-MCP) at a single rate of 25 g $ha^{-1}$ of active ingredient with no adjuvants or surfactants used. The 1-MCP formulation used was a soluble powder (3.8 % a.i.), which released 1-MCP gas when in contact with water. For each treatment, 1-MCP powder was mixed with water in the field immediately prior to application. All plots receiving 1-MCP were sprayed within 20 min. of mixing. Treatments were defined as:

1 – Control (C): No 1-MCP application

2 – Smartcrop$^{TM}$ (S): 1-MCP application triggered by a canopy stress temperature of 28°C, starting at pinhead square stage

3 – Ambient 35 ºC (A95): 1-MCP application triggered by forecasted maximum daily temperature of 35 ºC or higher for at least 3 consecutive days, starting at pinhead square stage

4 – Ambient 37.8 ºC (A100): 1-MCP application triggered by forecasted maximum daily temperature of 37.8 ºC or higher for at least 3 consecutive days, starting at pinhead square stage

As per the chemical (1-MCP) manufacturer instructions, there was a window of at least 14 days between applications, regardless of forecasted temperatures within that time frame. Treatments started based on each of the specified triggers at the pinhead square stage, and continued until plants reached maturity (open boll stage), after which point no more 1-MCP applications were made.

## Canopy temperature

To monitor crop canopy temperatures (CT), one SmartCrop$^{TM}$ (Smartfield Inc., Lubbock, TX) infrared thermometer (IRT) sensor was installed in the middle of the plot, on the third row, pointing southeast. These infrared sensors measure temperatures between -33 and 220 °C, with an accuracy of ± 0.6 °C between wavelengths of 5 and 14 µm. Use of these IRTs required a fairly homogeneous plant canopy coverage in between plants to reduce the impact of radiant energy emitted by the soil on canopy temperature measurements. Sensors were deployed at 42, 59, and 64 days after planting (DAP) in 2012, 2013, and 2014, respectively. The IRT installation occurred later in both 2013 and 2014 due to unseasonably cold temperatures following planting, which delayed the establishment and initial growth of the crop. Sensors were mounted on a bracket and attached to a 2-m perforated pole. The bracket maintained sensors at a fixed 45° angle from the soil surface and the perforated pole allowed changes in sensor height (Fig. 2.1). To account for crop growth, frequent adjustments in height were made during the growing season to maintain sensors around 20 to 30-cm above the crop canopy at all times, which resulted in an approximate 0.5 $m^2$ field of view. Canopy temperature data were automatically collected every minute and a 15 min average was wirelessly transferred to a base station (SmartWeather$^{TM}$), and then automatically uploaded to the CropInsight$^{TM}$ (Smartfield, Inc., Lubbock, TX) website (http://www.cropinsight.com/).

### Weather

Rainfall, ambient temperature, and wind speed data were collected by the SmartWeather$^{TM}$ weather station (Smartfield, Inc., Lubbock, TX), that also serves as a base station to wirelessly gather data from the infrared thermometer sensors.

### Soil water potential

Soil water potential was continuously measured using Watermark sensors model 200SS (Irrometer Company, Inc., Riverside, CA) and the SmartProfile$^{TM}$ system (Smartfield, Inc., Lubbock, TX). The SmartProfile$^{TM}$ system logged data from the sensors and wirelessly transferred them to the SmartWeather$^{TM}$ base station. Sensors were installed at depths of 15, 30, and 61 cm, approximately 10 cm from the center of the row at 80, 66, and 92 DAP in 2012, 2013, and 2014, respectively. One set of sensors (three depths) was installed per study (i.e. dryland and irrigated).

**Figure 2.1.** Smartcrop$^{TM}$ infrared sensors were installed on a 2 m perforated pole about half-way into each plot, on the third row, pointing southeast. Brackets mounted on the pole maintained sensors at a fixed 45° angle from the soil surface throughout the season. Constant adjustments in height were made to maintain sensors about 20-30 cm above the crop canopy, which resulted in an approximate 0.5 $m^2$ field of view.

### Photosynthetic activity and transpiration

Physiological parameters such as net photosynthesis (A), transpiration (E), and difference in vapor pressure between leaf and air ($\Delta_e$) were measured with a portable photosynthesis system model Li-Cor 6400 XT (LI-COR, Inc., Lincoln, NE). Each measurement series began at 10:00 and concluded by 14:00 at three distinct crop stages; early bloom (EB), full bloom (FB), and open boll (OB). Three random plants and one leaf per plant per plot were used. Measurements were made on the third uppermost fully-expanded leaf (Patterson et al., 1977). A photosynthetic photon flux density (PPFD) of 2,000 μmol $m^{-2}$ $s^{-1}$ was generated by a Red/Blue Light Source 6400-02B (Li-COR Inc., Lincoln, NE) on the adaxial surface of the leaf being measured. The closed leaf chamber of the equipment had an area of 6 $cm^2$ and a constant reference cell carbon dioxide ($CO_2$) concentration of 400 μmol $mol^{-1}$ was maintained throughout the measurements. Leaf adaptation to the conditions inside the closed chamber were monitored using the coefficient of variation (CV) on the instrument's display and values were not recorded until measurements were stable, which usually took around 60 to 360 s.

### Chlorophyll fluorescence

Chlorophyll fluorescence was measured using a portable chlorophyll fluorometer model PAM-2100 (Heinz Walz GmbH, Effeltrich, Germany) between the hours of 10:00 and 14:00, and completed within 30 min of recording the first data point. Five random plants per plot were measured using the third uppermost fully-expanded leaf. Chlorophyll fluorescence measurement indicates the quantum efficiency of the photosystem II by measuring the excess energy being re-emitted as light (Maxwell and Johnson, 2000). Quantum yield of photosystem II ($\phi PS_{II}$) was measured using the saturation pulse method in light adapted leaves and calculated as $Y = (F_m - F_t) / F_m$, where $F_m$ is maximum fluorescence and $F_t$ is fluorescence at given time.

## Leaf water potential

To examine the effect of 1-MCP on crop water status and assess the efficiency of the irrigation system in creating two distinct growing conditions, pre-dawn leaf water potential ($\psi_{wl}$) was measured with a pressure chamber (PMS Instrument Co., Corvallis, OR) between 4:30 and 6:30 using the method described by Scholander et al. (1965). Three plants per plot were sampled to collect data using the third uppermost fully-expanded leaf, at three distinct crop stages (EB, FB, and OB). About a third of the leaf petiole was cut using a razor at an approximate 45° angle. Leaves were placed into the chamber usually within 3 min of their removal from the plant. The pressure chamber was then slowly pressurized at a rate of approximately 0.03 MPa $s^{-1}$ as suggested by Turner (1988).

## Plant mapping

Plant mapping was conducted to assess the effects of 1-MCP application on plant growth and development. Six consecutive plants per plot, with the exception of very small plants, from either one of the outside rows were removed from the field for plant mapping. Data collection and input were handled according to Landivar (1992). Fruit set and fruit retention were determined according to the procedure described by Landivar et al. (1993) using an Excel version of the PMAP software (Plant Map Analysis Program for Cotton) obtained from Dr. Landivar (J. A. Landivar, personal communication, 2012).

Since there is evidence that plant height and total number of mainstem nodes are affected by the “alley effect” (Holman and Bednarz, 2001), both the first and last one meter of row were avoided when sampling plants. Plant sampling for mapping was conducted at three distinct crop stages (early bloom, full bloom, and harvest). The plant mapping method was used because it provides detailed information regarding fruit set and final fruit retention values.

### Yield and fiber quality characteristics

The two center rows were mechanically harvested using a custom 2-row cotton spindle picker, John Deere model 9910 (Deere & Company, Moline, IL). This equipment was modified for small-plot research and allowed yield to be established on a per plot basis. A sub-sample was collected and ginned to determine lint yield (gin turnout). Lint samples were analyzed for an array of fiber quality characteristics at the Fiber and Biopolymer Research Institute (Texas Tech University, Lubbock, TX) utilizing the standard High Volume Instrument (HVI) method.

### Statistical analysis

Data were analyzed using JMP Pro, Version 11.0.0 (SAS Institute Inc., Cary, NC). Analysis was performed on a yearly basis since significant Year x Treatment interaction was found. Means were separated using Fisher's LSD at the 5% probability level. Means comparisons were made between treatments within each irrigation regime (e.g. dryland or irrigated) and data were combined over years whenever permissible.

## RESULTS AND DISCUSSION

In-season rainfall totals were 503, 325, and 635 mm, and represented roughly 48, 32, and 50% of the total yearly rainfall for 2012, 2013, and 2014, respectively (Table 2.1). In 2012, the majority of daily rainfall totals were in the 2 – 10 mm range, but very well distributed throughout the growing season. Frequent, smaller (< 25 mm) rainfall events, coupled with fewer but stronger (> 25 mm) events were able to maintain reasonable amounts of water in the soil profile during the period studied (Table 2.1). During the 2013 growing season (between planting and harvest) however, plants received only about 65% of the amount of rain that fell in 2012, for roughly the same time period. Also, significant rainfall events during periods of high water demand (e.g. flowering to boll filling) were not as frequent in 2013 as they were in 2012. In 2014 the trial received unusually high amounts of rainfall between planting and harvest dates and events were also very well distributed along the season. Table 2.2 shows a summary of 1-MCP applications for all three years studied based on treatment triggers.

During all three growing seasons, more than 65% of the days reached temperatures above the midway point of the thermal kinetic window (TKW) of 28 °C, which indicated great potential for high temperature stress. Additionally, the average maximum temperature during all three seasons was greater than the upper TKW threshold of 31 °C. During the three years of the study, highest temperatures were consistently found between 12:00 and 17:00. Figure 2.2 shows graphic daily maximum temperatures relative to the lower (25 °C) and upper (31 °C) bounds of the TKW as well as rainfall events during the 2012 (Fig. 2.2 A), 2013 (Fig. 2.2 B), and 2014 (Fig. 2.2 C) seasons.

**Table 2.1.** Average soil water potential measured at depths of 15, 30, and 61 cm for dryland (Dry) and irrigated (Irr.) studies. Total rainfall for each year of the study and their respective in-season accumulations are also shown.

| | Soil Moisture (Dry) | | | Soil Moisture (Irr.) | | | Rainfall | |
|---|---|---|---|---|---|---|---|---|
| | 15 cm | 30 cm | 61 cm | 15 cm | 30 cm | 61 cm | Total | Season |
| Year | MPa | MPa | MPa | MPa | MPa | MPa | mm | mm |
| 2012 | 0.47 | 0.19 | 0.27 | 0.18 | 0.11 | 0.04 | 1,046.5 | 502.9 |
| 2013 | 1.18 | 0.41 | 0.32 | 0.35 | 0.26 | 0.10 | 998.2 | 325.1 |
| 2014 | 0.44 | 0.19 | 0.14 | 0.12 | 0.07 | 0.03 | 744.2 | 635.0 |

**Table 2.2**. Table shows timing of 1-methylcyclopropene (1-MCP) application based on different temperature thresholds (treatments). All applications were made using a powder formulation of 1-MCP at a single rate of 25 g a.i. $ha^{-1}$ with a small-plot sprayer and occurred for both dryland and irrigated studies on the same dates.

| | 1-MCP Applications | | |
|---|---|---|---|
| Treatment[¥] | 2012 | 2013 | 2014 |
| S | 5-Jul<br>5-Aug | 27-Jun<br>11-Jul<br>25-Jul | 2-Jul<br>24-Jul<br>8-Aug |
| A95 | 5-Jul<br>5-Aug | 11-Jun<br>27-Jun<br>11-Jul<br>25-Jul | 10-Jul<br>24-Jul<br>8-Aug |
| A100 | 5-Aug | 27-Jun<br>11-Jul<br>25-Jul | 8-Aug |

[¥] Smartcrop™ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)

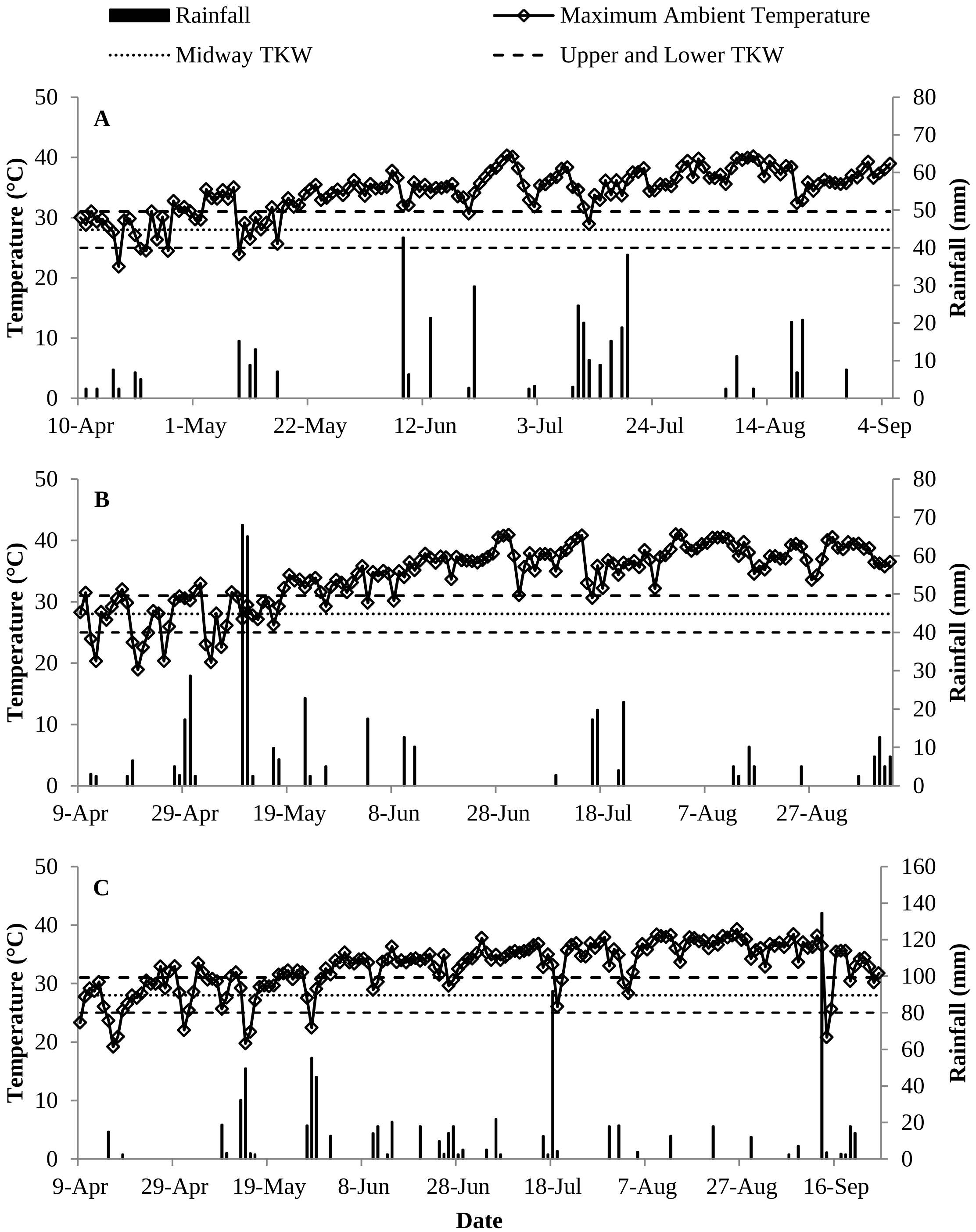

**Figure 2.2.** Daily maximum ambient temperature and rainfall during the season for 2012 (A), 2013 (B), and 2014 (C). Dashed horizontal lines represent the lower and upper bounds of the TKW (25 and 31 °C), and the dotted line represent the midway temperature of the TKW (28 °C). Notice the difference in rainfall scale for 2014 compared to 2012 and 2013.

Rainfall was both plentiful and well-distributed in 2012 and 2014, which maintained adequate amount of water in the soil profile even for the dryland study throughout most of the season (Table 2.1 and Figs. 2.2 A and 2.2 C). As a result of plentiful rainfall, differences in leaf water potential between the dryland and irrigated studies were only found at the OB stage for both 2012 and 2014 (Figs. 2.3 A and 2.3 C). During the 2013 season, however, reduced rainfall lowered soil available moisture (Table 2.1), such that differences in leaf water potential were found throughout the growing season, from EB through OB (Fig. 2.3 B). Across all three years, the irrigated study had lower leaf water potential at the OB stage (Fig. 2.3). Based on single measurements at midday, Kawakami et al. (2010b) reported an increase in stomatal resistance 5 days after 1-MCP treatment in water-stressed cotton plants, which led to lower leaf water potential when compared to the untreated control also under water stress. Conversely, during our studies no impact (positive or negative) of 1-MCP on pre-dawn water potential measurements between treatments was found in any of the three growth stages or years tested (Table 2.3). Although leaf water potential and transpiration (with the exception of the 2013 irrigated study at FB) measurements did not indicate any 1-MCP effect, there is evidence of temporary 1-MCP-induced decreases in respiration rates in fresh-cut broccoli (*Brassica rapa* L.) florets (Cefola et al., 2010), reduction in fresh weight loss in basil (*Ocimum basilicum* L.) leaves (Hassan and Mahfouz, 2010), and inhibition of respiration in bamboo (*Phyllostachys praecox f. prevernalis*) shoots (Luo et al., 2007).

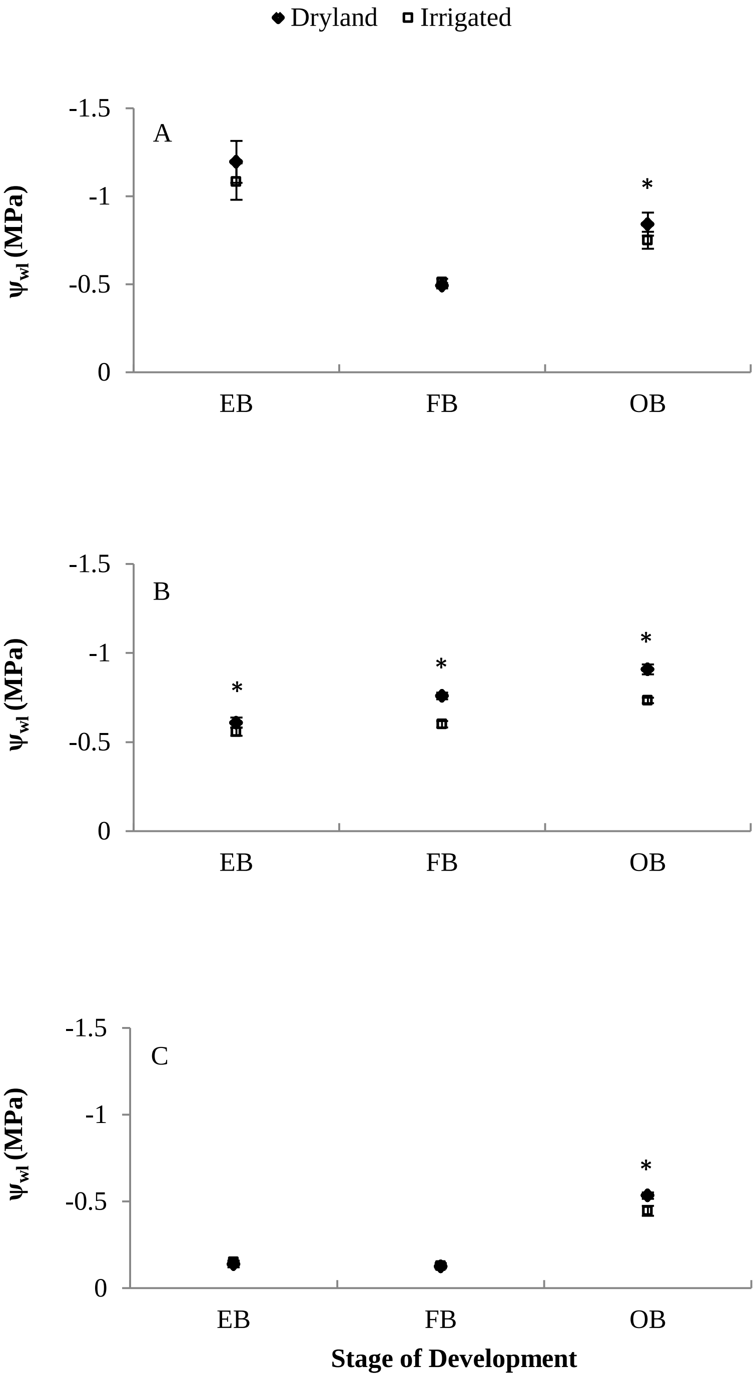

**Figure 2.3.** Pre-dawn leaf water potential ($\psi_{wl}$) measurements are shown for cotton grown during the summers of 2012 (A), 2013 (B), and 2014 (C). Values are averages of all four treatments combined within each growth stage (n = 48): early bloom (EB), full bloom (FB), and open boll (OB). Error bars represent ± SE , and * represents statistical significance between studies at the 5% probability level within each growth stage.

**Table 2.3.** Effect of 1-methylcyclopropene (1-MCP) on leaf water potential at early bloom (EB), full bloom (FB), and open boll (OB) growth stages of field cotton grown during the summers of 2012, 2013, and 2014 under irrigated (IRR) and dryland (DRY) conditions. Values are averages of three samples and four replications per treatment (n = 12).

| | | EB | | FB | | OB | |
|---|---|---|---|---|---|---|---|
| Year | Treatment[¥] | IRR | DRY | IRR | DRY | IRR | DRY |
| | | | | MPa | | | |
| 2012 | C | 1.08 | 1.20 | 0.51 | 0.49 | 0.75 | 0.84 |
| | S | 1.09 | 1.30 | 0.50 | 0.54 | 0.75 | 0.88 |
| | A95 | 1.13 | 1.23 | 0.50 | 0.55 | 0.81 | 0.92 |
| | A100 | 1.01 | 1.19 | 0.52 | 0.51 | 0.72 | 0.83 |
| | Sig. [€] | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| 2013 | C | 0.56 | 0.61 | 0.60 | 0.76 | 0.73 | 0.91 |
| | S | 0.56 | 0.61 | 0.61 | 0.74 | 0.75 | 0.88 |
| | A95 | 0.57 | 0.58 | 0.56 | 0.75 | 0.73 | 0.87 |
| | A100 | 0.53 | 0.62 | 0.57 | 0.78 | 0.75 | 0.92 |
| | Sig. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| 2014 | C | 0.15 | 0.14 | 0.13 | 0.13 | 0.45 | 0.53 |
| | S | 0.14 | 0.15 | 0.18 | 0.15 | 0.43 | 0.48 |
| | A95 | 0.17 | 0.15 | 0.16 | 0.13 | 0.47 | 0.46 |
| | A100 | 0.12 | 0.14 | 0.16 | 0.16 | 0.48 | 0.49 |
| | Sig. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |

[¥] Control (C), Smartcrop$^{TM}$ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)

[€] Significance (Sig.) of differences between treatments at the 5% probability level. Not significant (n.s.)

Water stressed plants exhibit higher canopy temperatures (CT) when compared to the ambient or non-stressed plants (Idso et al., 1977; Jackson et al., 1977). Across years and regardless of 1-MCP treatment, higher CTs occurred when air temperature was higher and rainfall was lower (2013). In contrast, lower CTs were found when air temperatures were lower and rainfall was higher (2014). Canopy temperatures for each treatment in the dryland plots were consistently higher than those in irrigated plots (Figs. 2.4 A and 2.4 B). Those differences were more pronounced in the drier 2013 season than they were on the other two growing seasons (2012 and 2014).

When daily plant canopy temperature was averaged within each season, no effect of 1-MCP treatment was found in any of the years when the plants were grown under dryland conditions (Fig. 2.4 A). P-values were 0.852, 0.293, and 0.287 for 2012, 2013, and 2014, respectively. Under irrigation, however, 1-MCP impacted canopy temperatures in all three years tested (Fig. 2.4 B). P-values for such analyses were 0.025, 0.027, and < 0.0001, for 2012, 2013, and 2014, respectively. In 2012 the highest CTs were found for the S treatment, which were higher than both the C and A95. In 2013 all 1-MCP treatments had significantly higher CTs when compared to the C. In 2014 the A100 treatment had higher CT than both the C and A95.

The evidence of 1-MCP-induced increase in stomatal resistance (Kawakami et al., 2010b), reduction in stomatal conductance (da Costa and Cothren, 2011), and decrease in respiration rates (Cefola et al., 2010) may help explain the CT results shown on Figs. 2.4 A and 2.4 B. While grown under irrigation at least one 1-MCP treatment displayed significantly higher CT when compared to the untreated control. Although research on the effects of 1-MCP in cotton shows that its effects are only temporary (da Costa and Cothren, 2011; Kawakami et al., 2010b; Su and Finlayson, 2012), it is possible that multiple 1-MCP applications during the season were capable of affecting the in-season average CT by temporarily reducing transpiration and thus the plants' transpirational cooling, which may have led to higher CT. Furthermore, da Costa and Cothren (2011) found a decrease in stomatal conductance and transpiration coupled with increased leaf temperature in 1-MCP-treated cotton plants grown in a greenhouse. Interesting to note is the fact that such effects were only significant when the plants were grown in well-watered conditions. Plants grown under water deficit stress did not exhibit the same responses to 1-MCP application.

Physiological parameters measured were not affected by 1-MCP application when cotton was grown under dryland conditions in any of the three crop stages and years studied (Tables 2.4, 2.6, and 2.8). In general, under dryland conditions net photosynthesis was higher early and during the peak reproductive phases (EB and FB), and substantially decreased by the time the crop reached the OB stage (late reproductive phase). These reductions in photosynthetic activity as the crop matures were not unexpected, and have also been reported elsewhere (Bauer et al., 2000; Peng and Krieg, 1991; Pettigrew et al., 1993). Transpiration also followed the same trend, such that ~ 50% decrease in transpiration was detected towards the latter part of the growing season when late season (OB) measurements were compared to early-season measurements (EB and FB).

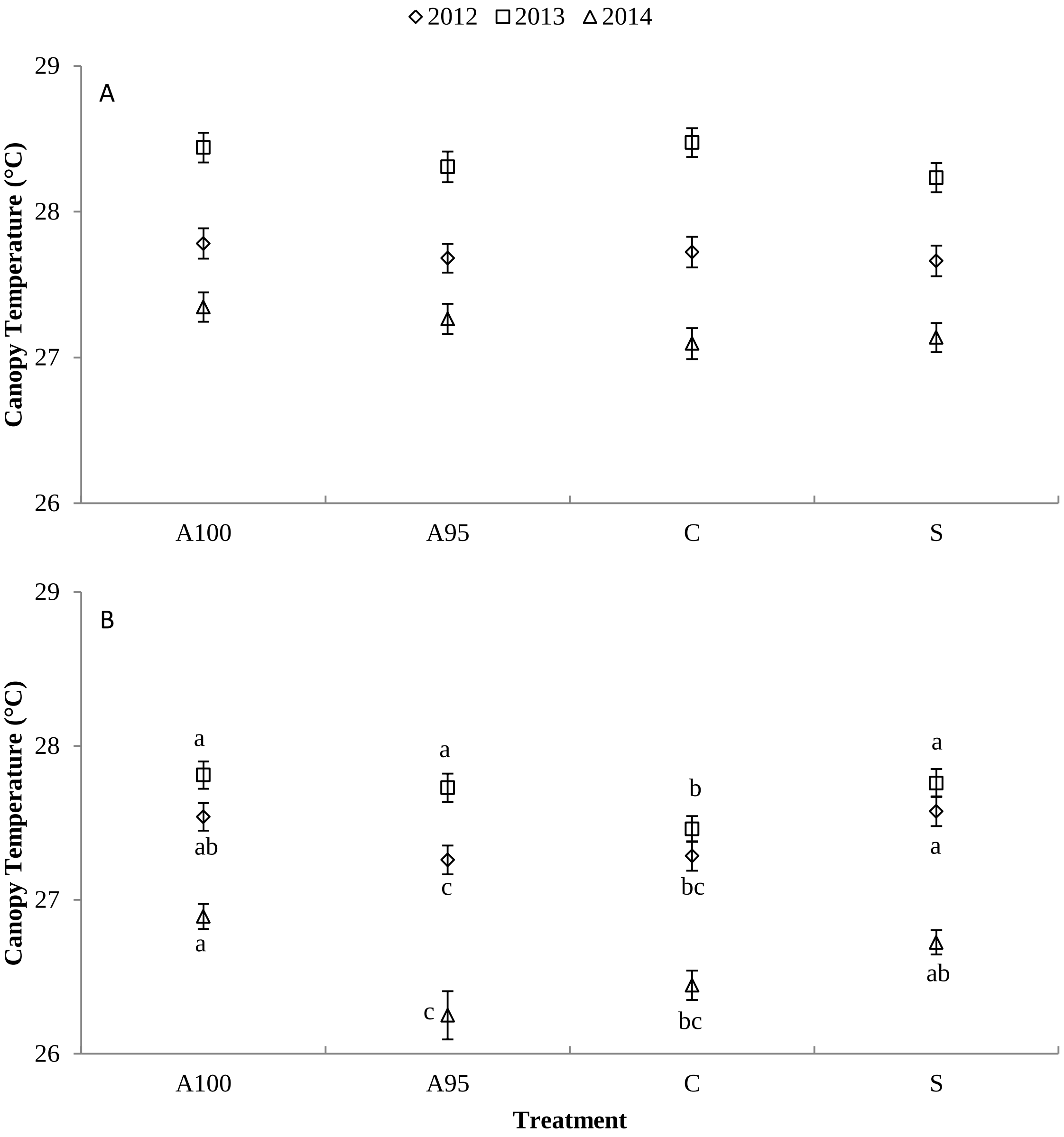

**Figure 2.4.** Effect of 1-methylcyclopropene (1-MCP) on different treatments for cotton grown during the summers of 2012, 2013, and 2014 under dryland (A) and irrigated (B) conditions. Values are shown as the average of daily canopy temperature throughout the season. Bars represent ± SE when greater than the symbols. Different letters within years represent significance at the 5% level of probability between treatments.

Vapor pressure differences between the leaf and the air ($\Delta_e$) increased as the season progressed from EB to OB. Such $\Delta_e$ increases ranged from 2.19 - 2.38, 0.82 - 1.23, and 1.21 - 1.35 kPa for dryland, and from 1.99 - 2.32, 0.01 - 0.36, and 0.0 - 0.07 kPa for irrigated studies in 2012, 2013, and 2014, respectively (Tables 2.4 to 2.8).

In the irrigated trials, differences among treatments were found for $\Delta_e$ at the EB stage in 2012 (Table 2.5), however, at this point such differences may not be attributed to 1-MCP since the first application occurred on 3 July, post EB measurements. During the 2013 season all three parameters measured showed differences among treatments at the FB stage (Table 2.7). Both net photosynthesis and transpiration for the S and A100 treatments were higher than those of the control plots at FB. $\Delta_e$ was higher in C plots when compared to the higher temperature threshold treatment (A100). At the FB stage in 2013, S and A100 treatments had received one 1-MCP application while the A95 treatment had received two 1-MCP applications, on 27 June and 11 and 27 June, respectively (Table 2.2). In 2014 there were no differences between treatments in any of the three crop stages (Table 2.9). Results were not consistent within years and/or across growth stages, which may possibly be attributed to the transient effects of 1-MCP. Previous studies of 1-MCP effects on cotton plants and cotton plant parts showed that its effects usually lasted less than 72 h (da Costa and Cothren, 2011; Su and Finlayson, 2012). Indeed, our measurements showed that although some differences among treatments were found in the FB growth stage in 2013, those differences were undetectable by the time the crop reached the latter phase of its reproductive stage (OB).

**Table 2.4.** Net photosynthesis (A), transpiration (E), and difference in vapor pressure between leaf and the air ($\Delta_e$) measurements were collected at three crop stages for dryland cotton in 2012. The third uppermost fully-expanded leaf was used for the measurements. Values are averages of three random plants per plot and four replications per treatment per growth stage (n = 12).

| | | 2012 Dryland | | |
|---|---|---|---|---|
| | | A | E | $\Delta_e$ |
| Treatment[¥] | Growth Stage[€] | (µmol $CO_2$ $m^{-2}$ $s^{-1}$) | (mmol $H_2O$ $m^{-2}$ $s^{-1}$) | (kPa) |
| C | EB | 36.23 | 9.29 | 0.80 |
| S | EB | 35.71 | 9.07 | 0.82 |
| A95 | EB | 36.32 | 9.10 | 0.86 |
| A100 | EB | 37.72 | 9.42 | 0.73 |
| C | FB | 37.40 | 10.64 | 1.00 |
| S | FB | 35.43 | 10.22 | 1.08 |
| A95 | FB | 39.43 | 10.80 | 0.95 |
| A100 | FB | 36.80 | 10.66 | 1.00 |
| C | OB | 15.65 | 5.56 | 3.13 |
| S | OB | 15.53 | 5.44 | 3.06 |
| A95 | OB | 16.49 | 5.69 | 3.05 |
| A100 | OB | 15.52 | 5.56 | 3.11 |

| ANOVA | | P > F | |
|---|---|---|---|
| EB | 0.2519 | 0.4941 | 0.0872 |
| FB | 0.2572 | 0.6792 | 0.3242 |
| OB | 0.9556 | 0.9895 | 0.9802 |

[¥] Control (C), Smartcrop™ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)
[€] Early Bloom (EB), Full Bloom (FB), and Open Boll (OB)

**Table 2.5.** Net photosynthesis (A), transpiration (E), and difference in vapor pressure between leaf and the air ($\Delta_e$) at three crop stages for irrigated cotton in 2012. The third uppermost fully-expanded leaf was used for the measurements. Values are averages of three random plants per plot and four replications per treatment per growth stage (n = 12).

| | | 2012 Irrigated | | |
|---|---|---|---|---|
| | | A | E | $\Delta_e$ |
| Treatment[¥] | Growth Stage[€] | ($\mu$mol $CO_2$ $m^{-2}$ $s^{-1}$) | (mmol $H_2O$ $m^{-2}$ $s^{-1}$) | (kPa) |
| C | EB | 36.68 | 9.79 | 0.81 |
| S | EB | 35.82 | 9.33 | 0.84 |
| A95 | EB | 37.55 | 9.58 | 0.69 |
| A100 | EB | 37.41 | 9.52 | 0.74 |
| C | FB | 38.10 | 10.95 | 1.04 |
| S | FB | 37.69 | 11.13 | 1.03 |
| A95 | FB | 38.96 | 11.15 | 0.98 |
| A100 | FB | 39.00 | 11.20 | 0.93 |
| C | OB | 17.60 | 5.97 | 3.03 |
| S | OB | 18.87 | 6.39 | 2.85 |
| A95 | OB | 20.21 | 7.15 | 2.67 |
| A100 | OB | 16.87 | 6.35 | 3.06 |
| ANOVA | | | P > F | |
| EB | | 0.6553 | 0.7271 | 0.0103 |
| FB | | 0.6249 | 0.6512 | 0.2204 |
| OB | | 0.6139 | 0.6672 | 0.3293 |

[¥] Control (C), Smartcrop™ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)
[€] Early Bloom (EB), Full Bloom (FB), and Open Boll (OB)

**Table 2.6.** Net photosynthesis (A), transpiration (E), and difference in vapor pressure between leaf and the air ($\Delta_e$) at three crop stages for dryland cotton in 2013. The third uppermost fully-expanded leaf was used for the measurements. Values are averages of three random plants per plot and four replications per treatment per growth stage (n = 12).

| | | 2013 Dryland | | |
|---|---|---|---|---|
| | | A | E | $\Delta_e$ |
| Treatment[¥] | Growth Stage[€] | (µmol $CO_2$ $m^{-2}$ $s^{-1}$) | (mmol $H_2O$ $m^{-2}$ $s^{-1}$) | (kPa) |
| C | EB | 28.89 | 10.89 | 1.30 |
| S | EB | 27.35 | 10.73 | 1.26 |
| A95 | EB | 28.74 | 10.52 | 1.37 |
| A100 | EB | 29.59 | 10.57 | 1.38 |
| C | FB | 21.88 | 8.38 | 1.51 |
| S | FB | 23.62 | 8.08 | 1.59 |
| A95 | FB | 21.95 | 7.60 | 1.70 |
| A100 | FB | 23.16 | 8.49 | 1.56 |
| C | OB | 19.69 | 6.04 | 2.53 |
| S | OB | 20.98 | 6.86 | 2.33 |
| A95 | OB | 23.07 | 7.85 | 2.19 |
| A100 | OB | 21.91 | 6.76 | 2.44 |
| ANOVA | | | P > F | |
| EB | | 0.6960 | 0.8808 | 0.4083 |
| FB | | 0.7364 | 0.5447 | 0.6800 |
| OB | | 0.2837 | 0.2095 | 0.3718 |

[¥] Control (C), Smartcrop$^{TM}$ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)
[€] Early Bloom (EB), Full Bloom (FB), and Open Boll (OB)

**Table 2.7.** Net photosynthesis (A), transpiration (E), and difference in vapor pressure between leaf and the air ($\Delta_e$) at three crop stages for irrigated cotton in 2013. The third uppermost fully-expanded leaf was used for the measurements. Values are averages of three random plants per plot and four replications per treatment per growth stage (n = 12).

| | | 2013 Irrigated | | |
|---|---|---|---|---|
| | | A | E | $\Delta_e$ |
| Treatment[¥] | Growth Stage[€] | (µmol $CO_2$ $m^{-2}$ $s^{-1}$) | (mmol $H_2O$ $m^{-2}$ $s^{-1}$) | (kPa) |
| C | EB | 33.19 | 11.47 | 1.13 |
| S | EB | 30.10 | 10.83 | 1.31 |
| A95 | EB | 29.08 | 11.03 | 1.44 |
| A100 | EB | 29.27 | 10.89 | 1.37 |
| C | FB | 22.17 | 9.13 | 1.25 |
| S | FB | 28.19 | 10.54 | 1.11 |
| A95 | FB | 24.78 | 9.86 | 1.12 |
| A100 | FB | 28.44 | 10.77 | 0.97 |
| C | OB | 31.53 | 11.32 | 1.49 |
| S | OB | 29.67 | 11.11 | 1.48 |
| A95 | OB | 32.36 | 11.20 | 1.44 |
| A100 | OB | 34.24 | 12.09 | 1.40 |
| ANOVA | | | P > F | |
| EB | | 0.1859 | 0.7091 | 0.1118 |
| FB | | 0.0111 | 0.0014 | 0.0499 |
| OB | | 0.0745 | 0.2118 | 0.6308 |

[¥] Control (C), Smartcrop™ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)

[€] Early Bloom (EB), Full Bloom (FB), and Open Boll (OB)

**Table 2.8.** Net photosynthesis (A), transpiration (E), and difference in vapor pressure between leaf and the air ($\Delta_e$) at three crop stages for dryland cotton in 2014. The third uppermost fully-expanded leaf was used for the measurements. Values are averages of three random plants per plot and four replications per treatment per growth stage (n = 12).

| | | 2014 Dryland | | |
|---|---|---|---|---|
| | | A | E | $\Delta_e$ |
| Treatment[¥] | Growth Stage[€] | (µmol $CO_2$ $m^{-2}$ $s^{-1}$) | (mmol $H_2O$ $m^{-2}$ $s^{-1}$) | (kPa) |
| C | EB | 41.26 | 13.93 | 1.20 |
| S | EB | 40.20 | 13.83 | 1.14 |
| A95 | EB | 41.18 | 13.79 | 1.08 |
| A100 | EB | 39.95 | 13.50 | 1.16 |
| C | FB | 33.15 | 13.02 | 1.09 |
| S | FB | 33.42 | 13.14 | 1.09 |
| A95 | FB | 31.75 | 12.96 | 1.10 |
| A100 | FB | 32.16 | 12.95 | 1.08 |
| C | OB | 21.59 | 6.20 | 2.43 |
| S | OB | 21.78 | 5.88 | 2.44 |
| A95 | OB | 22.56 | 6.49 | 2.29 |
| A100 | OB | 19.61 | 5.67 | 2.51 |

| ANOVA | | P > F | |
|---|---|---|---|
| EB | 0.4473 | 0.4549 | 0.2590 |
| FB | 0.5845 | 0.8575 | 0.9842 |
| OB | 0.8170 | 0.8753 | 0.8806 |

[¥] Control (C), Smartcrop$^{TM}$ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)
[€] Early Bloom (EB), Full Bloom (FB), and Open Boll (OB)

**Table 2.9.** Net photosynthesis (A), transpiration (E), and difference in vapor pressure between leaf and the air ($\Delta_e$) measurements were collected at three crop stages for irrigated cotton in 2014. The third uppermost fully-expanded leaf was used for the measurements. Values are averages of three random plants per plot and four replications per treatment per growth stage (n = 12).

| | | 2014 Irrigated | | |
|---|---|---|---|---|
| | | A | E | $\Delta_e$ |
| Treatment[¥] | Growth Stage[€] | (µmol $CO_2$ m$^{-2}$ s$^{-1}$) | (mmol $H_2O$ m$^{-2}$ s$^{-1}$) | (kPa) |
| C | EB | 39.48 | 13.28 | 1.17 |
| S | EB | 40.76 | 13.73 | 1.18 |
| A95 | EB | 39.18 | 13.44 | 1.16 |
| A100 | EB | 40.33 | 13.14 | 1.22 |
| C | FB | 31.44 | 12.67 | 1.14 |
| S | FB | 31.13 | 12.71 | 1.10 |
| A95 | FB | 29.18 | 12.76 | 1.13 |
| A100 | FB | 31.05 | 12.65 | 1.20 |
| C | OB | 33.71 | 11.82 | 1.19 |
| S | OB | 33.79 | 11.98 | 1.11 |
| A95 | OB | 32.63 | 11.63 | 1.16 |
| A100 | OB | 33.28 | 11.49 | 1.24 |
| | | | | |
| ANOVA | | | P > F | |
| EB | | 0.7250 | 0.1953 | 0.7387 |
| FB | | 0.3593 | 0.9876 | 0.3022 |
| OB | | 0.6668 | 0.5161 | 0.4771 |

[¥] Control (C), Smartcrop$^{TM}$ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)

[€] Early Bloom (EB), Full Bloom (FB), and Open Boll (OB)

Photosystem II quantum yield ($\phi PS_{II}$) measurements showed differences early in the season (EB) for irrigated plots in 2013 and 2014 (Table 2.10). In 2013 $\phi PS_{II}$ measurements were higher for the A95 when compared to the C plots, whereas in 2014, C plots showed higher $\phi PS_{II}$ when compared to the S treatment. However, at the time of EB measurements treatment A95 in 2013 was the only treatment that had received 1-MCP application, which happened 2 weeks prior to measurements. No 1-MCP applications had been made prior to $\phi PS_{II}$ measurements in 2014 (see Table 2.2).

In the 2013 irrigated study, 1-MCP increased $\phi PS_{II}$ at EB when compared to the C. Differences found early at the EB stage in the 2014 irrigated study may not be attributed to 1-MCP since the first application didn't occur until July 2, post EB measurements. Throughout the rest of the growing season (FB and OB), no differences were found between treatments within each study and growth stage. In general, higher $\phi PS_{II}$ values were found early in the season at the EB stage, and declined as the season progressed, such that the lowest values were found at the OB stage. Furthermore, cotton plants in the irrigated study were able to maintain sligthly higher $\phi PS_{II}$ throughout the growing seasons than those in the dryland study.

**Table 2.10.** Effect of 1-methylcyclopropene (1-MCP) on the quantum yield of photosystem II ($\phi PS_{II}$) for cotton grown during the summers of 2012, 2013, and 2014. Quantum yield of PSII was measured using the saturation pulse method in light adapted leaves and calculated as $Y = (F_m - F_t) / F_m$, where $F_m$ = maximum fluorescence and $F_t$ = fluorescence at given time. Data is presented for both irrigated (IRR) and dryland (DRY) studies as a mean of 5 plants per plot per treatment (n = 20). Data was collected at early bloom (EB), full bloom (FB), and open boll (OB).

| | | EB | | FB | | OB | |
|---|---|---|---|---|---|---|---|
| Year | Treatment[¥] | IRR | DRY | IRR | DRY | IRR | DRY |
| 2012 | C | 0.649 | 0.670 | 0.426 | 0.419 | 0.516 | 0.360 |
| | S | 0.659 | 0.646 | 0.450 | 0.398 | 0.529 | 0.409 |
| | A95 | 0.641 | 0.667 | 0.401 | 0.383 | 0.586 | 0.375 |
| | A100 | 0.663 | 0.664 | 0.393 | 0.395 | 0.572 | 0.363 |
| | Sig. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| 2013 | C | 0.498b | 0.560 | 0.548 | 0.534 | 0.513 | 0.596 |
| | S | 0.554ab | 0.594 | 0.580 | 0.512 | 0.503 | 0.620 |
| | A95 | 0.607a | 0.558 | 0.584 | 0.514 | 0.515 | 0.614 |
| | A100 | 0.545ab | 0.546 | 0.542 | 0.515 | 0.535 | 0.594 |
| | Sig. | * | n.s. | n.s. | n.s. | n.s. | n.s. |
| 2014 | C | 0.508a | 0.469 | 0.448 | 0.481 | 0.367 | 0.342 |
| | S | 0.453b | 0.433 | 0.456 | 0.469 | 0.376 | 0.334 |
| | A95 | 0.473ab | 0.429 | 0.463 | 0.433 | 0.390 | 0.339 |
| | A100 | 0.477ab | 0.438 | 0.436 | 0.437 | 0.381 | 0.415 |
| | Sig. | * | n.s. | n.s. | n.s. | n.s. | n.s. |

Significance (Sig.): * significant at $P \leq 0.05$, not significant (n.s.)

[¥] Control (C), Smartcrop$^{TM}$ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)

There were no differences in seed cotton yields (SCY) among treatments in any of the three years of the study post 1-MCP applications (Table 2.11). Seedcotton production ranged from 2,464 to 5,083 Kg ha$^{-1}$ and from 3,785 to 5,603 Kg ha$^{-1}$ for the dryland and irrigated studies, respectively (Table 2.11). Within each of the three years studied the irrigated study always had higher SCY when compared to the dryland studies (Fig. 2.5). This difference was more pronounced during the drier 2013 season. The 3-year SCY average was 3,922 and 4,777 Kg ha$^{-1}$ for dryland and irrigated studies, respectively.

**Table 2.11.** Effect of 1-methylcyclopropene (1-MCP) application on final seedcotton yield of cotton grown during the summers of 2012, 2013, and 2014. Values are average treatment seedcotton yield for four replications (Reps) (n = 4), and are shown for both dryland (DRY) and irrigated (IRR) studies. Statistical significance (Sig.) at the 5% level of probability is shown. Non-significant (n.s.).

| | | 2012 | | 2013 | | 2014 | |
|---|---|---|---|---|---|---|---|
| Treatment[¥] | Reps | IRR | DRY | IRR | DRY | IRR | DRY |
| | | Kg ha$^{-1}$ | | | | | |
| C | 4 | 5,137 | 4,408 | 3,785 | 2,464 | 5,331 | 4,854 |
| S | 4 | 4,862 | 4,485 | 4,119 | 2,490 | 5,326 | 4,920 |
| A95 | 4 | 4,957 | 4,511 | 4,033 | 2,533 | 5,603 | 5,083 |
| A100 | 4 | 5,014 | 4,485 | 3,796 | 2,527 | 5,529 | 4,602 |
| Sig. | | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |

[¥] Control (C), Smartcrop$^{TM}$ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)

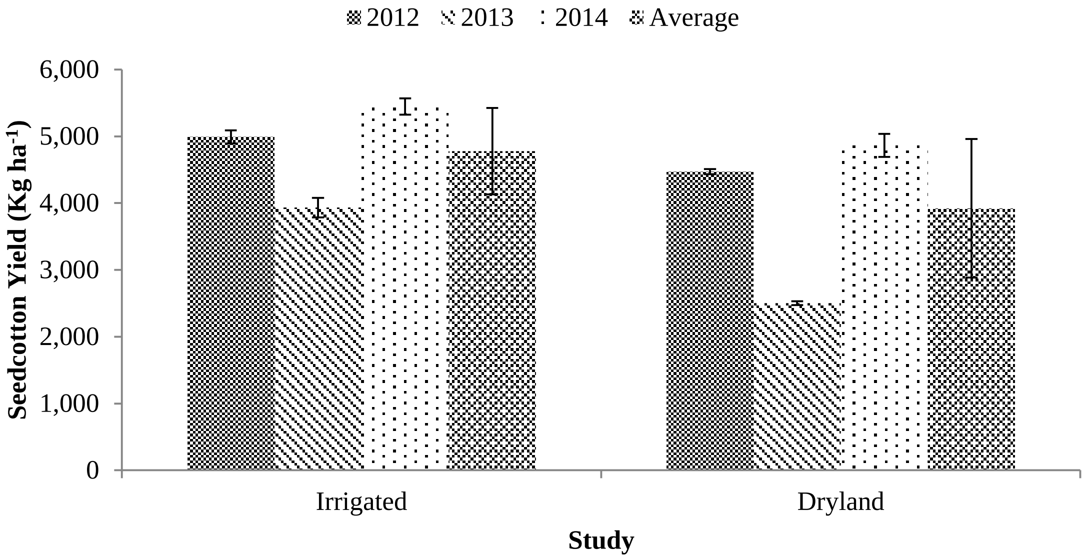

**Figure 2.5.** Average seed cotton yield across treatments for each of the three years studied. The 3-year average is included for reference and shown on the far right of each study. Bars represent ± 1 standard deviation.

Since most cotton is an indeterminate plant, it has the ability to compensate for both biotic and abiotic stresses occurring throughout the growing season. Plant mapping analysis provides good insight into the crop's responses to adverse conditions, which may negatively impact yield depending on the timing and duration of such occurrences. Number of bolls per unit area is the most important variable contributing to cotton yield (Boquet et al., 2004; Wu et al., 2005). This variable was indirectly assessed by analyzing fruit retention (FR) values. FR was calculated as the percentage of reproductive structures (squares, green bolls, and open bolls) retained in the plant at the time of measurement, to the total number of fruiting sites in both monopodial and sympodial branches (whole plant). Cotton growth responses to 1-MCP applications in 2012, 2013, and 2014 are detailed on tables 2.12, 2.13, and 2.14, respectively. Plant mapping data showed that 1-MCP applications did impact at least one growth characteristic in all three years studied. Those responses, however, did not necessarily translate into differences in final fruit retention (FR) among treatments within studies and years.

Height to node ratio (H:N) is the ratio between total plant height (measured from the cotyledons to the top terminal of the plant) and total number of nodes (including both monopodial and sympodial nodes). It provides an integrated measure of the crop's stress level and source-sink balance (Kerby et al., 1998). Additionally, Silvertooth et al. (1996) reported that the average length of the top five internodes (ALT5) is a good indicator of main stem elongation (vigor of the plant). High ALT5 values (4.6 - 6.1 cm) indicate high plant vigor, while values lower than 3.6 cm were said to indicate low plant vigor. According to the same authors, while ALT5 may be considered essentially the same measurement as H:N when the plants are small, as they grow ALT5 accounts only for the actual active zone of growth, rather than the plant as a whole. As such, the ALT5 measurement may be used as a trigger for the use of plant growth regulators, as well as to monitor crop growth.

Across years and growth stages, our results showed that H:N ranged from 3.7 – 4.7 cm and 4.0 – 4.7 cm for the dryland and irrigated studies, respectively (Tables 2.12, 2.13, and 2.14). 1-MCP impacted H:N at harvest (HA) only for the irrigated studies in 2012 and 2013. In the 2012 irrigated study the S and A95 treatments had lower H:N when compared to the C, while the A100 treatment although lower, was not significantly different than the C or any of the other two 1-MCP treatments (Table 2.12). In 2013 both S and A95 treatments had a H:N of 4.0 cm at harvest. These values were lower than both the A100 treatment (4.3 cm) and the C (4.2 cm), although differences were only significant against the A100 treatment (Table 2.13). In the last year of the study (2014), H:N was not affected by 1-MCP at harvest in neither the dryland nor the irrigated trial (Table 2.14).

**Table 2.12.** Effects of 1-methylcyclopropene (1-MCP) application on morphological characteristics of cotton grown in 2012. Plant height (PH), height to node ratio (H:N), number of vegetative nodes (VN), number of reproductive nodes (RN), number of mainstem nodes (MSN), total number of reproductive structures (TRS), and final fruit retention (FR) were collected for both irrigated (IRR) and dryland (DRY) studies at three distinct growth stages: Early bloom (EB), full bloom (FB), and harvest (HA). Values are average of 24 plants per treatment (TRT) (n = 24). Same letter in a column within a study and growth stage (GS) are not significantly different at the 5% level of probability.

| Year | Study | TRT | GS | PH | H:N | VN | RN | MSN | TRS | FR |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | cm | | | | | | (%) |
| 2012 | IRR | C | EB | 83.7a | 4.7a | 4.8a | 13.3a | 18.1a | 24.3a | 98.7a |
| | | S | EB | 83.0a | 4.5a | 5.2a | 13.2a | 18.4a | 24.7a | 98.9a |
| | | A95 | EB | 78.8b | 4.6a | 4.5a | 12.8a | 17.3a | 24.5a | 97.9a |
| | | A100 | EB | 83.8a | 4.6a | 5.3a | 12.8a | 18.2a | 24.2a | 98.8a |
| 2012 | IRR | C | FB | 89.4a | 4.4a | 5.6a | 15.0a | 20.5a | 32.4a | 62.2a |
| | | S | FB | 88.7a | 4.1a | 6.2a | 15.5a | 21.6a | 35.2a | 53.9b |
| | | A95 | FB | 87.5a | 4.3a | 5.7a | 15.0a | 20.6a | 34.7a | 64.1a |
| | | A100 | FB | 85.9a | 4.3a | 5.5a | 14.6a | 20.2a | 32.8a | 60.1a |
| 2012 | IRR | C | HA | 96.4a | 4.7a | 5.5a | 15.3a | 20.8a | 34.0a | 44.0a |
| | | S | HA | 92.1b | 4.4b | 5.7a | 15.5a | 21.3a | 33.1a | 44.2a |
| | | A95 | HA | 89.9b | 4.3b | 6.1a | 14.9a | 21.0a | 33.3a | 43.8a |
| | | A100 | HA | 93.6ab | 4.5ab | 6.3a | 14.7a | 21.0a | 28.6a | 44.1a |
| 2012 | DRY | C | EB | 82.8a | 4.7a | 5.7a | 11.9a | 17.6a | 22.0a | 96.4a |
| | | S | EB | 82.9a | 4.7a | 4.9a | 12.7a | 17.6a | 25.6a | 96.9a |
| | | A95 | EB | 81.7a | 4.5a | 5.3a | 12.8a | 18.2a | 24.5a | 99.0a |
| | | A100 | EB | 80.7a | 4.6a | 5.4a | 12.4a | 17.7a | 22.6a | 97.5a |
| 2012 | DRY | C | FB | 88.0a | 4.3ab | 5.3a | 15.2a | 20.5a | 31.7a | 56.0a |
| | | S | FB | 88.3a | 4.4a | 5.6a | 14.5a | 20.2a | 31.4a | 58.3a |
| | | A95 | FB | 89.2a | 4.2ab | 5.9a | 15.4a | 21.3a | 33.3a | 59.4a |
| | | A100 | FB | 83.9b | 4.0b | 5.8a | 15.0a | 20.8a | 31.2a | 58.3a |
| 2012 | DRY | C | HA | 88.5a | 4.4a | 5.8a | 14.4a | 20.2a | 30.1a | 44.9a |
| | | S | HA | 85.5a | 4.2a | 5.8a | 14.4a | 20.3a | 28.7a | 44.1a |
| | | A95 | HA | 87.9a | 4.3a | 6.2a | 14.3a | 20.5a | 30.3a | 42.6a |
| | | A100 | HA | 86.3a | 4.3a | 5.5a | 14.5a | 20.0a | 29.7a | 45.5a |

**Table 2.13.** Effects of 1-methylcyclopropene (1-MCP) application on morphological characteristics of cotton grown in 2013. Plant height (PH), height to node ratio (H:N), number of vegetative nodes (VN), number of reproductive nodes (RN), number of mainstem nodes (MSN), total number of reproductive structures (TRS), and final fruit retention (FR) were collected for both irrigated (IRR) and dryland (DRY) studies at three distinct growth stages: Early bloom (EB), full bloom (FB), and harvest (HA). Values are average of 24 plants per treatment (TRT) (n = 24). Same letter in a column within a study and growth stage (GS) are not significantly different at the 5% level of probability.

| Year | Study | TRT | GS | PH | H:N | VN | RN | MSN | TRS | FR |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | cm | | | | | | (%) |
| 2013 | IRR | C | EB | 65.7a | 4.5a | 6.3a | 8.3a | 14.5a | 14.3a | 81.7bc |
| | | S | EB | 65.1a | 4.3a | 6.4a | 8.8a | 15.2a | 16.4a | 86.3ab |
| | | A95 | EB | 65.8a | 4.5a | 6.2a | 8.7a | 14.8a | 16.4a | 92.4a |
| | | A100 | EB | 68.8a | 4.5a | 6.2a | 9.3a | 15.5a | 17.8a | 79.2c |
| 2013 | IRR | C | FB | 84.3a | 4.5a | 6.8a | 12.2a | 18.9a | 24.3a | 51.6a |
| | | S | FB | 86.9a | 4.5a | 6.4a | 13.0a | 19.4a | 28.0a | 49.3a |
| | | A95 | FB | 84.7a | 4.4a | 6.7a | 12.8a | 19.5a | 28.5a | 52.7a |
| | | A100 | FB | 87.4a | 4.5a | 6.8a | 12.9a | 19.6a | 26.6a | 54.0a |
| 2013 | IRR | C | HA | 86.5a | 4.2ab | 6.7a | 13.8b | 20.5b | 25.6a | 45.7a |
| | | S | HA | 88.3a | 4.0b | 6.5a | 15.3a | 22.2a | 31.0a | 42.1a |
| | | A95 | HA | 89.1a | 4.0b | 7.1a | 15.1a | 22.2a | 32.1a | 42.0a |
| | | A100 | HA | 91.8a | 4.3a | 6.8a | 14.5ab | 21.3ab | 28.8a | 46.2a |
| 2013 | DRY | C | EB | 67.4ab | 4.4a | 6.6a | 8.7a | 15.3a | 15.8a | 78.0b |
| | | S | EB | 70.5a | 4.6a | 6.5a | 9.0a | 15.5a | 14.7a | 77.5b |
| | | A95 | EB | 65.5b | 4.3a | 6.6a | 8.6a | 15.2a | 15.7a | 90.4a |
| | | A100 | EB | 70.8a | 4.5a | 6.5a | 9.3a | 15.7a | 18.3a | 84.5ab |
| 2013 | DRY | C | FB | 75.9a | 4.3a | 6.3a | 11.5a | 17.8a | 23.6a | 41.7a |
| | | S | FB | 74.3a | 4.3a | 6.6a | 10.9a | 17.5a | 20.2a | 36.8a |
| | | A95 | FB | 78.8a | 4.3a | 6.8a | 11.3a | 18.1a | 21.9a | 40.2a |
| | | A100 | FB | 73.8a | 4.2a | 6.7a | 11.0a | 17.7a | 20.5a | 40.4a |
| 2013 | DRY | C | HA | 77.0a | 3.9a | 7.0a | 12.9a | 19.9a | 25.0a | 33.8a |
| | | S | HA | 77.8a | 3.8a | 6.6a | 14.0a | 20.6a | 27.9a | 31.0a |
| | | A95 | HA | 77.3a | 3.7a | 6.7a | 14.2a | 20.8a | 26.0a | 31.4a |
| | | A100 | HA | 76.3a | 3.7a | 7.1a | 13.3a | 20.4a | 25.9a | 37.0a |

**Table 2.14.** Effects of 1-methylcyclopropene (1-MCP) application on morphological characteristics of cotton grown in 2014. Plant height (PH), height to node ratio (H:N), number of vegetative nodes (VN), number of reproductive nodes (RN), number of mainstem nodes (MSN), total number of reproductive structures (TRS), and final fruit retention (FR) were collected for both irrigated (IRR) and dryland (DRY) studies at three distinct growth stages: Early bloom (EB), full bloom (FB), and harvest (HA). Values are average of 24 plants per treatment (TRT) (n = 24). Same letter in a column within a study and growth stage (GS) are not significantly different at the 5% level of probability.

| Year | Study | TRT | GS | PH | H:N | VN | RN | MSN | TRS | FR |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | cm | | | | | | (%) |
| 2014 | IRR | C | EB | 60.0b | 4.0a | 6.6a | 8.4a | 15.0b | 14.0a | 79.5a |
| | | S | EB | 66.0a | 4.1a | 6.8a | 9.3a | 16.1a | 16.4a | 83.4a |
| | | A95 | EB | 67.7a | 4.2a | 7.1a | 9.0a | 16.1a | 15.9a | 87.0a |
| | | A100 | EB | 65.5a | 4.1a | 6.8a | 9.4a | 16.3a | 16.0a | 87.3a |
| 2014 | IRR | C | FB | 91.0a | 4.6a | 7.2a | 12.8a | 20.0a | 29.3a | 85.4b |
| | | S | FB | 89.2a | 4.7a | 7.4a | 11.8a | 19.1a | 26.1a | 82.0b |
| | | A95 | FB | 89.6a | 4.6a | 7.4a | 12.2a | 19.5a | 29.8a | 91.7a |
| | | A100 | FB | 90.0a | 4.7a | 6.8a | 12.4a | 19.2a | 28.7a | 85.5b |
| 2014 | IRR | C | HA | 105.8a | 4.7a | 7.8a | 14.8a | 22.6a | 33.4a | 43.4b |
| | | S | HA | 105.8a | 4.6a | 7.8a | 15.2a | 23.0a | 33.3a | 47.5ab |
| | | A95 | HA | 103.4a | 4.6a | 7.1b | 15.4a | 22.5a | 34.3a | 46.8b |
| | | A100 | HA | 107.3a | 4.7a | 7.2b | 15.5a | 22.6a | 36.8a | 52.3a |
| 2014 | DRY | C | EB | 62.8a | 3.9b | 7.2a | 9.0a | 16.2ab | 16.4a | 85.4a |
| | | S | EB | 67.2a | 4.2b | 7.0a | 9.2a | 16.1ab | 16.4a | 86.2a |
| | | A95 | EB | 67.9a | 4.5a | 7.3a | 7.9b | 15.3b | 13.8a | 84.2a |
| | | A100 | EB | 68.0a | 4.0b | 7.3a | 9.6a | 16.8a | 17.8a | 85.4a |
| 2014 | DRY | C | FB | 78.4c | 4.2a | 7.3a | 11.4a | 18.7a | 24.0a | 80.6b |
| | | S | FB | 83.4ab | 4.3a | 7.1a | 12.2a | 19.3a | 28.9a | 88.8a |
| | | A95 | FB | 87.4a | 4.5a | 7.3a | 12.3a | 19.6a | 28.0a | 83.6ab |
| | | A100 | FB | 81.0bc | 4.3a | 7.6a | 11.3a | 18.9a | 24.5a | 85.1ab |
| 2014 | DRY | C | HA | 90.4b | 4.3a | 7.7a | 13.7a | 21.3bc | 28.5b | 51.6a |
| | | S | HA | 97.8a | 4.3a | 7.3a | 15.3a | 22.6a | 29.3b | 47.9a |
| | | A95 | HA | 98.4a | 4.5a | 7.4a | 14.8a | 22.2ab | 36.7a | 48.7a |
| | | A100 | HA | 87.3b | 4.2a | 7.1a | 14.0a | 21.1c | 28.1b | 49.0a |

By combining plant mapping and yield data over studies and years, preliminary analysis demonstrated a high positive correlation between H:N and seed cotton yield at harvest, such that the highest yields were found for plots with a H:N greater than 4.5 cm (Fig. 2.6). Final fruit retention was generally higher at EB and decreased as the crop matured. Lowest FR values were found at harvest (HA), and ranged across years from 42-52% and 31-51% for the irrigated and dryland studies, respectively, regardless of 1-MCP treatment. Not surprisingly, FR was highly correlated with final seedcotton yield at harvest (Fig. 2.7). A negative effect of 1-MCP application was detected at the FB stage in the 2012 irrigated study for the S treatment, which showed an 8% reduction in fruit retention when compared to the untreated control, at the same growth stage (Table 2.12). Interestingly, da Costa et al. (2011) also found negative impacts of 1-MCP application on fruit retention. The authors reported that both 1-MCP rates (25 and 50 g a.i. $ha^{-1}$) tested without surfactants produced the lowest boll retention values 50 d after treatment. Additionally, Chen et al. (2014) also indicated lower FR in plants treated with 1-MCP at 10 g a.i. $ha^{-1}$ when compared to untreated controls. In 2013 the A95 treatment was first sprayed with 1-MCP on June 11th (Table 2.2). Two weeks later when plots were sampled for the EB plant mapping there was a beneficial effect of 1-MCP on FR. When compared to their respective control plots, the A95 treatment had 10 and 12% higher FR at EB for the irrigated and dryland studies, respectively (Table 2.13). During the 2014 season, 1-MCP treatment benefited FR on the irrigated study for A95 and A100 at FB and HA, respectively, while under dryland conditions 1-MCP improved FR of the S treatment by 8% at FB when compared to the control (Table 2.14).

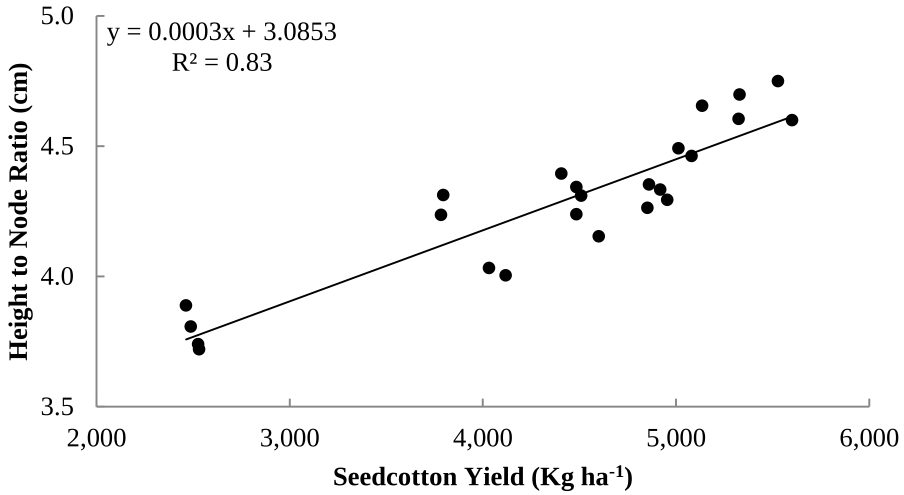

**Figure 2.6.** Relationship between height to node ratio and seedcotton yield at harvest, for cotton grown during the summers of 2012, 2013, and 2014. Data shown are a combination of both, irrigated and dryland studies across three years studied.

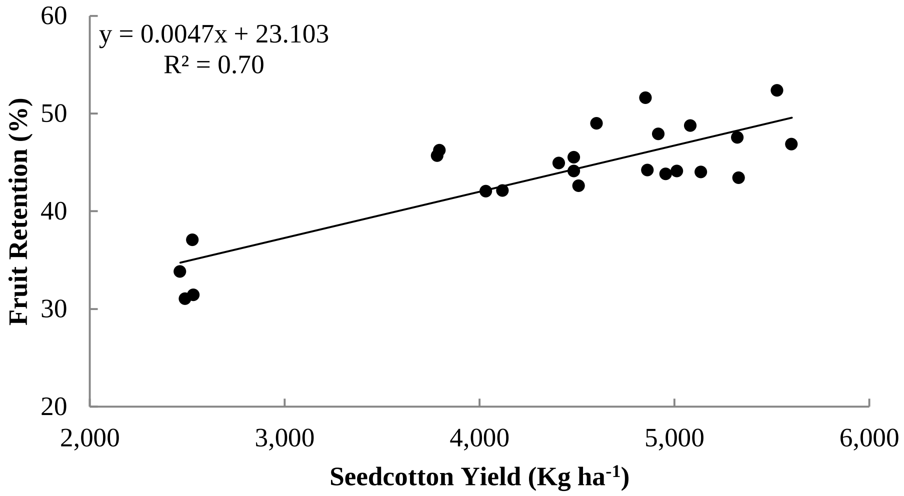

**Figure 2.7.** Relationship between fruit retention and final seedcotton yield at harvest, for cotton grown during the summers of 2012, 2013, and 2014. Data shown are a combination of both, irrigated and dryland studies across three years studied.

All fiber parameters measured were similar to the average for the southwest cotton production areas of the United States, which includes Texas, Oklahoma, and Kansas (Table 2.15). Analysis of fiber quality characteristics as measured by the High Volume Instrument (HVI) method showed no effect of 1-MCP application on most fiber quality parameters such as micronaire, length, strength, elongation, and leaf grade (Table 2.16). Although significant differences in reflectance (Rd) and/or yellowness (+b) were found in both 2012 and 2013 irrigated trials, and dryland trial in 2014, such differences are not likely to cause any positive or negative effects on fiber value in the current market. Since effects of 1-MCP were minimal and unlikely to cause any impact on the market value for the fiber, these effects may be considered negligible under the conditions tested.

**Table 2.15.** Average values for micronaire (MIC), length (LGH), uniformity (UNIF), and strength (STG) for the southwest cotton-producing region of the United States (SW Region), which includes Texas, Oklahoma, and Kansas. Same parameters for both our irrigated (IRR) and dryland (DRY) studies are included for reference.

| Year | Sample | Source | MIC | LGH | UNIF | STG |
|---|---|---|---|---|---|---|
| | | | | (in.) | (%) | (g/tex) |
| 2013-2014[¥] | 4,247,152 | SW Region | 4.0 | 1.1 | 80.2 | 30.2 |
| 2012 | 32 | IRR | 4.7 | 1.1 | 84.1 | 31.8 |
| 2012 | 32 | DRY | 4.7 | 1.1 | 84.2 | 31.3 |
| 2013 | 32 | IRR | 5.1 | 1.1 | 83.2 | 31.7 |
| 2013 | 32 | DRY | 4.8 | 1.1 | 82.0 | 30.2 |
| 2014 | 32 | IRR | 4.7 | 1.1 | 82.5 | 32.8 |
| 2014 | 32 | DRY | 4.8 | 1.1 | 82.9 | 32.8 |

[¥] Source: Cotton Incorporated: http://www.cottoninc.com/fiber/quality/US-Fiber-Chart/Properties-of-the-Growing-Regions/

**Table 2.16.** Effects of 1-methylcyclopropene (1-MCP) treatment on fiber quality characteristics of cotton plants grown during the summers of 2012, 2013, and 2014 under irrigated (IRR) and dryland (DRY) conditions. Means are average of 4 replications per treatment. Fiber characteristics were assessed using the high volume instrument (HVI) method.

| Year | Study | Treatment | MIC | LGH | UNIF | STG | ELON | Rd | +b | LEAF |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | (in.) | (%) | (g/tex) | (%) | (%) | | |
| 2012 | IRR | C | 4.7 | 1.1 | 82.9 | 31.5 | 8.2 | 66.9 | 8.2 | 7.3 |
| | | S | 4.9 | 1.1 | 84.1 | 31.1 | 8.2 | 67.1 | 8.2 | 7.0 |
| | | A95 | 4.7 | 1.2 | 85.0 | 32.4 | 8.4 | 66.6 | 7.8 | 7.8 |
| | | A100 | 4.7 | 1.1 | 84.2 | 32.4 | 8.3 | 69.4 | 8.4 | 6.8 |
| | | Sig. | n.s. | n.s. | n.s. | n.s. | n.s. | * | ** | n.s. |
| 2012 | DRY | C | 4.6 | 1.1 | 84.2 | 31.0 | 8.5 | 65.6 | 7.9 | 8.0 |
| | | S | 4.7 | 1.1 | 84.6 | 31.7 | 8.0 | 65.6 | 8.0 | 8.0 |
| | | A95 | 4.6 | 1.1 | 84.1 | 30.9 | 8.4 | 66.2 | 8.0 | 7.5 |
| | | A100 | 4.7 | 1.1 | 83.9 | 31.6 | 8.4 | 66.5 | 7.9 | 7.5 |
| | | Sig. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| 2013 | IRR | C | 5.2 | 1.1 | 83.1 | 31.2 | 7.7 | 61.6 | 8.3 | 7.5 |
| | | S | 5.1 | 1.1 | 83.2 | 32.1 | 7.6 | 61.5 | 8.2 | 7.0 |
| | | A95 | 5.0 | 1.1 | 83.0 | 31.4 | 7.6 | 61.2 | 8.2 | 6.5 |
| | | A100 | 5.1 | 1.1 | 83.6 | 32.1 | 7.4 | 63.1 | 8.7 | 6.5 |
| | | Sig. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. |
| 2013 | DRY | C | 4.7 | 1.0 | 81.7 | 30.2 | 7.9 | 60.7 | 8.6 | 6.5 |
| | | S | 4.8 | 1.1 | 81.9 | 30.2 | 7.7 | 61.3 | 8.7 | 7.3 |
| | | A95 | 4.9 | 1.1 | 82.8 | 31.0 | 7.9 | 62.3 | 8.4 | 6.5 |
| | | A100 | 4.8 | 1.0 | 81.6 | 29.3 | 7.9 | 61.2 | 8.7 | 7.5 |
| | | Sig. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| 2014 | IRR | C | 4.7 | 1.1 | 82.5 | 32.4 | 6.8 | 55.9 | 8.0 | 7.5 |
| | | S | 4.5 | 1.1 | 82.4 | 32.9 | 7.2 | 58.1 | 8.1 | 7.8 |
| | | A95 | 4.8 | 1.1 | 82.2 | 32.9 | 6.9 | 56.7 | 8.3 | 7.5 |
| | | A100 | 4.8 | 1.1 | 83.1 | 32.9 | 7.0 | 57.4 | 8.4 | 7.5 |
| | | Sig. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| 2014 | DRY | C | 4.8 | 1.2 | 83.4 | 33.2 | 7.0 | 58.1 | 7.8 | 8.0 |
| | | S | 4.7 | 1.1 | 83.2 | 33.1 | 7.0 | 56.9 | 7.8 | 8.0 |
| | | A95 | 4.8 | 1.1 | 82.6 | 32.8 | 6.9 | 58.2 | 8.1 | 8.0 |
| | | A100 | 4.7 | 1.1 | 82.3 | 32.2 | 6.7 | 57.8 | 8.3 | 7.3 |
| | | Sig. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. |

Significance (Sig.): * significant at $P \leq 0.05$, ** significant at $P \leq 0.01$, not significant (n.s.)
Control (C), Smartcrop$^{TM}$ (S), Ambient 35 °C (A95), and Ambient 37.8 °C (A100)
Micronaire (MIC), Length 100's (LGH), Uniformity (UNIF), Strength (STG), Elongation (ELON), Reflectance (Rd), Yellowness (+b), Leaf grade (LEAF)

## CONCLUSIONS

Results of this study indicated that 1-MCP had little to no significant effect on physiological and morphological parameters of field grown cotton at different stages of crop development. 1-MCP treatment had no impact on pre-dawn leaf water potential. Average daily plant canopy temperature, net photosynthesis, transpiration, and photosystem II quantum yield were affected by 1-MCP treatment when plants were grown under irrigation, but not under dryland conditions.

Both positive and negative effects of 1-MCP on fruit retention found during early and peak reproductive phases were mostly undetectable by harvest. Further, 1-MCP-treated plots showed no significant increase in seed cotton yield when compared to the untreated control, in any of the three years studied and regardless of which temperature threshold was used to trigger applications. The differences found in fiber quality characteristics due to 1-MCP treatment were minimal and also unlikely to cause any positive or negative impact on fiber value.

In conclusion, the effects of 1-MCP applications during the different seasons were variable and somewhat inconsistent. Ultimately, 1-MCP treatment effects were not enough to cause a significant increase in seedcotton yield under the conditions tested.

# CHAPTER III

# ASSOCIATION BETWEEN CANOPY TEMPERATURE-BASED STRESS INDICES AND YIELD OF COTTON

## OVERVIEW

Researchers have established numerous useful associations between crop canopy temperature and important physiological and agronomic characteristics. Due to their direct contribution to plant performance and ultimately yield, multiple canopy temperature-based stress indices have been developed. The objective of this study was to investigate the association of canopy temperature (CT), canopy temperature depression (CTD), stress degree day (SDD), thermal stress index (TSI), and crop water stress index (CWSI) with final cotton (*Gossypium hirsutum* L.) yield. Studies were conducted at the Texas A&M University Field Laboratory in Burleson County, TX during the summers of 2012 – 2014. Initial analysis showed that all stress indices performed similarly during individual years. Over the combined years CT ($r^2 = 0.66$), TSI ($r^2 = 0.70$), and CWSI ($r^2 = 0.58$) were significantly correlated to final seedcotton yield while CTD and SDD were not. Removal of the drier 2013 season from the regression analysis substantially improved fit for CTD ($r^2$ from 0.16 to 0.64) and SDD ($r^2$ from 0.16 to 0.64). Ultimately, TSI had the best fit and was a better predictor of yield under the conditions tested. Neither the number of bolls per plant nor fruit retention were significantly correlated with any of the indices studied.

## INTRODUCTION

The impact of changes in weather patterns on crop yields are of great concern. Empirical data show evidence of greater intra- and inter-annual rainfall variability, with events becoming fewer but more intense (Allan and Soden, 2008; Heisler-White et al., 2009). This has significantly increased the duration of prolonged dry episodes in several regions of the United States (Groisman and Knight, 2008). Along with changes in rainfall patterns, temperatures in the U.S. are expected to increase as much as 3 to 5 °C on average in the next 100 years, if greenhouse gas emissions continue to grow (MacCracken et al., 2003). While increases in the duration of dry periods may be damaging to crop yields in their own right, Lobell and Asner (2003) have indicated that temperature changes have had a substantial impact on crop yield trends, and that yields may decrease as much as 17% for every °C increase during the growing season.

Among environmental variables, ambient temperature is a major factor determining plant distribution in different geographical locations (Lambers et al., 2008). Depending upon a combination of several morphological and physiological characteristics, plants are adapted to live and survive in a wide range of environments. In terms of crop production, however, survival does not translate into higher yields under high temperatures since different plants usually have a relatively narrow species-specific range of temperature optimum. This optimum temperature range may be represented by the thermal kinetic window (TKW), a term first coined by Mahan et al. (1987) and defined as the temperature range in which the apparent Michaelis constant ($K_m$) remains within 200% of the minimum for optimum enzyme function. The first TKW studies on cotton (*G. hirsutum* L.) reported optimum temperatures ranging from 23.5 to 32 °C, and were based on the activity of glutathione and glyoxylate reductase for nicotinamide adenine dinucleotide (Burke et al., 1988; Mahan et al., 1987). More recently, Burke and Wanjura (2010) indicated that the optimum temperature for enzyme function, germination, flowering, lint production, and root/shoot development of cotton is centered around 28 ± 3 °C.

Cotton often faces ambient temperatures well above the upper threshold of the TKW (31 °C) throughout the season in most growing regions, which is especially true during mid to late season. In cotton, high temperatures have been implicated in decreased flower survival and fruit set (Reddy et al., 1991a), reduced biomass production and abortion of reproductive structures (Reddy et al., 1991b), decreased pollen germination (Kakani et al., 2005), and reduced boll retention (Zhao et al., 2005), all of which are likely to negatively impact final crop yield. Burke et al. (1988) measured canopy temperatures of cotton and wheat (*Triticum aestivum* L.) throughout most of the 1984 season and found that both species were within their respective TKW for less than 30% of the season and that biomass production was related to the time in which the crop canopies remained within the bounds of the TKW. This information led the researchers to suggest that approximately 70% of the season is still available to increase crop production either through improvements in crop management practices or genetics. Furthermore, according to Carmo-Silva et al. (2012) significant decreases in yield and plant productivity may occur if temperatures during the season deviate as little as one or two degrees from the plant's optimum.

Since the mid 1900's researchers have worked to establish useful associations between crop canopy temperature and soil water depletion (Aston and Vanbavel, 1972; Ehrler, 1973), plant water status (Ehrler et al., 1978; Tanner, 1963), selection in plant breeding (Chaudhuri et al., 1986; Gardner et al., 1986; Mckinney et al., 1989; Mtui et al., 1981), photosynthesis (Choudhury, 1986), irrigation scheduling (Jones, 1999; Wanjura and Upchurch, 1997), and yield (Blum et al., 1989; Diaz et al., 1983; Harris et al., 1984; Walker and Hatfield, 1979). Due to its great potential as an important variable contributing to plant performance and ultimately yield, multiple canopy temperature-based stress indices have been developed. The simplest index is known as the canopy temperature depression (CTD), which only accounts for the difference in temperature between the crop canopy and its surrounding air. It is based on the idea that a freely transpiring plant canopy should maintain its temperature below that of the ambient through evaporative cooling. Although water use by plants is a passive process, the large amount of energy required to change water from liquid to gas phase (~ 44 kJ mol$^{-1}$) allows plants to cool themselves.

Following the idea of CTD, Idso et al. (1977) and Jackson et al. (1977) developed the stress degree day (SDD) concept, where they hypothesized not only that crop yield was linearly related to the accumulation of SDD's over a certain critical period during the crop development, but also that the concept could be useful to schedule irrigation and to determine the amount of water needed. The same authors also demonstrated that wheat (*Triticum durum* Desf. var. Produra) yields decreased with increased SDDs (Idso et al., 1977). Later, Idso et al. (1981) and Jackson et al. (1981)

further improved the SDD index to account for environmental variability. Based on experiments by Ehrler (1973) that showed great dependency of the canopy-air temperature differential on the atmospheric vapor pressure deficit (VPD) Idso, Jackson, and colleagues created the crop water stress index (CWSI), which is sometimes referred to as the empirical form of CWSI. A year later Jackson derived what is known today as the analytical form of the CWSI based on the energy balance of a surface (Jackson, 1982). This variation of the CWSI accounts for most of the environmental variables affecting foliage temperature, although according to Gardner et al. (1992) its routine usage is hampered by the difficulty to obtain all the values needed for its calculation.

The thermal stress index (TSI) was developed by Burke et al. (1990) and was based on enzyme kinetics and the concept of a biochemically-derived range of species-specific temperature for optimum enzyme function (TKW). The usefulness of TSI was attributed to the fact that it was positively correlated to CWSI with an $r^2$ of 0.92, and for the simplicity in its calculation (only the canopy temperature is needed) (Burke et al., 1990).

The objective this study was to calculate multiple canopy temperature-based stress indices and compare their association with the final yield of field-grown cotton. Additionally, the correlation of two yield components (number of bolls plant$^{-1}$ and fruit retention) and the stress indices was assessed.

## MATERIALS AND METHODS

### Cultural practices

Field trials were conducted at the Texas A&M AgriLife Field Laboratory in Burleson County (30°33'01.67" N, 96°26'07.07" W), approximately 8 miles west of College Station, TX, on a Weswood silt loam soil (fine-silty, mixed, superactive, thermic, Udifluventic Haplustepts), during the summers of 2012 - 2014. The study area was equipped with a sub-surface drip irrigation system installed at a depth of 45.7 cm, with emitters spaced 45.7 cm apart. Drip lines were spaced at 1.02 m apart and located at the center of each row (i.e. directly under the cotton plants).

Management practices such as fertility, disease prevention, weed and insect control followed the guidelines provided by the Texas A&M AgriLife Extension service for the region. Cotton (*G. hirsutum* L. cv. Phytogen 499 WRF) seeds were sown on April 10 in 2012 and April 09 in 2013 and 2014, at a rate of 108,000 seeds ha$^{-1}$ in northwest to southeast oriented rows, spaced 1.02-m apart. Plant growth regulator applications consisted of a combination of cyclanilide (1-(2,4-dichlorophenylaminocarbonyl)-cyclopropane carboxylic acid; 0.003 kg a.i. ha$^{-1}$) and mepiquat chloride (N,N-dimethylpiperidinium chloride; 0.012 kg a.i. ha$^{-1}$), which were applied as needed during the growing season. Harvest aids were applied when cotton plants exhibited approximately 60-70% open bolls, and consisted of a combination of thidiazuron (*N*-phenyl-*N*-1,2,3-thidiazol-5-ylurea; 0.056 kg a.i. ha$^{-1}$), ethephon (2-chloroethyl phosphonic acid; 1.106 kg a.i. ha$^{-1}$), and cyclanilide (1-(2,4-dichlorophenylaminocarbonyl)-cyclopropane carboxylic acid; 0.069 kg a.i. ha$^{-1}$).

### Experimental design and treatments

The study was arranged as a randomized complete block design. Plots were four rows wide, 9.73-m in length with a 3-m alley in between, and the 2 treatments (dryland and irrigated) were replicated four times. Treatments consisted of two irrigation regimes, namely, dryland (DRY) and irrigated (IRR). Irrigation was arbitrarily set at 80% crop evapotranspiration ($ET_c$) replacement. Amounts were adjusted based on crop stage following guidelines by Fisher and Udeigwe (2012). All plots were fully irrigated until crop establishment approximately 30 days after planting (DAP). Irrigation treatment was then initiated and maintained throughout the season until the crop reached maturity. Irrigated and dryland will be referred to as water regimes throughout the manuscript.

### Canopy temperature

To monitor crop canopy temperatures, one SmartCrop$^{TM}$ (Smartfield Inc., Lubbock, TX) infrared thermometer sensor was installed per plot, approximately half-way into the plots, on the third row, pointing southeast. These infrared sensors are able to measure temperatures between -33 – 220 °C, with an accuracy of ±0.6 °C between wave lengths of 5 – 14 µm. Installation occurred at 42, 59, and 64 days after planting (DAP) in 2012, 2013, and 2014, respectively. Sensors were mounted on a bracket and attached to a 2-m perforated pole. The bracket maintained sensors at a fixed 45° angle from the soil surface and the perforated pole allowed changes in sensor height. To account for crop growth, frequent adjustments in height were made during the growing season to maintain sensors approximately 30 to 40-cm above the crop canopy, which resulted in an approximate 0.5 $m^2$ field of view. Canopy temperature data were automatically collected every minute and a 15 min average was wirelessly transferred to a base station (SmartWeather$^{TM}$), and then automatically uploaded to the CropInsight$^{TM}$ (Smartfield, Inc., Lubbock, TX) website (http://www.cropinsight.com/).

### Weather

Rainfall, ambient temperature, and wind speed data were collected by the SmartWeather$^{TM}$ weather station (Smartfield, Inc., Lubbock, TX), that also serves as a base station to wirelessly gather data from the infrared thermometer sensors. Sensors on the base station were at a fixed 2 m height above the soil surface.

### Plant mapping

Six consecutive plants per plot, with the exception of very small plants, from either one of the outside rows were removed from the field for plant mapping. Data collection and input were handled according to Landivar (1992). Fruit retention was determined according to the procedure described by Landivar et al. (1993) using an Excel version of the PMAP software (Plant Map Analysis Program for Cotton) obtained from Dr. Landivar (J.A. Landivar, personal communication, 2012). Number of bolls per plant and fruit retention values is presented as the average of six plants for each replication.

### Yield

The two center rows were mechanically harvested using a custom 2-row cotton spindle picker, John Deere model 9910 (Deere & Company, Moline, IL). This equipment was modified for small-plot research and allowed yield to be established on a per plot basis. Final crop yield is presented as seedcotton in kilograms per hectare (kg ha$^{-1}$). Yield and seedcotton yield will be used interchangeably throughout the manuscript.

### Stress indices

All canopy temperature and weather data used to calculate stress indices were hourly averages collected every 15 min during the crop's reproductive phase, from 15 June through 15 August at 14:00. These dates represent days of the year (DOY) 167 – 228 and 166 – 227, for 2012 (leap year), and 2013 and 2014 (regular years), respectively. Stress indices are presented as the average value during data collection; except for stress degree day (SDD) which is presented as the sum of the difference between canopy and air temperatures over the same period. Stress indices were calculated as follows:

Canopy temperature (CT)

$$CT = (T_{c1} + T_{c2} + \cdots + T_{cn})/n$$

Where, $T_c$ = canopy temperature in °C, $n$ = number of days or samples, Range: some realistic positive range (e.g. 25 to 45 °C)

Canopy temperature depression (CTD)

$$CTD = T_c - T_a$$

Where, $T_c$ = canopy temperature in °C, $T_a$ = air temperature in °C, Range: some positive to some negative number (usually within ± 10 °C)

Stress degree days (SDD) (Idso et al., 1977; Jackson et al., 1977)

$$SDD = \sum_{n=i}^{N} (T_c - T_a)n$$

Where, $T_c$ = canopy temperature in °C, $T_a$ = air temperature in °C, summed over N days beginning at day *i*, Range: same as CTD, although because it is a sum over a certain period values tend to be a lot larger (positive) or smaller (negative)

Crop water stress index (CWSI) (Idso et al., 1981)

$$CWSI = \frac{(CTD) - T_{nws}}{T_{ws} - T_{nws}}$$

Where, CTD = canopy temperature ($T_c$) in °C - air temperature ($T_a$) in °C, $T_{nws}$ = non-water stressed baseline (function of CDT and atmospheric vapor pressure deficit (VPD)), $T_{ws}$ = water-stressed baseline (equal to the maximum difference between $T_c$ and $T_a$ in °C), Range: from 0 (non-stressed) to 1 (severely stressed)

Idso (1982) developed non-water stressed baselines for several well-watered crops, including cotton, from data collected at the University of Arizona's Cotton Research Center in Phoenix, AZ. However, preliminary analysis showed that his baselines generated CWSI values well below the lower index threshold of 0 for cotton grown in this study. According to Burke et al. (1990), this usually happens in areas with high humidity and VPD < 1.0 kPa due to limitations of CWSI in resolving $T_c$ and $T_a$ differences. Since environmental conditions between Phoenix, AZ and College Station, TX may differ greatly, individual non-stressed baselines ($T_{nws}$) were computed from the irrigated plots for each year based on single day measurements during sunlit hours from 7:00 to 19:00 (Table 3.1). When CWSI values were recalculated with individual $T_{nws}$ very few values exceeded the index thresholds (Fig. 3.2 A, B, and C). Upon inspection of the daily average CWSI values for the dryland plots over the period studied it was observed that values calculated using the $T_{nws}$ provided by Idso (1982) underestimated stress levels, especially at relatively low stress levels (CWSI < ~ 0.2). This trend was accentuated in both humid years (i.e. 2012 and 2014) (Fig. 3.2 A, and C), but was also apparent in the drier 2013 season (Fig. 3.2 B). It is worth noting, however, that while under some stress (i.e. CWSI > ~ 0.2) the $T_{nws}$ published by Idso (1982) also yielded CWSI values that were remarkably similar to those generated by the individual $T_{nws}$ computed for this study, despite being developed for a different region. This was most evident during good portions of 2012 and 2013 (Fig. 3.2 A and B) and the latter part of 2014 (Fig. 3.2 C).

Water-stressed baselines ($T_{ws}$) were determined for each year based on the average maximum difference between $T_c$ of four replications and $T_a$ (from 15 June to 15 August at 14:00). $T_{ws}$ was set as 3.0, 2.25, and 3.3 °C for 2012, 2013, and 2014, respectively.

**Table 3.17.** Non-water stressed baseline equations used to calculate the crop water stress index (CWSI) for each year. For reference, the range of solar radiation (SR) and atmospheric vapor pressure deficit (VPD) are shown for each date when data was collected. Data collected from 7:00 to 19:00 at specified dates.

| Year | Date | SR | VPD | Slope | Intercept | $r^2$ |
|---|---|---|---|---|---|---|
| | | $W\ m^{-2}$ | kPa | | | |
| 2012 | 2-Jul | 82 - 776 | 0.09 - 3.31 | -1.3657 | -1.0885 | 0.92 |
| 2013 | 9-Jul | 80 - 876 | 0.06 - 4.27 | -1.6213 | -0.2519 | 0.98 |
| 2014 | 5-Jul | 32 - 933 | 0.09 - 2.66 | -1.6442 | -0.9331 | 0.90 |

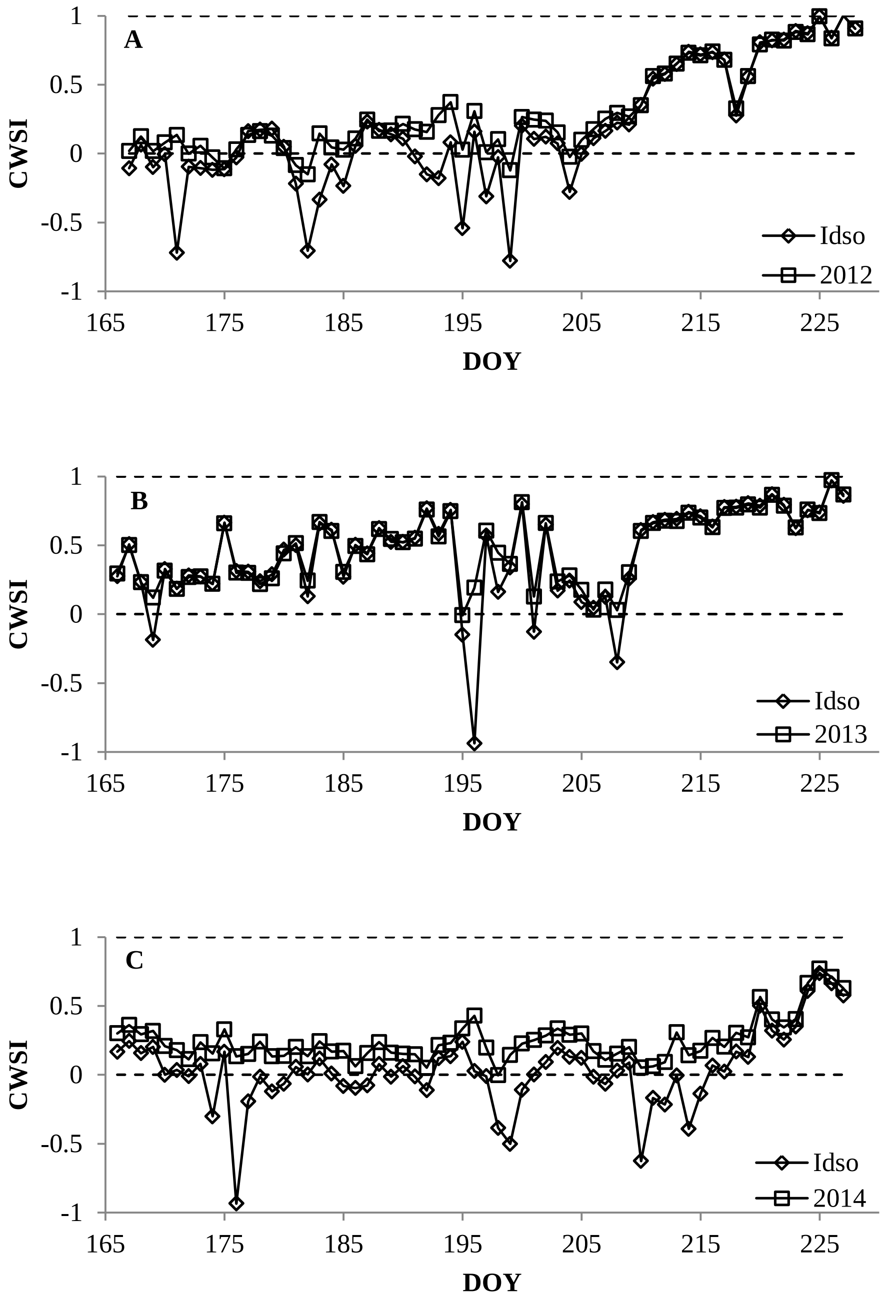

**Figure 3.8.** Dryland crop water stress index (CWSI) comparisons of average (4 replications) daily values at 14:00 for different days of the year (DOY). CWSI were computed for 2012 (A), 2013 (B), and 2014 (C) using the non-water stressed baseline ($T_{nws}$) provided by Idso (1982) and compared to those calculated using $T_{nws}$ developed for each year individually based on data collected at the experimental site. The water-stressed baseline ($T_{ws}$) used was the same for both $T_{nws}$ but based on maximum canopy-air temperature differential for each individual year. Dashed horizontal lines represent the CWSI thresholds (from 0 to 1).

Thermal stress index (TSI) (Burke et al., 1990)

$$TSI = \frac{(T_c > T_b) - T_b}{T_b}$$

Where, $T_c$ = canopy temperature in °C, $T_b$ = biochemically determined baseline temperature for optimum enzyme function (defined for the purpose of this study as the midway point of the TKW for cotton (28 °C)), Range: from 0 (non-stressed) to some positive value (greater number indicating increasing stress). Upper limit is restricted to a thermal stress resulting from the inability of plants to cool due to limiting soil-available water or physical environmental conditions (Burke et al., 1990).

### Statistical analysis

Data were analyzed using JMP Pro, Version 11.0.0 (SAS Institute Inc., Cary, NC). Analysis was performed on combined data over the three different growing seasons. Correlation coefficients were considered significant at the 5% probability level.

## RESULTS AND DISCUSSION

Yearly rainfall totals of 1,270, 998, and 1,045 mm were recorded for 2012, 2013, and 2014, respectively. Within the planting and harvest dates (growing season), rainfall totals were 635, 325, and 502 mm for 2012, 2013, and 2014, respectively. Figure 3.2 shows a graphic representation of the historical rainfall totals as well as within season (April – September) accumulation for the region, from 2000 through 2014. Data for 2012-2014 was collected on site, while data for 2000-2011 was obtained from the National Oceanic and Atmospheric Administration (NOAA) website, which collects data at the Easterwood Airport in College Station, TX, approximately 8 km northeast of the experimental site.

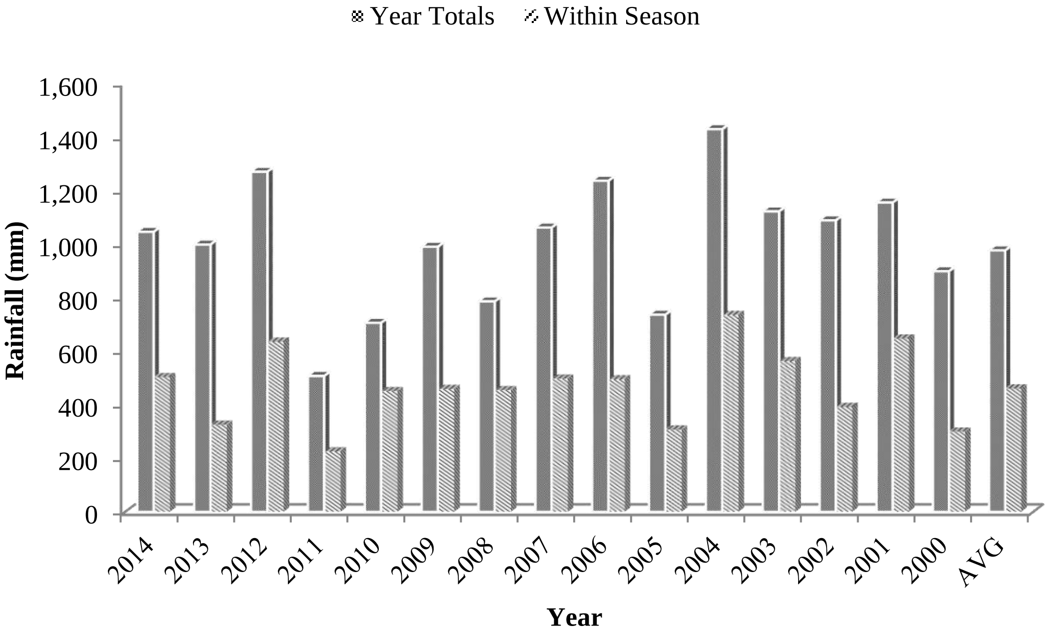

**Figure 3.9.** Figure shows yearly and within season (April through September) rainfall totals for the region. Data for 2012, 2013, and 2014 were collected by a weather station at the experimental site. Historical data for other years (2000-2011) were obtained from the National Oceanic and Atmospheric Administration (NOAA) website (http://www.srh.noaa.gov/hgx/?n=climate_cll_normals_summary), from which the average (AVG) was calculated. Historic data was collected by NOAA at Easterwood airport in College Station, TX, approximately 8 km northeast of the experimental site.

During all three growing seasons there was great potential for high temperature stress. Daily average temperatures were higher than the midway point of the TKW (28 °C) for 83, 76, and 69% of the time in 2012, 2013, and 2014, respectively, whilst the average maximum temperatures were always higher than the upper TKW threshold (31 °C) for cotton during the crop's reproductive phase (Table 3.2). Average atmospheric vapor pressure deficit (VPD) within the same period ranged from 2.2 to 3.5 kPa for 2014 and 2013, respectively, and wind speed averages ranged from 3.4 to 5.3 m $s^{-1}$ for 2012 and 2013, respectively (Table 3.2). Weather-wise 2012 and 2014 could be grouped as having similar humid environmental conditions, while 2013 was a very distinct hot and dry year.

Table 3.3 shows a summary of yield and yield components collected at harvest. Reduced rainfall (also high temperatures and high atmospheric vapor pressure deficit) negatively impacted both seedcotton yield and the number of bolls per plant in 2013 when compared to 2012 and 2014. Fruit retention for dryland plots in 2013 was also affected by environmental conditions and averaged 34 % retention while irrigated plots maintained on average 46 % of the bolls produced (Table 3.3). Average seedcotton yield was higher for irrigated plots than they were for dryland plots in all three years studied. Across the different growing seasons, irrigated cotton had a similar number of bolls per plant, although it was slightly lower during 2013 (approximately 3 fewer bolls per plant). Fruit retention was comparable under irrigation for all three years (Table 3.3). A visual overview of the canopy and ambient temperature data sets used in this study are provided on Figure 3.3.

**Table 3.18.** Summary of weather conditions for 2012 - 2014. Temperature, relative humidity (RH), solar radiation (SR), wind speed (WS), and atmospheric vapor pressure deficit (VPD) are presented as averages from 15 June to 15 August at 14:00. Average daily temperature greater than 28 °C (> TKW) and rainfall are shown from planting to harvest.

| | Temperature[¥] | | | RH | SR | WS | VPD | > TKW | Rainfall |
|---|---|---|---|---|---|---|---|---|---|
| | Avg. | Max. | Min. | % | W $m^{-2}$ | m $s^{-1}$ | kPa | % | mm |
| Year | °C | °C | °C | | | | | | |
| 2012 | 35.7 | 40.8 | 26.9 | 55 | 756 | 3.4 | 2.79 | 83 | 502.9 |
| 2013 | 36.9 | 40.9 | 25.9 | 45 | 700 | 5.3 | 3.54 | 76 | 325.1 |
| 2014 | 34.0 | 38.9 | 25.1 | 61 | 758 | 4.2 | 2.18 | 69 | 635.0 |

[¥] Average (Avg.), maximum (Max.) and minimum (Min.) temperatures

**Table 3.19.** Seedcotton yield (SDCT), number of open bolls per plant, and fruit retention for cotton grown under dryland and irrigated conditions in 2012, 2013, and 2014. Values are shown for each of the four replications (Rep). Average yearly values (Avg.) per irrigation regime are included for reference.

| | | Dryland | | | Irrigated | | |
|---|---|---|---|---|---|---|---|
| Year | Rep | SDCT kg ha$^{-1}$ | Bolls plant$^{-1}$ | Fruit retention % | SDCT kg ha$^{-1}$ | Bolls plant$^{-1}$ | Fruit retention % |
| 2012 | 1 | 4505.2 | 13.0 | 40.7 | 5397.1 | 15.7 | 44.0 |
| | 2 | 4333.7 | 13.0 | 44.5 | 4665.3 | 13.2 | 39.1 |
| | 3 | 4093.6 | 13.3 | 47.2 | 4939.7 | 16.7 | 43.5 |
| | 4 | 4699.6 | 14.2 | 47.4 | 5545.7 | 14.5 | 49.6 |
| | Avg. | 4408.0 | 13.4 | 45.0 | 5136.9 | 15.0 | 44.1 |
| 2013 | 1 | 2298.3 | 7.5 | 36.7 | 3453.2 | 12.5 | 47.3 |
| | 2 | 2275.5 | 7.5 | 27.6 | 3704.8 | 13.2 | 42.6 |
| | 3 | 2938.7 | 8.5 | 40.4 | 3716.2 | 11.2 | 49.3 |
| | 4 | 2344.1 | 8.3 | 30.6 | 4265.1 | 9.7 | 43.5 |
| | Avg. | 2464.1 | 8.0 | 33.8 | 3784.8 | 11.6 | 45.7 |
| 2014 | 1 | 4836.8 | 17.3 | 56.5 | 5625.8 | 14.7 | 48.4 |
| | 2 | 5088.4 | 11.2 | 49.9 | 4974.0 | 11.5 | 47.1 |
| | 3 | 5305.6 | 17.3 | 51.7 | 5088.4 | 12.3 | 33.6 |
| | 4 | 4185.0 | 13.3 | 48.4 | 5637.2 | 19.8 | 47.4 |
| | Avg. | 4853.9 | 14.8 | 51.6 | 5331.3 | 14.6 | 44.1 |

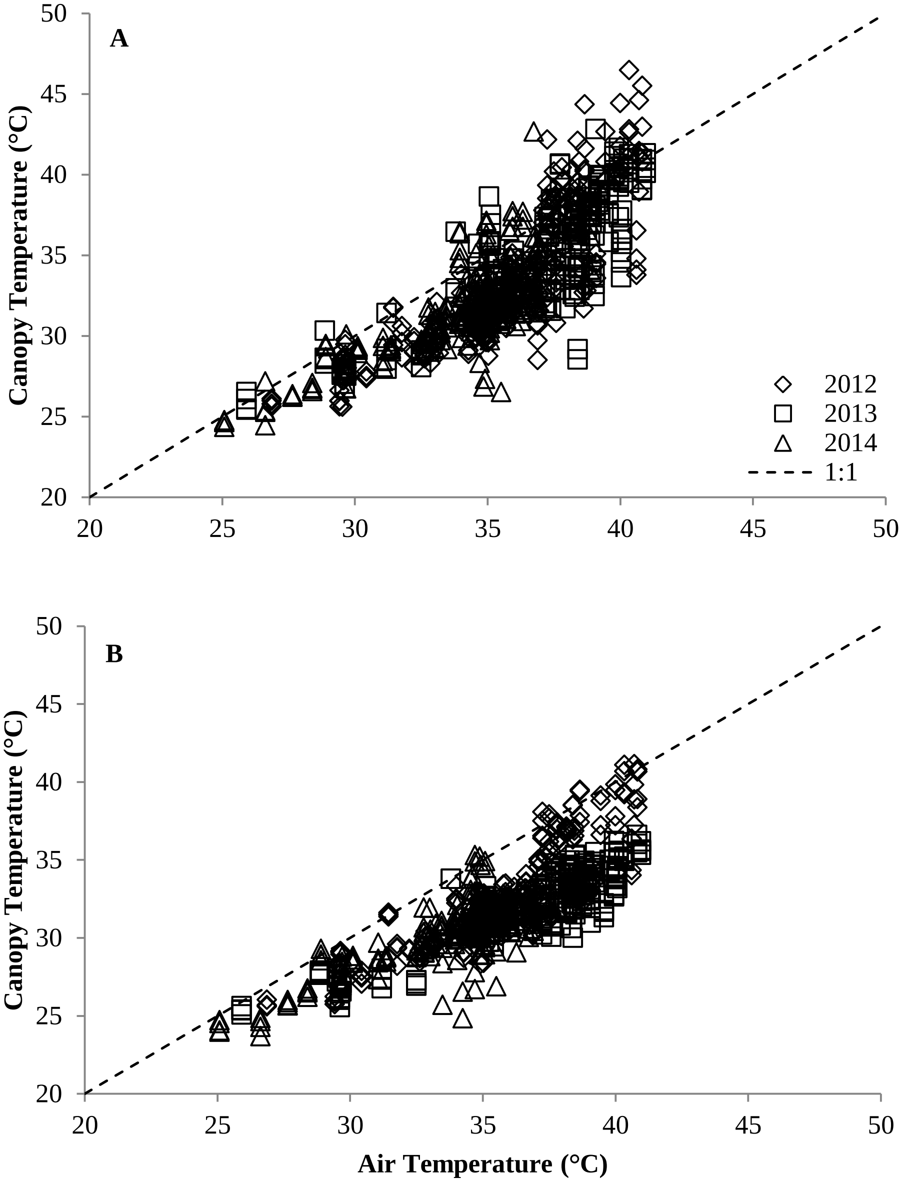

**Figure 3.10.** Visual overview of canopy and ambient temperature data used for the study collected from dryland (A) and irrigated (B) cotton. Data were collected during the crop's reproductive phase (from 15 June through 15 August at 14:00).

All indices performed reasonably well in distinguishing stress levels between dryland (DRY) and irrigated (IRR) plots. There were two instances where stress levels between the irrigation regimes were clearly different (first occurring between DOY 185 and 195 and second after DOY 208), which happened consistently during the different seasons (Figs. 3.4, 3.5, and 3.6).

In 2012, canopy temperatures of both DRY and IRR plots fluctuated between 25 and 35 °C until DOY 210, after which point CT slowly increased over the next two weeks reaching temperatures as high as 39 and 43 °C for IRR and DRY, respectively by DOY 227 (Fig. 3.4 A). During 2013 the IRR cotton stayed within a relatively narrow range of CT (30 – 35 °C) for most of the time while the dryland crop CT was noticeably warmer (usually between 30 – 40 °C). Differences in CTs were apparent starting at DOY 179 (Fig. 3.5 A).

Across different years, 2014 was the most humid. Within the period studied there was a rainfall acumulation of 263 mm, compared to 190 and 89 for 2012 and 2013, respectively. Further, rainfall events were both significant (i.e. usually > 25 mm) and well distributed in 2014, which helped maintain CTs within 25 – 35 °C for most of the time (Fig. 3.6 A).

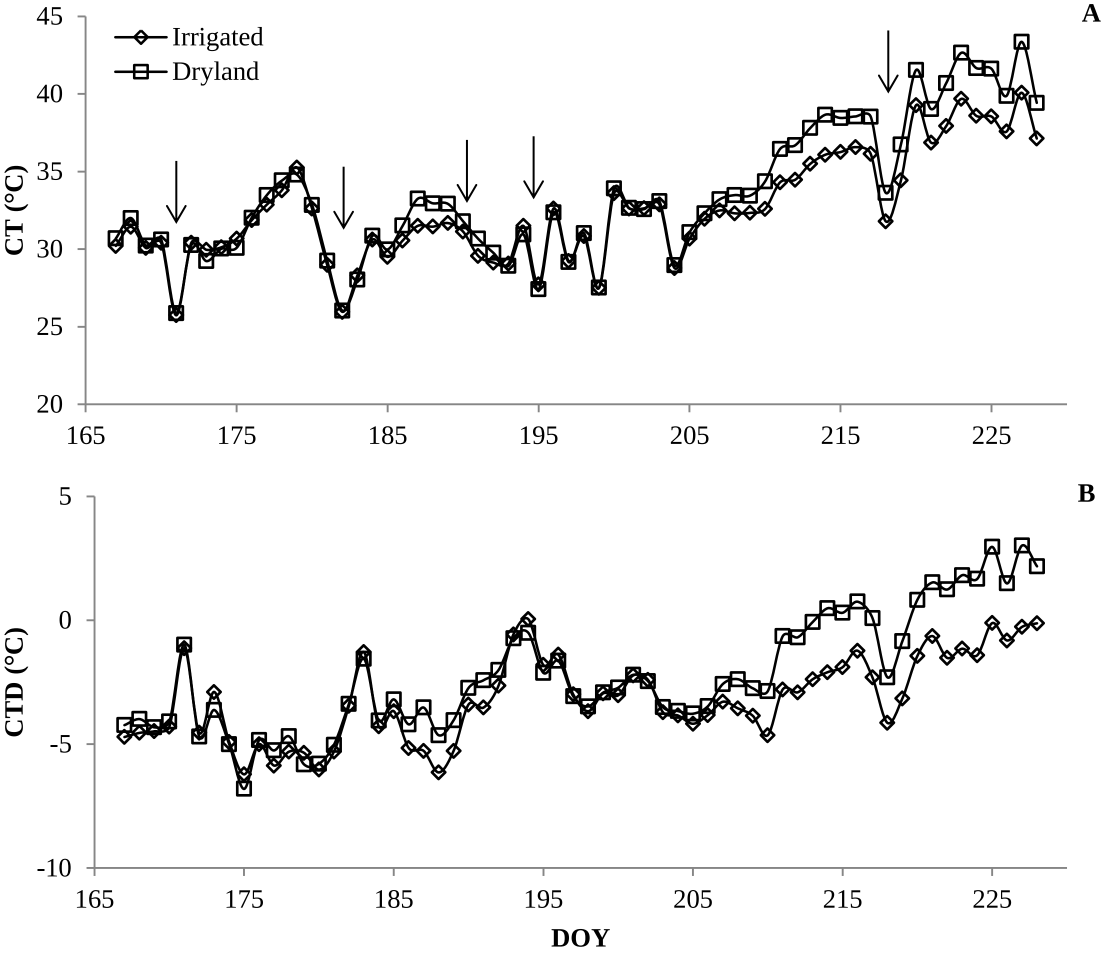

**Figure 3.11.** Comparison of stress levels between dryland and irrigated cotton grown in 2012 as measured by canopy temperature (CT; A), canopy temperature depression (CTD; B), stress degree days (SDD; C), thermal stress index (TSI; D), and crop water stress index (CWSI; E). Values are presented as the average of four replications (at 14:00) between days of the year (DOY) 167 and 228. In days where canopy temperature was lower than 28 °C TSI values were changed to zero for graphing purposes. Down-pointing arrows indicate a rainfall event. From left to right arrows represent DOY 171-172, 182-183, 190-193, 195-200, and 218-223 with rainfall totals of 35.5, 3.6, 57.9, 81, and 11.7 mm, respectively. For clarity rainfall events are shown on figure (A) but omitted on others (B, C, D, and E). Legend shown on figure (A) is the same for others (B, C, D, and E).

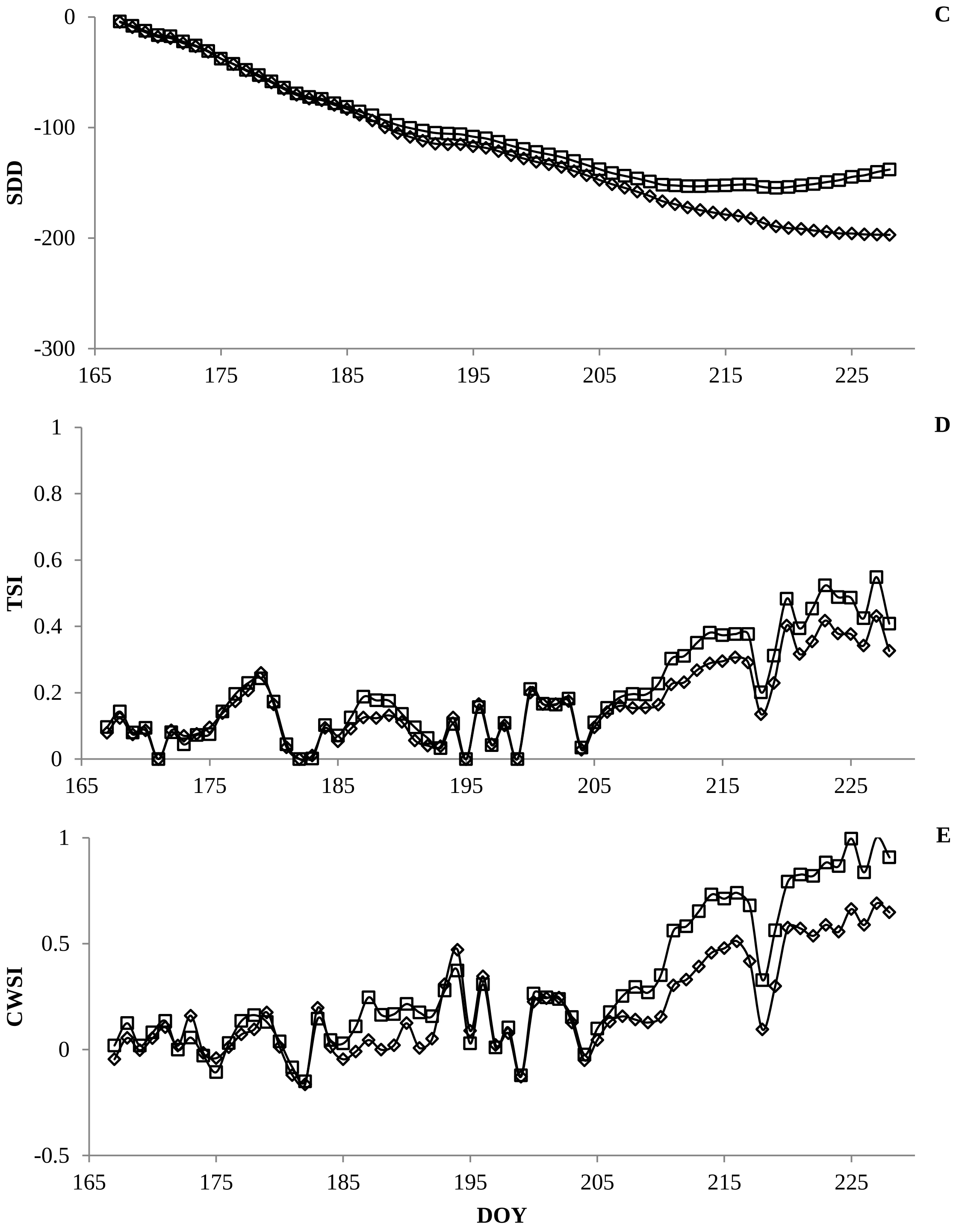

**Figure 3.11.** Continued.

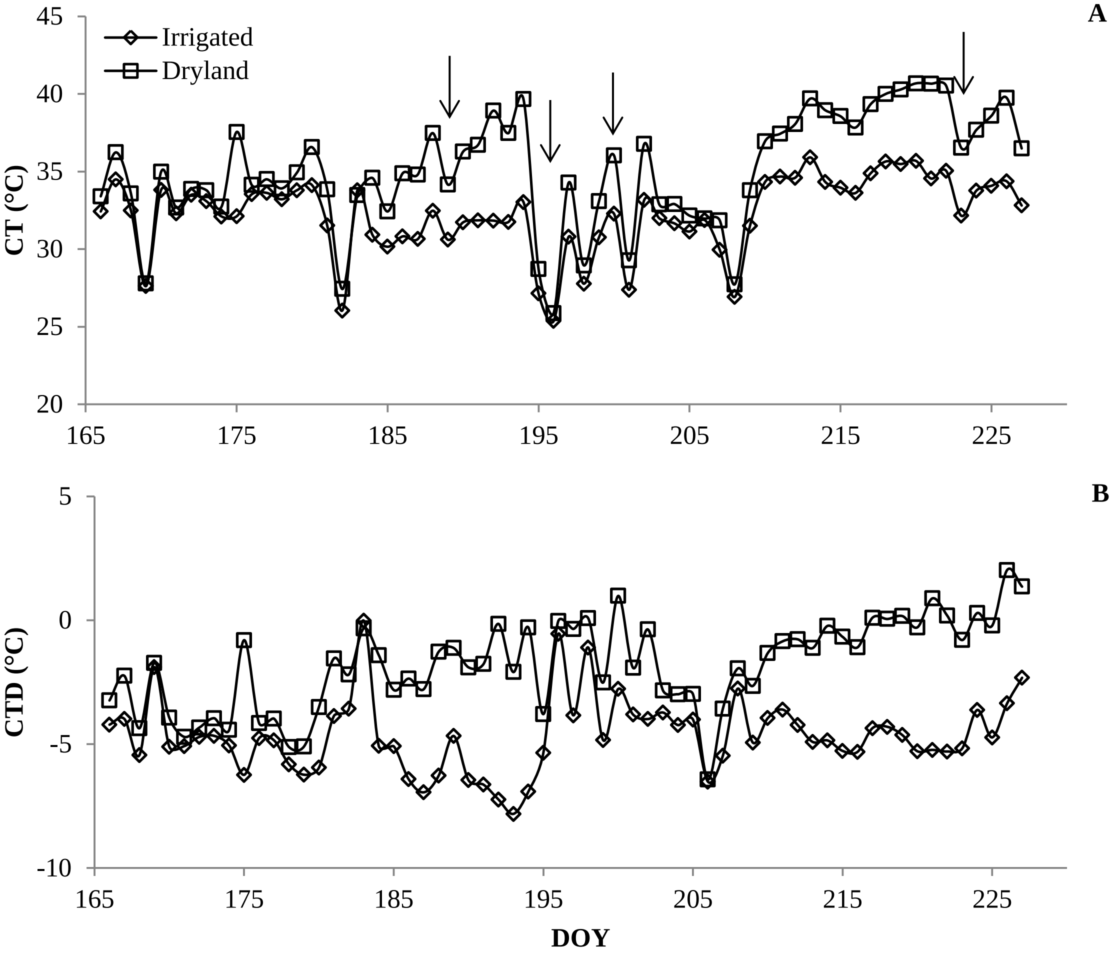

**Figure 3.12.** Comparison of stress levels between dryland and irrigated cotton grown in 2013 as measured by canopy temperature (CT; A), canopy temperature depression (CTD; B), stress degree days (SDD; C), thermal stress index (TSI; D), and crop water stress index (CWSI; E). Values are presented as the average of four replications (at 14:00) between days of the year (DOY) 166 and 227. In days where canopy temperature was lower than 28 °C TSI values were changed to zero for graphing purposes. Down-pointing arrows indicate a rainfall event. From left to right arrows represent DOY 189, 196-197, 200-201, and 223-227 with rainfall totals of 2.8, 37.1, 25.9, and 22.9 mm, respectively. For clarity rainfall events are shown on figure (A) but omitted on others (B, C, D, and E). Legend shown on figure (A) is the same for others (B, C, D, and E).

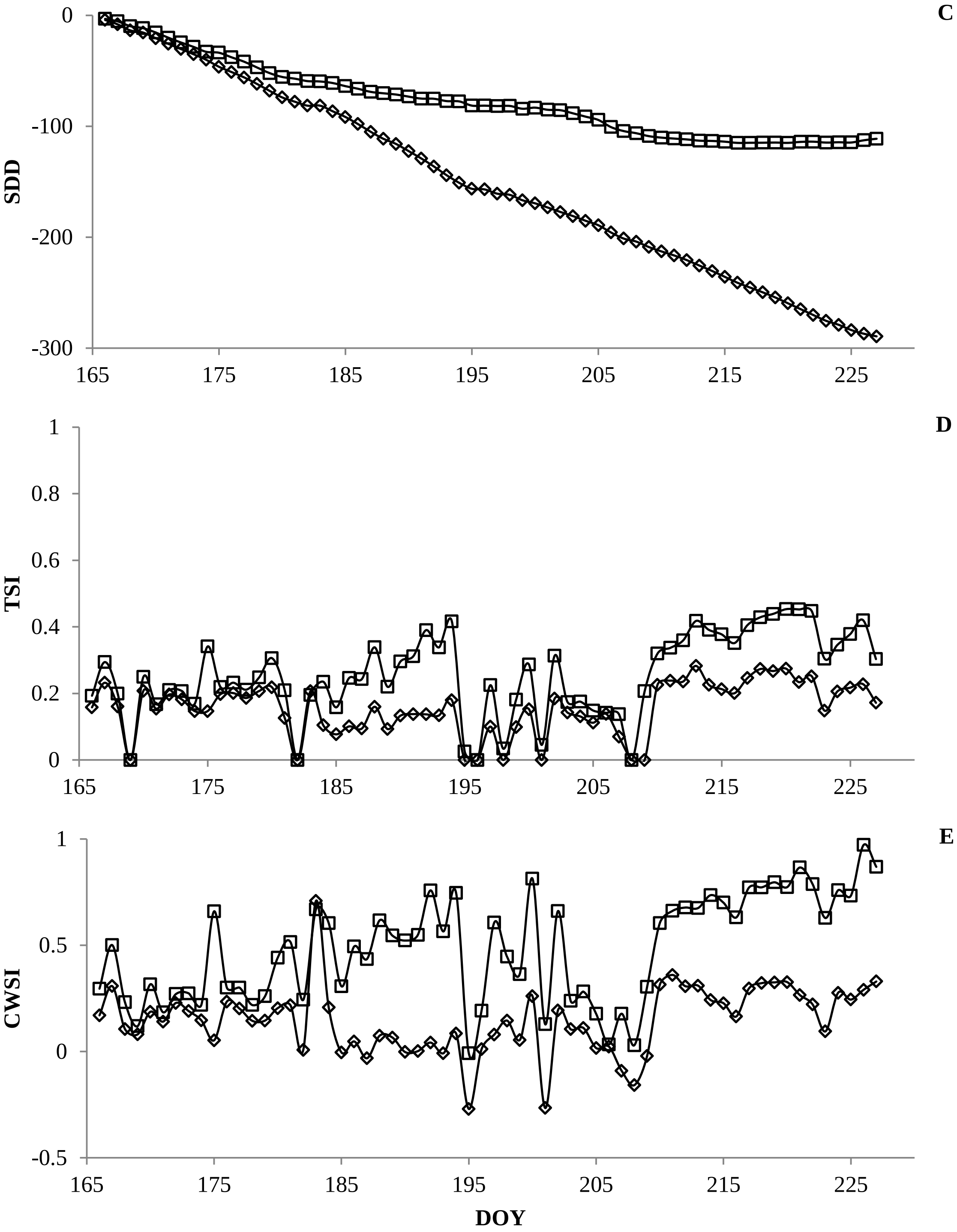

**Figure 3.12.** Continued.

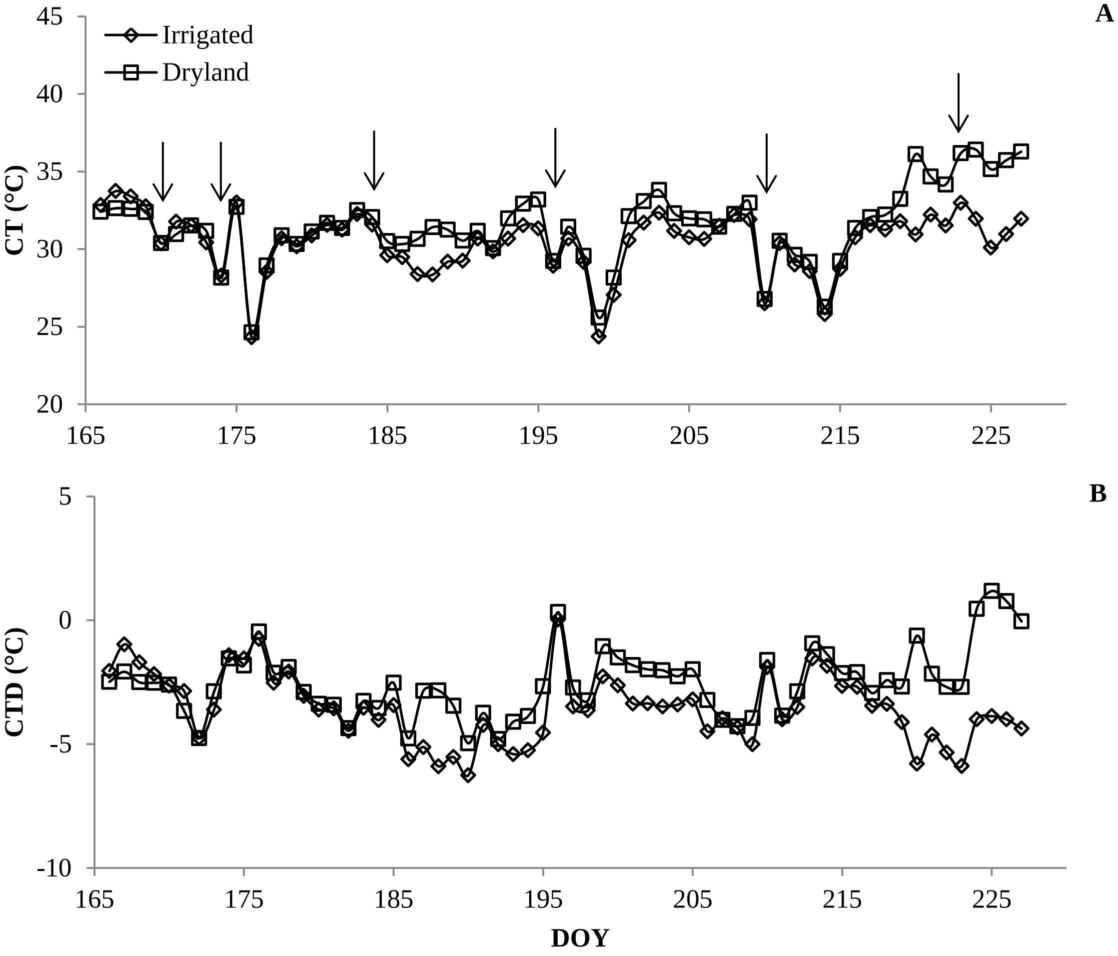

**Figure 3.13.** Comparison of stress levels between dryland and irrigated cotton grown in 2014 as measured by canopy temperature (CT; A), canopy temperature depression (CTD; B), stress degree days (SDD; C), thermal stress index (TSI; D), and crop water stress index (CWSI; E). Values are presented as the average of four replications (at 14:00) between days of the year (DOY) 166 and 227. In days where canopy temperature was lower than 28 °C TSI values were changed to zero for graphing purposes. Down-pointing arrows indicate a rainfall event. From left to right arrows represent DOY 170, 174-179, 184-187, 196-199, 210-216, and 223 with rainfall totals of 17.8, 52.1, 29.5, 111.2, 39.9, and 12.7 mm, respectively. For clarity rainfall events are shown on figure (A) but omitted on others (B, C, D, and E). Legend shown on figure (A) is the same for others (B, C, D, and E).

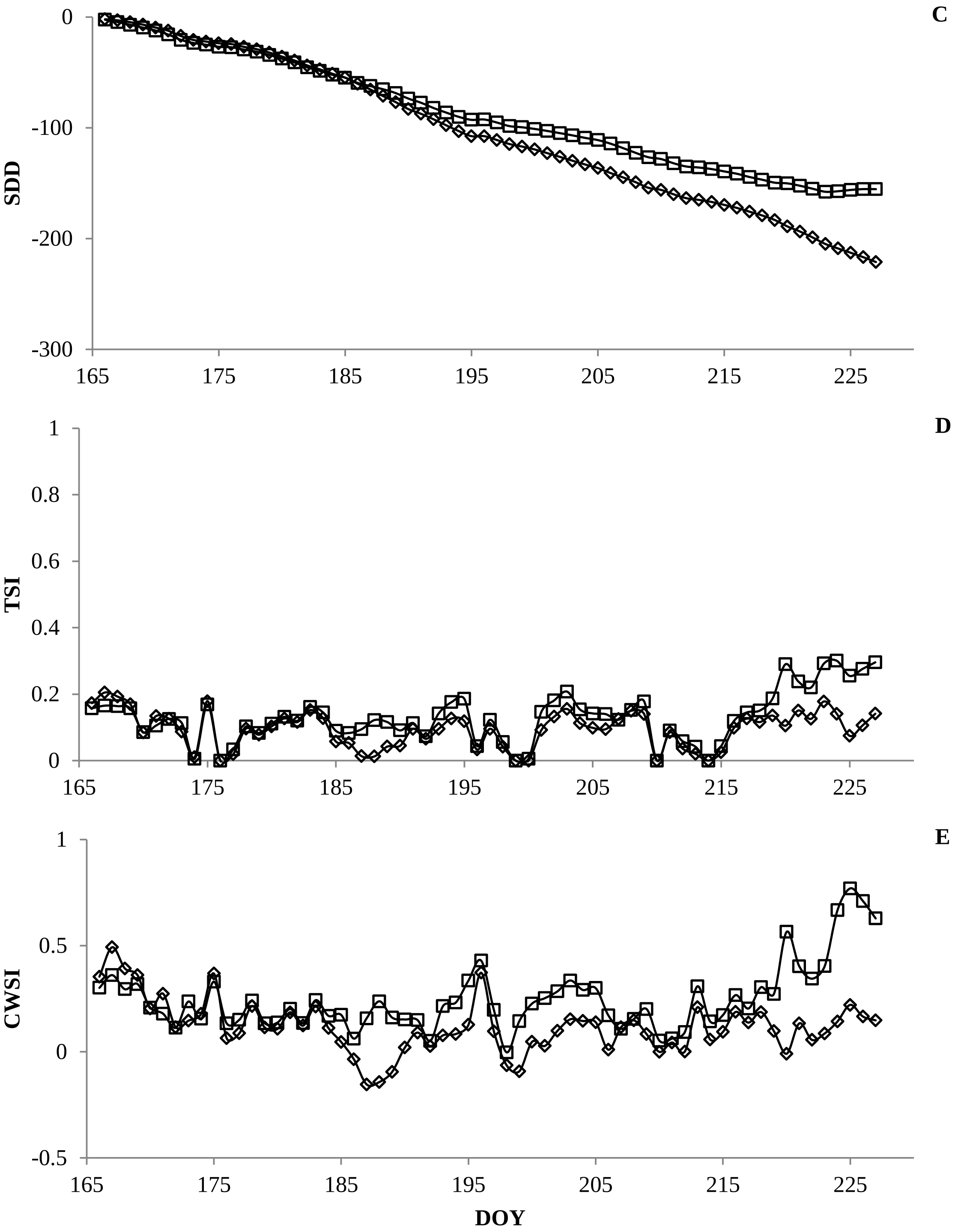

**Figure 3.13.** Continued.

Temperatures of dryland plots were consistently higher than the ambient temperatures only towards the latter part of the season. During the period studied canopy temperature depression showed that both DRY and IRR cotton CTs stayed well below air temperature longer than they did otherwise (i.e. warmer than the air) (Figs. 3.4 B, 3.5 B, and 3.6 B). As a result, the acumulated stress degree day (SDD) over the whole period was negative during the three different seasons. Irrigated plots always had a lower accumulated SDD (more negative) when compared to DRY plots. At the last day of measurements the differences were 59, 178, and 66 SDD for 2012, 2013, and 2014, respectively (Figs. 3.4 C, 3.5 C, and 3.6 C).

The biochemically-based TSI indicated that both IRR and DRY CTs were below the midway point of the TKW (28 °C) in five occasions (DOY 171, 182, 183, 195, and 199) during 2012 (Fig. 3.4 D). In 2013 there were eight days (DOY 169, 182, 195, 196, 198, 201, 209, and 209) when CT of IRR plots were below 28 °C compared to four days for the DRY crop (DOY 169, 182, 196, and 209) (Fig. 3.5 D). During 2014 both IRR and DRY plots stayed at TSI values below 0.3 throughout the days measured. Canopy temperatures of IRR and DRY plots were below 28 °C in five (DOY 176, 199, 200, 210, and 214) and four (DOY 176, 199, 210, and 214) days, respectively (Fig. 3.6 D).

Crop water stress index values suggested that both DRY and IRR plots in 2012 experienced moderate to low levels of stress (CWSI < 0.5) prior to DOY 210. Post DOY 210 CWSI values steadily increased reaching a maximum of 0.99 and 0.69 for DRY and IRR, respectively, on the last few days of measurements (Fig. 3.4 E). In 2013, rainfall and irrigation maintained the IRR cotton at CWSI < 0.4 throughout the period studied while the DRY cotton experienced consistent CWSI higher than 0.4 as early as DOY 180. Similar to what happened in 2012 there was also a trend of increasing CWSI values towards the latter part of 2013, particularly evident on DRY plots (Fig. 3.5 E). The pattern in 2014 was similar to that of 2012. The IRR cotton stayed below CWSI values of 0.5 throughout the whole period whereas the DRY plots experienced CWSI values greater than 0.5 in five different days (DOY 220 and from 224 to 227) during the last week of measurements (Fig. 3.6 E).

The relationships between final seedcotton yield and canopy temperature (CT), canopy temperature depression (CTD), stress degree day (SDD), thermal stress index (TSI), and crop water stress index (CWSI) are shown in Fig. 3.7, with their regressions and respective coefficients detailed in Table 3.4. Within individual years all indices performed similarly since no big differences in $r^2$ values were found between them (Table 3.4). Significant positive correlations among all indices tested were found (Table 3.5).

There appears to be no relationship between CTD and yield ($r^2$ = 0.16) or SDD and yield ($r^2$ = 0.16) when data were combined, despite fairly good linear relationships for individual years (Figs. 3.7 B and C, Table 3.4). Correlations between CT and CTD with yield were also non-significant (Table 3.5). The 2013 data did not follow the same linear pattern as 2012 and 2014 (Fig. 3.7 B, C). Interesting to note that slopes for all three regressions were similar among years, but intercepts were different (Table 3.4).

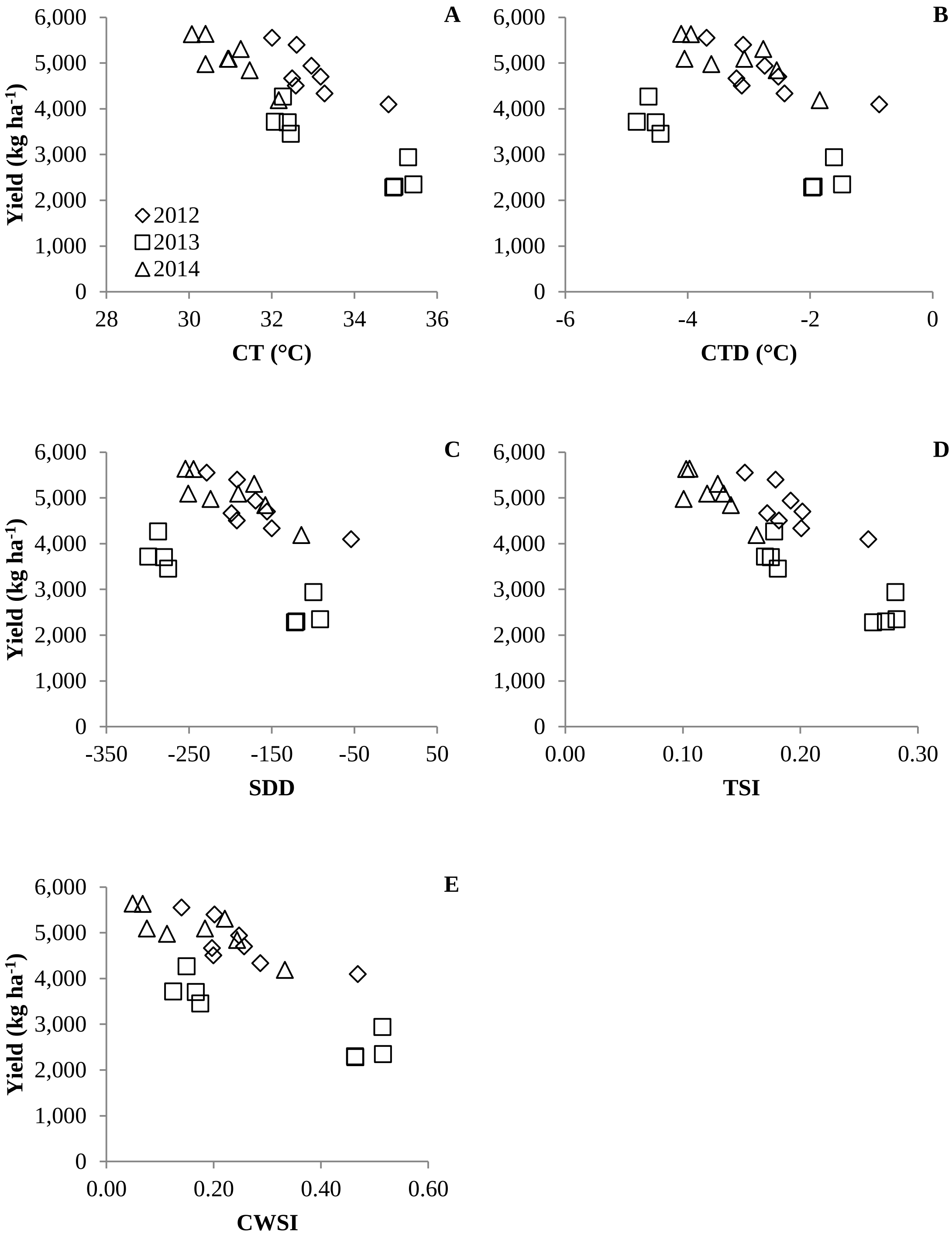

**Figure 3.14.** Relationship between seedcotton yield (Yield) and canopy temperature (CT; A), canopy temperature depression (CTD; B), stress degree day (SDD; C), thermal stress index (TSI; D), and crop water stress index (CWSI; E) for cotton grown under dryland and irrigated conditions.

**Table 3.20.** Regression coefficients relating seedcotton yield and canopy temperature (CT), canopy temperature depression (CTD), stress degree day (SDD), thermal stress index (TSI), and crop water stress index (CWSI) for cotton grown under dryland and irrigated conditions. Slope, intercept, and $r^2$ values are shown for each year individually (2012-2014), 2012 and 2014 combined (2012 + 2014), as well as all three years combined.

| | 2012 | | | 2013 | | |
|---|---|---|---|---|---|---|
| | Slope | Intercept | $r^2$ | Slope | Intercept | $r^2$ |
| Yield | | | | | | |
| CT | -444.5 | 19438.0 | 0.56 | -451.7 | 18362.0 | 0.82 |
| CTD | -444.5 | 3571.3 | 0.56 | -451.7 | 1690.0 | 0.82 |
| SDD | -7.2 | 3568.8 | 0.57 | -7.3 | 1690.3 | 0.82 |
| TSI | -12333.0 | 7145.0 | 0.58 | -12956.0 | 6042.8 | 0.80 |
| CWSI | -3788.6 | 5719.0 | 0.56 | -3823.6 | 4354.8 | 0.81 |

| | 2014 | | | 2012 + 2014 | | |
|---|---|---|---|---|---|---|
| | Slope | Intercept | $r^2$ | Slope | Intercept | $r^2$ |
| Yield | | | | | | |
| CT | -582.2 | 23115.0 | 0.72 | -270.4 | 13581 | 0.49 |
| CTD | -452.9 | 3625.4 | 0.63 | -464.1 | 3553.6 | 0.64 |
| SDD | -7.3 | 3624.8 | 0.63 | -7.5 | 3552.3 | 0.64 |
| TSI | -17404.0 | 7268.2 | 0.65 | -8029.9 | 6206.8 | 0.49 |
| CWSI | -3775.6 | 5699.8 | 0.66 | -3747.7 | 5702 | 0.65 |

| | Combined | | |
|---|---|---|---|
| | Slope | Intercept | $r^2$ |
| Yield | | | |
| CT | -537.9 | 21846.0 | 0.66 |
| CTD | -382.0 | 3168.9 | 0.16 |
| SDD | -6.2 | 3169.8 | 0.16 |
| TSI | -15712.0 | 7171.8 | 0.70 |
| CWSI | -5583.0 | 5692.9 | 0.58 |

**Table 3.21.** Correlation coefficient for seedcotton yield (SDCT), number of bolls per plant (BOLLS), and fruit retention (FR) with different stress indices. Canopy temperature (CT), canopy temperature depression (CTD), stress degree day (SDD), thermal stress index (TSI), and crop water stress index (CWSI). Correlation coefficients were calculated based on combined data over the three years studied (2012 – 2014). * represents significance at the 5% probability level.

| | CT | CTD | SDD | TSI | CWSI |
|---|---|---|---|---|---|
| SDCT | -0.814* | -0.400 | -0.400 | -0.836* | -0.764* |
| BOLLS | 0.252 | -0.123 | -0.123 | 0.285 | 0.094 |
| FR | 0.178 | -0.268 | -0.269 | 0.188 | -0.044 |
| CT | | 0.689* | 0.689* | 0.996* | 0.915* |
| CTD | | | 1* | 0.657* | 0.878* |
| SDD | | | | 0.657* | 0.878* |
| TSI | | | | | 0.903* |

Although higher yields were generally found with increased CTD and SDD (more negative) and lower yields with less negative values, the drier environmental conditions in 2013 and the irrigation regime created two distinct clusters of data clearly separated from 2012 and 2014, with no data points lying in between (Figs. 3.7 B and 3.7 C). This also led to high $r^2$ (0.82) for the relationships between yield and CTD and yield and SDD when the 2013 data were analyzed individually. In fact, high $r^2$ values were also found for CT (0.82), TSI (0.80), and CWSI (0.81) in 2013 and may also be attributed to the dry conditions and irrigation regime effect on the data distribution (Figs. 3.7 A, D, and E, Table 3.4).

Based on the distribution and analysis of the 2012 and 2014 data separately, one might assume that data points from gradual changes in irrigation levels during a dry year could possibly fall between the two clusters (i.e. same line) created by the dryland and irrigated regimes in 2013. However, it is important that any assumptions and/or interpretations based on the 2013 data alone be made with extreme caution. It is impossible to predict based on the data presented here, whether additional data pairs (e.g. yield and CTD or yield and SDD) from multiple years with contrasting environmental conditions would all fall within the same combined line (with a larger scatter) or if data points would fall within the 2013 line, creating different relationships between yield and CTD and yield and SDD for a dry environment compared to a humid one.

Canopy temperature (CT) and TSI do not directly account for year-to-year environmental variability (i.e. no environmental variables are used in their calculations).

Both had negative relationships with yield and good fit, $r^2$ 0.66 and 0.77 for CT and TSI, respectively (Fig. 3.7 A and E, Table 3.4). Correlations between the two (CT and TSI) with yield were significant (Table 3.5). CWSI was also significantly correlated with yield (Table 3.5), although regression showed the fit was lower ($r^2$ = 0.58) when compared to those of CT and TSI (Table 3.4). The difference between indices accounting for environmental variation across growing seasons (CTD, SDD, and CWSI) and those not accounting for such variability (CT and TSI) was clear. CTD and SDD in particular showed substantial differences between the humid (2012 and 2014) and dry (2013) years (Fig. 3.7 B, C). To a lesser extent, this pattern was also apparent for CWSI (Fig. 3.7 E). CT and TSI, on the other hand, showed almost no distinction between inter-annual weather variability and data points from both humid and dry years fell roughly within the same line (Fig. 3.7 A, D).

By removing the distinct (weather-wise) 2013 season from the regression analysis, there was an apparent improvement in fit for CTD ($r^2$ from 0.16 to 0.64), SDD ($r^2$ from 0.16 to 0.64), and CWSI ($r^2$ from 0.58 to 0.65) (Table 3.4), all of which directly account for some year-to-year differences in environmental conditions on their calculations (e.g. air temperature for CTD and SDD, air temperature and atmospheric vapor pressure deficit for CWSI). This suggests that if those indices (CTD, SDD, and CWSI) are used to associate yield losses to stress levels, one should interpret results with caution, particularly in locations where great inter-annual weather variability may occur. Conversely, removal of the 2013 data from the regression analysis decreased by ~ 17 and 21 %, respectively, the amount of variability accounted for by the CT and TSI models (Table 3.4), suggesting that these relationships are stronger across growing seasons with weather differences.

It has been demonstrated that the number of bolls (per unit area) is the major variable contributing to cotton yield (Gerik et al., 1996; Pettigrew, 2004). This variable was indirectly assessed through plant mapping by using the number of bolls plant$^{-1}$ and final fruit retention values collected just prior to the mechanical harvest of experimental plots. In a study conducted at Maricopa, AZ in 1992, Radin et al. (1994) mapped plants of an $F_3$ Pima cotton (*Gossypium barbadense* L.) population selected solely for stomatal conductance and reported a negative relationship between leaf temperature and the number of fruits set during the hottest part of the summer (mid-June to mid-August). Correlation analysis of data collected for this study showed that neither number of bolls plant$^{-1}$ nor final fruit retention were significantly correlated to any of the indices studied (Table 3.5). It is important to note here significant differences between the two studies (e.g. location, environment, boll set during hottest part of the summer vs. boll set during the whole season). Moreover, the inherent differences between *G. hirsutum* and *G. barbasense*, in particular those regarding heat adaptation (Ehleringer and Hammond, 1987; Lu et al., 1997), physiology (Lu et al., 1997; Wise et al., 2000), leaf morphology (Wise et al., 2000), and yield (Lu et al., 1997; Unruh and Silvertooth, 1996) hinder a direct comparison between the contrasting results.

## CONCLUSIONS

Data showed that the non-water stressed regression ($T_{nws}$) developed in Arizona to calculate CWSI was inappropriate for use in central Texas since it tended to underestimate stress levels. Correlation and regression analyses showed significant negative relationships between yield and CT ($r^2 = 0.66$), yield and TSI ($r^2 = 0.70$), and yield and CWSI ($r^2 = 0.58$). CTD and SDD were not significantly correlated with yield and the fit for the regression analysis was poor ($r^2 = 0.16$ for both). In 2013 the dry environment and irrigation regimes created two distinct clusters of data, leading to high $r^2$ values (> 0.80) for all indices tested. Removal of the 2013 season from the regression analysis substantially improved fit for CTD ($r^2$ from 0.16 to 0.64), and SDD ($r^2$ from 0.16 to 0.64), while only a marginal improvement for CWSI was observed ($r^2$ from 0.58 to 0.65). Conversely, CT and TSI models decreased by ~ 17 and 21 %, respectively, the amount of variability accounted for by removing the 2013 data. Ultimately, TSI performed better under the conditions tested and had the best fit. Also, TSI is very simple and only requires measurements of canopy temperatures.

When associating potential yield losses to stress levels, evidence suggests that interpretation of yield and CTD, SDD, and CWSI models should be made with caution when prominent year-to-year environmental variability is likely to occur (or have occurred). Further, despite significant relationships of yield with CT, TSI, and CWSI, yield components (number of bolls plant$^{-1}$ and fruit retention) were not significantly correlated to any of the stress indices studied.

# CHAPTER IV

# CONCLUSIONS

Conclusions of this study are:

1. Effects of 1-MCP on the physiology and morphology of field grown cotton are inconsistent within and between different growing seasons.

2. Plant canopy temperature, net photosynthesis, transpiration, and photosystem II quantum yield are only affected by 1-MCP treatment when the crop is irrigated. Under dryland conditions 1-MCP had no effect on any of the physiological parameters measured.

3. Changes in plant morphology due to 1-MCP treatment occurring during mid and peak reproductive stages are mostly undetectable by harvest. This is applicable to both positive and negative effects and indicates a rather transient effect of 1-MCP.

5. Pre-dawn leaf water potential is not affected by 1-MCP applications (neither positively, nor negatively) despite evidence on the literature of 1-MCP-induced decreases in stomatal conductance and midday leaf water potential.

6. 1-MCP causes only minor changes on fiber quality parameters. No impact on fiber value is expected.

7. 1-MCP treatment does not cause an increase in final seedcotton yield under the conditions tested, regardless of the temperature used to trigger applications.

8. The non-water stressed regression ($T_{nws}$) developed in Arizona by Idso (1982) to calculate crop water stress index is inappropriate for use in central Texas because it tends to underestimate stress levels for this location.

9. Canopy temperature (CT), canopy temperature depression (CTD), stress degree day (SDD), crop water stress index (CWSI), and thermal stress index (TSI) perform similarly in predicting crop yield within individual years.

10. CT, TSI and CWSI have a negative relationship with final seedcotton yield despite year-to-year environmental variability.

11. The interpretation of CTD, SDD, and CWSI should be made with caution in locations where great inter-annual weather variability may occur. The evidence suggests that these models are particularly sensitive to environmental conditions.

12. Due to its simplicity and better overall performance TSI is the superior index to predict cotton yield at this location.

# REFERENCES

Abeles, F.B. and G.R. Leather. 1971. Abscission: control of cellulase secretion by ethylene. Planta 97: 87-91.

Allan, R.P. and B.J. Soden. 2008. Atmospheric warming and the amplification of precipitation extremes. Science 321: 1481-1484.

Aston, A.R. and C.H. Vanbavel. 1972. Soil surface water depletion and leaf temperature. Agron. J. 64: 368-373.

Bapat, V.A., P.K. Trivedi, A. Ghosh, V.A. Sane, T.R. Ganapathi and P. Nath. 2010. Ripening of fleshy fruit: molecular insight and the role of ethylene. Biotechnol Adv 28: 94-107.

Bauer, P.J., J.R. Frederick, J.M. Bradow, E.J. Sadler and D.E. Evans. 2000. Canopy photosynthesis and fiber properties of normal- and late-planted cotton. Agron. J. 92: 518-523.

Blankenship, S.M. 2003. Discovery and commercialization of 1-methylcyclopropene as an ethylene inhibitor. Issues and Advances in Postharvest Horticulture, Vols 1 and 2: 189-191.

Blankenship, S.M. and J.M. Dole. 2003. 1-methylcyclopropene: a review. Postharvest Biol Tec 28: 1-25.

Bleecker, A.B. 1999. Ethylene perception and signaling: an evolutionary perspective. Trends Plant Sci. 4: 269-274.

Blum, A., L. Shpiler, G. Golan and J. Mayer. 1989. Yield stability and canopy temperature of wheat genotypes under drought-stress. Field Crop. Res. 22: 289-296.

Boquet, D.J., R.L. Hutchinson and G.A. Breitenbeck. 2004. Long-term tillage, cover crop, and nitrogen rate effects on cotton: Plant growth and yield components. Agron. J. 96: 1443-1452.

Boyer, J.S. 1982. Plant productivity and environment. Science 218: 443-448.

Burke, J.J., J.L. Hatfield and D.F. Wanjura. 1990. A thermal-stress index for cotton. Agron. J. 82: 526-530.

Burke, J.J., J.R. Mahan and J.L. Hatfield. 1988. Crop-specific thermal kinetic windows in relation to wheat and cotton biomass production. Agron. J. 80: 553-556.

Burke, J.J. and M.J. Oliver. 1993. Optimal thermal environments for plant metabolic processes (Cucumis-Sativus L) - light-harvesting chlorophyll-a/b pigment-protein complex of photosystem-ii and seedling establishment in cucumber. Plant Physiol. 102: 295-302.

Burke, J.J. and D.R. Upchurch. 1989. Leaf temperature and transpirational control in cotton. Environ. Exp. Bot. 29: 487-492.

Burke, J.J. and D.F. Wanjura. 2010. Plant responses to temperature extremes. *In*: J. M. Stewart et al. (ed.), Physiology of cotton. Springer Netherlands. p. 123-128.

Carmo-Silva, A.E., M.A. Gore, P. Andrade-Sanchez, A.N. French, D.J. Hunsaker and M.E. Salvucci. 2012. Decreased $CO_2$ availability and inactivation of Rubisco limit photosynthesis in cotton plants under heat and drought stress in the field. Environ. Exp. Bot. 83: 1-11.

Cefola, M., M.L. Amodio, R. Rinaldi, S. Vanadia and G. Colelli. 2010. Exposure to 1-methylcyclopropene (1-MCP) delays the effects of ethylene on fresh-cut broccoli raab (Brassica rapa L.). Postharvest Biol Tec 58: 29-35.

Chae, H.S., F. Faure and J.J. Kieber. 2003. The eto1, eto2, and eto3 mutations and cytokinin treatment increase ethylene biosynthesis in Arabidopsis by increasing the stability of ACS protein. Plant Cell 15: 545-559.

Chaudhuri, U.N., M.L. Deaton, E.T. Kanemasu, G.W. Wall, V. Marcarian and A.K. Dobrenz. 1986. A procedure to select drought-tolerant sorghum and millet genotypes using canopy temperature and vapor-pressure deficit. Agron. J. 78: 490-494.

Chaves, A.L.S. and P.C. de Mello-Farias. 2006. Ethylene and fruit ripening: From illumination gas to the control of gene expression, more than a century of discoveries. Genet Mol Biol 29: 508-515.

Chen, Y., D. Chen, J.T. Cothren, A.M.H. Ibrahim and L. Lombardini. 2014. Effect of 1-MCP on boll development and subtending leaves of cotton ( Gossypium hirsutum L.) plants. American journal of plant sciences 5: 3345-3353.

Chen, Y.F., M.D. Randlett, J.L. Findell and G.E. Schaller. 2002. Localization of the ethylene receptor ETR1 to the endoplasmic reticulum of Arabidopsis. J Biol Chem 277: 19861-19866.

Chou, C., J.Y. Tu and P.H. Tan. 2007. Asymmetry of tropical precipitation change under global warming. Geophys Res Lett 34.

Choudhury, B. 1986. An analysis of observed linear correlations between net photosynthesis and a canopy-temperature-based plant water-stress index. Agr. Forest Meteorol. 36: 323-333.

Clements, H.F. 1934. Significance of transpiration. Plant Physiol. 9: 165-172.

Clum, H.H. 1926. The effect of transpiration and environmental factors on leaf temperatures I. Tanspiration. Am J Bot 13: 194-216.

Curtis, O.F. 1926. What is the significance of transpiration? Science 63: 267-271.

Curtis, O.F. 1938. Wallace and Clum "leaf temperatures" - A critical analysis with additional data. Am J Bot 25: 761-771.

da Costa, V.A. and J.T. Cothren. 2011. Drought effects on gas exchange, chlorophyll, and plant growth of 1-methylcyclopropene treated cotton. Agron. J. 103: 1230-1241.

da Costa, V.A., J.T. Cothren and J.B. Bynum. 2011. Abiotic stress effects on plant growth and yield components of 1-MCP treated cotton plants. Agron. J. 103: 1591-1596.

de Brito, G.G., A.C.D. Ferreira, A.L.D.C. Borin and C.D.L. Morello. 2013. 1-Methylcyclopropene and Aminoethoxyvinylglycine Effects on Yield Components of Field-Grown Cotton. Cienc Agrotec 37: 9-16.

De Grauwe, L., F. Vandenbussche, O. Tietz, K. Palme and D. Van Der Straeten. 2005. Auxin, ethylene and brassinosteroids: tripartite control of growth in the Arabidopsis hypocotyl. Plant Cell Physiol 46: 827-836.

Dexter, R.J., B.A. Underwood and D.G. Clark. 2007. Ethylene-regulated floral volatile synthesis in Petunia x hybrida. Advances in Plant Ethylene Research: 141-146.

Diaz, R.A., A.D. Matthias and R.J. Hanks. 1983. Evapo-transpiration and yield estimation of spring wheat from canopy temperature. Agron. J. 75: 805-810.

Easterling, D.R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl and L.O. Mearns. 2000. Climate extremes: observations, modeling, and impacts. Science 289: 2068-2074.

Ecker, J.R. 1995. The ethylene signal-transduction pathway in plants. Science 268: 667-675.

Ehleringer, J.R. and S.D. Hammond. 1987. Solar tracking and photosynthesis in cotton leaves. Agr. Forest Meteorol. 39: 25-35.

Ehrler, W.L. 1973. Cotton leaf temperatures as related to soil-water depletion and meteorological factors. Agron. J. 65: 404-409.

Ehrler, W.L., S.B. Idso, R.D. Jackson and R.J. Reginato. 1978. Wheat canopy temperature: relation to plant water potential. Agron. J. 70: 251-256.

Evans, D.E., T. Bengochea, A.J. Cairns, J.H. Dodds and M.A. Hall. 1982. Studies on ethylene binding by cell-free preparations from cotyledons of Phaseolus-Vulgaris L - sub-cellular localization. Plant Cell Environ. 5: 101-107.

Fisher, K. and T. Udeigwe. 2012. Cotton water requirements. In: P. Calvin et al., editors, Cotton irrigation management for humid regions. Cotton Incorporated. p. 14-16.

Fluhr, R. and A.K. Mattoo. 1996. Ethylene - Biosynthesis and perception. Crit Rev Plant Sci 15: 479-523.

Foo, E., J.J. Ross, N.W. Davies, J.B. Reid and J.L. Weller. 2006. A role for ethylene in the phytochrome-mediated control of vegetative development. Plant J 46: 911-921.

Gane, R. 1934. Production of ethylene by some ripening fruits. Nature 134: 1008-1008.

Gardner, B.R., B.L. Blad and G.D. Wilson. 1986. Characterizing corn hybrid moisture stress sensitivity using canopy temperature-measurements. Remote Sens Environ 19: 207-211.

Gardner, B.R., D.C. Nielsen and C.C. Shock. 1992. Infrared thermometry and the crop water-stress index. I. History, theory, and baselines. J Prod Agric 5: 462-466.

Gerik, T.J., K.L. Faver, P.M. Thaxton and K.M. ElZik. 1996. Late season water stress in cotton: I. Plant growth, water use, and yield. Crop Sci. 36: 914-921.

Gniazdowska, A., U. Krasuska, K. Czajkowska and R. Bogatek. 2010. Nitric oxide, hydrogen cyanide and ethylene are required in the control of germination and undisturbed development of young apple seedlings. Plant Growth Regul 61: 75-84.

Goodenough, P.W. 1986. A review of the role of ethylene in biochemical control of ripening in tomato fruit. Plant Growth Regul 4: 125-137.

Groisman, P.Y. and R.W. Knight. 2008. Prolonged dry episodes over the conterminous united states: new tendencies emerging during the last 40 years. J Climate 21: 1850-1862.

Harris, D.S., W.T. Schapaugh and E.T. Kanemasu. 1984. Genetic diversity in soybeans for leaf canopy temperature and the association of leaf canopy temperature and yield. Crop Sci. 24: 839-842.

Hassan, F.A.S. and S.A. Mahfouz. 2010. Effect of 1-methylcyclopropene (1-MCP) treatment on sweet basil leaf senescence and ethylene production during shelf-life. Postharvest Biol Tec 55: 61-65.

Heisler-White, J.L., J.M. Blair, E.F. Kelly, K. Harmoney and A.K. Knapp. 2009. Contingent productivity responses to more extreme rainfall regimes across a grassland biome. Global Change Biol. 15: 2894-2904.

Hofman, P.J., M. Jobin-Decor, G.F. Meiburg, A.J. Macnish and D.C. Joyce. 2001. Ripening and quality responses of avocado, custard apple, mango and papaya fruit to 1-methylcyclopropene. Aust J Exp Agr 41: 567-572.

Holman, E.M. and C.W. Bednarz. 2001. Alley effect on several cotton cultivars in small plot research. Commun Soil Sci Plan 32: 119-126.

Idso, S.B. 1982. Non-water-stressed baselines: A key to measuring and interpreting plant water-stress. Agr. Meteorol. 27: 59-70.

Idso, S.B., R.D. Jackson, P.J. Pinter, R.J. Reginato and J.L. Hatfield. 1981. Normalizing the stress-degree-day parameter for environmental variability. Agr. Meteorol. 24: 45-55.

Idso, S.B., R.D. Jackson and R.J. Reginato. 1977. Remote-sensing of crop yields. Science 196: 19-25.

Jackson, R.D. 1982. Canopy temperature and crop water stress. Adv. Irrig. 1: 43-85.

Jackson, R.D., S.B. Idso, R.J. Reginato and P.J. Pinter. 1981. Canopy temperature as a crop water-stress indicator. Water Resour Res 17: 1133-1138.

Jackson, R.D., R.J. Reginato and S.B. Idso. 1977. Wheat canopy temperature: a practical tool for evaluating water requirements. Water Resour Res 13: 651-656.

Jiang, Y.M., D.C. Joyce and L.A. Terry. 2001. 1-Methylcyclopropene treatment affects strawberry fruit decay. Postharvest Biol Tec 23: 227-232.

Johnson, K.A. and R.S. Goody. 2011. The original michaelis constant: Translation of the 1913 Michaelis-Menten paper. Biochemistry-Us 50: 8264-8269.

Jones, H.G. 1999. Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. Agr. Forest Meteorol. 95: 139-149.

Jones, M.L., P.B. Larsen and W.R. Woodson. 1995. Ethylene-regulated expression of a carnation cysteine proteinase during flower petal senescence. Plant Mol Biol 28: 505-512.

Kakani, V.G., K.R. Reddy, S. Koti, T.P. Wallace, P.V.V. Prasad, V.R. Reddy, et al. 2005. Differences in in vitro pollen germination and pollen tube growth of cotton cultivars in response to high temperature. Ann. Bot. (London) 96: 59-67.

Karl, T.R. and K.E. Trenberth. 2003. Modern global climate change. Science 302: 1719-1723.

Kawakami, E.M., D.M. Oosterhuis and J.L. Snider. 2010a. 1-methylcyclopropene effects on the physiology and yield of field-grown cotton. Journal of Cotton Science 14: 233 - 239.

Kawakami, E.M., D.M. Oosterhuis and J.L. Snider. 2010b. Physiological effects of 1-methylcyclopropene on well-watered and water-stressed cotton plants. J Plant Growth Regul 29: 280-288.

Kerby, T.A., R.E. Plant, S. Johnson-Hake and R.D. Horrocks. 1998. Environmental and cultivar effects on height-to-node ratio and growth rate in Acala cotton. J Prod Agric 11: 420-427.

Ku, V.V.V. and R.B.H. Wills. 1999. Effect of 1-methylcyclopropene on the storage life of broccoli. Postharvest Biol Tec 17: 127-132.

Lambers, H., F.S. Chapin and T.L. Pons. 2008. Leaf energy budgets: effects of radiation and temperature. *In*: H. Lambers et al. (ed.), Plant Physiological Ecology. Springer, New York. p. 225-236.

Landivar, J.A. 1992. PMAP: a plant map analysis program for cotton. The Texas Agricultural Experimental Station MP-1740, College Station, TX.

D. J. Herber et al. 1993. Monitoring plant growth and yield in short-season cotton production using plant map data. Beltwide Cotton Conferences, New Orleans, LA. 10-14 January. National Cotton Council of America, Memphis, TN.

Linkies, A. and G. Leubner-Metzger. 2012. Beyond gibberellins and abscisic acid: how ethylene and jasmonates control seed germination. Plant Cell Rep 31: 253-270.

Lobell, D.B. and G.P. Asner. 2003. Climate and management contributions to recent trends in US agricultural yields. Science 299: 1032-1032.

Lu, Z.M., J.W. Chen, R.G. Percy and E. Zeiger. 1997. Photosynthetic rate, stomatal conductance and leaf area in two cotton species (Gossypium barbadense and Gossypium hirsutum) and their relation with heat resistance and yield. Aust J Plant Physiol 24: 693-700.

Lu, Z.M., J.W. Radin, E.L. Turcotte, R. Percy and E. Zeiger. 1994. High yields in advanced lines of pima cotton are associated with higher stomatal conductance, reduced leaf-area and lower leaf temperature. Physiol. Plantarum 92: 266-272.

Luo, Z.S., X.L. Xu, Z.Z. Cai and M. Yan. 2007. Effects of ethylene and 1-methylcyclopropene (1-MCP) on lignification of postharvest bamboo shoot. Food Chem 105: 521-527.

MacCracken, M.C., E.J. Barron, D.R. Easterling, B.S. Felzer and T.R. Karl. 2003. Climate change scenarios for the US national assessment. B Am Meteorol Soc 84: 1711-1723.

Mahan, J.R., J.J. Burke and K.A. Orzech. 1987. The thermal kinetic window as an indicator of optimum plant temperature. Plant Physiol 82: 518-522.

Malloch, K.R. and D.J. Osborne. 1975. Ethylene control of growth in maize seedlings in relation to auxin metabolism. Ann Appl Biol 81: 98-98.

Maxwell, K. and G.N. Johnson. 2000. Chlorophyll fluorescence - a practical guide. J. Exp. Bot. 51: 659-668.

Mckinney, N.V., W.T. Schapaugh and E.T. Kanemasu. 1989. Selection for canopy temperature differential in 6 populations of soybean. Crop Sci. 29: 255-259.

Mohapatra, R. and P.K. Mohapatra. 2006. Ethylene control of seed coat development in low and high sterile semidwarf indica rice cultivars. Plant Growth Regul 50: 47-55.

Morgan, P.W. and M.C. Drew. 1997. Ethylene and plant responses to stress. Physiol. Plantarum 100: 620-630.

Morgan, P.W., C.J. He and M.C. Drew. 1992. Intact leaves exhibit a climacteric-like rise in ethylene production before abscission. Plant Physiol. 100: 1587-1590.

Mtui, T.A., E.T. Kanemasu and C. Wassom. 1981. Canopy temperatures, water-use, and water-use efficiency of corn genotypes. Agron. J. 73: 639-643.

Orzaez, D., R. Blay and A. Granell. 1999. Programme of senescence in petals and carpels of Pisum sativum L. flowers and its control by ethylene. Planta 208: 220-226.

Patterson, D.T., J.A. Bunce, R.S. Alberte and E. Vanvolkenburgh. 1977. Photosynthesis in Relation to Leaf Characteristics of Cotton from Controlled and Field Environments. Plant Physiol. 59: 384-387.

Peng, S. and D.R. Krieg. 1991. Single leaf and canopy photosynthesis response to plant age in cotton. Agron. J. 83: 704-708.

Pettigrew, W.T. 2004. Moisture deficit effects on cotton lint yield, yield components, and boll distribution. Agron. J. 96: 377-383.

Pettigrew, W.T., J.J. Heitholt and W.R. Meredith. 1993. Early season ethephon application effects on cotton photosynthesis. Agron. J. 85: 821-825.

Pierik, R., R. Sasidharan and L.A.C.J. Voesenek. 2007. Growth control by ethylene: adjusting phenotypes to the environment. J Plant Growth Regul 26: 188-200.

Radin, J.W., Z.M. Lu, R.G. Percy and E. Zeiger. 1994. Genetic variability for stomatal conductance in pima cotton and its relation to improvements of heat adaptation. P Natl Acad Sci USA 91: 7217-7221.

Reddy, V.R., D.N. Baker and H.F. Hodges. 1991a. Temperature effects on cotton canopy growth, photosynthesis, and respiration. Agron. J. 83: 699-704.

Reddy, V.R., K.R. Reddy and D.N. Baker. 1991b. Temperature effect on growth and development of cotton during the fruiting period. Agron. J. 83: 211-217.

Reicosky, D.C., R.C.G. Smith and W.S. Meyer. 1985. Foliage temperature as a means of detecting stress of cotton subjected to a short-term water-table gradient. Agr. Forest Meteorol. 35: 193-203.

Reid, M.S. and M.J. Wu. 1992. Ethylene and flower senescence. Plant Growth Regul 11: 37-43.

Scholander, P.F., H.T. Hammel, E.D. Bradstreet and E.A. Hemmingsen. 1965. Sap pressure in vascular plants: negative hydrostatic pressure can be measured in plants. Science 148: 339-346.

Sharp, R.E. and M.E. LeNoble. 2002. ABA, ethylene and the control of shoot and root growth under water stress. J. Exp. Bot. 53: 33-37.

Shull, C.A. 1919. Transpiration as energy dispersal. School Science and Mathematics 19: 1-6.

Silvertooth, J.C., D.S. Wrona, D.S. Guthrie, K. Hake, T.A. Kerby and J.A. Landivar. 1996. Vigor indices for cotton management. Cotton Physiology Today 7:9-12.

Sisler, E.C. and S.M. Blankenship. 1996. Method of counteracting an ethylene response in plants. 5,518,988. Date issued: May 21, 1996.

Sisler, E.C. and M. Serek. 1997. Inhibitors of ethylene responses in plants at the receptor level: recent developments. Physiol. Plantarum 100: 577-582.

Sisler, E.C., M. Serek, E. Dupille and R. Goren. 1999. Inhibition of ethylene responses by 1-methylcyclopropene and 3-methylcyclopropene. Plant Growth Regul 27: 105-111.

Sisler, E.C. and S.F. Yang. 1984. Ethylene, the gaseous plant hormone. Bioscience 34: 234-238.

Steffens, B. and M. Sauter. 2005. Epidermal cell death in rice is regulated by ethylene, gibberellin, and abscisic acid. Plant Physiol. 139: 713-721.

Su, H.W. and S. Finlayson. 2012. 1-Methylcyclopropene prevents cotton physiological and molecular responses to ethylene. Plant Growth Regul 68: 57-66.

Taiz, L. and E. Zeiger. 2002. Ethylene: the gaseous hormone. *In*: L. Taiz et al. (ed.), Plant Physiol. Sinauer Associates, Sunderland. p. 219-238.

Tanner, C.B. 1963. Plant temperatures. Agron. J. 55: 210-211.

Thompson, J.S., R.L. Harlow and J.F. Whitney. 1983. Copper(I)-olefin complexes - Support for the proposed role of copper in the ethylene effect in plants. J Am Chem Soc 105: 3522-3527.

Turner, N.C. 1988. Measurement of plant water status by the pressure chamber technique. Irrigation Sci 9: 289-308.

Underwood, B.A., D.M. Tieman, K. Shibuya, R.J. Dexter, H.M. Loucas, A.J. Simkin, et al. 2005. Ethylene-regulated floral volatile synthesis in petunia corollas. Plant Physiol. 138: 255-266.

Unruh, B.L. and J.C. Silvertooth. 1996. Comparisons between an upland and a Pima cotton cultivar: I. Growth and yield. Agron. J. 88: 583-589.

Upchurch, D.R. and J.R. Mahan. 1988. Maintenance of constant leaf temperature by plants: II. Experimental observations in cotton. Environ. Exp. Bot. 28: 359-366.

Walker, G.K. and J.L. Hatfield. 1979. Test of the stress-degree-day concept using multiple planting dates of red kidney beans. Agron. J. 71: 967-971.

Wallace, R.H. and H.H. Clum. 1938. Leaf temperatures. Am J Bot 25: 83-97.

Wanjura, D.F. and D.R. Upchurch. 1997. Accounting for humidity in canopy-temperature-controlled irrigation scheduling. Agr Water Manage 34: 217-231.

Wills, R.B.H. and V.V.V. Ku. 2002. Use of 1-MCP to extend the time to ripen of green tomatoes and postharvest life of ripe tomatoes. Postharvest Biol Tec 26: 85-90.

Wise, R.R., G.F. Sassenrath-Cole and R.G. Percy. 2000. A comparison of leaf anatomy in field-grown Gossypium hirsutum and G. barbadense. Ann. Bot. (London) 86: 731-738.

Wu, J.X., J.N. Jenkins, J.C. McCarty and C.E. Watson. 2005. Comparisons of two statistical models for evaluating boll retention in cotton. Agron. J. 97: 1291-1294.

Xuebin, Z., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, et al. 2007. Detection of human influence on twentieth-century precipitation trends. Nature 448: 461-465.

Zhao, D., K.R. Reddy, V.G. Kakani, S. Koti and W. Gao. 2005. Physiological causes of cotton fruit abscission under conditions of high temperature and enhanced ultraviolet-B radiation. Physiol. Plantarum 124: 189-199.

## APENDIX 1

## JULIAN DAY CALENDAR FOR LEAP YEARS (2012)

| | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1 | 32 | 61 | 92 | 122 | 153 | 183 | 214 | 245 | 275 | 306 | 336 |
| **2** | 2 | 33 | 62 | 93 | 123 | 154 | 184 | 215 | 246 | 276 | 307 | 337 |
| **3** | 3 | 34 | 63 | 94 | 124 | 155 | 185 | 216 | 247 | 277 | 308 | 338 |
| **4** | 4 | 35 | 64 | 95 | 125 | 156 | 186 | 217 | 248 | 278 | 309 | 339 |
| **5** | 5 | 36 | 65 | 96 | 126 | 157 | 187 | 218 | 249 | 279 | 310 | 340 |
| **6** | 6 | 37 | 66 | 97 | 127 | 158 | 188 | 219 | 250 | 280 | 311 | 341 |
| **7** | 7 | 38 | 67 | 98 | 128 | 159 | 189 | 220 | 251 | 281 | 312 | 342 |
| **8** | 8 | 39 | 68 | 99 | 129 | 160 | 190 | 221 | 252 | 282 | 313 | 343 |
| **9** | 9 | 40 | 69 | 100 | 130 | 161 | 191 | 222 | 253 | 283 | 314 | 344 |
| **10** | 10 | 41 | 70 | 101 | 131 | 162 | 192 | 223 | 254 | 284 | 315 | 345 |
| **11** | 11 | 42 | 71 | 102 | 132 | 163 | 193 | 224 | 255 | 285 | 316 | 346 |
| **12** | 12 | 43 | 72 | 103 | 133 | 164 | 194 | 225 | 256 | 286 | 317 | 347 |
| **13** | 13 | 44 | 73 | 104 | 134 | 165 | 195 | 226 | 257 | 287 | 318 | 348 |
| **14** | 14 | 45 | 74 | 105 | 135 | 166 | 196 | 227 | 258 | 288 | 319 | 349 |
| **15** | 15 | 46 | 75 | 106 | 136 | 167 | 197 | 228 | 259 | 289 | 320 | 350 |
| **16** | 16 | 47 | 76 | 107 | 137 | 168 | 198 | 229 | 260 | 290 | 321 | 351 |
| **17** | 17 | 48 | 77 | 108 | 138 | 169 | 199 | 230 | 261 | 291 | 322 | 352 |
| **18** | 18 | 49 | 78 | 109 | 139 | 170 | 200 | 231 | 262 | 292 | 323 | 353 |
| **19** | 19 | 50 | 79 | 110 | 140 | 171 | 201 | 232 | 263 | 293 | 324 | 354 |
| **20** | 20 | 51 | 80 | 111 | 141 | 172 | 202 | 233 | 264 | 294 | 325 | 355 |
| **21** | 21 | 52 | 81 | 112 | 142 | 173 | 203 | 234 | 265 | 295 | 326 | 356 |
| **22** | 22 | 53 | 82 | 113 | 143 | 174 | 204 | 235 | 266 | 296 | 327 | 357 |
| **23** | 23 | 54 | 83 | 114 | 144 | 175 | 205 | 236 | 267 | 297 | 328 | 358 |
| **24** | 24 | 55 | 84 | 115 | 145 | 176 | 206 | 237 | 268 | 298 | 329 | 359 |
| **25** | 25 | 56 | 85 | 116 | 146 | 177 | 207 | 238 | 269 | 299 | 330 | 360 |
| **26** | 26 | 57 | 86 | 117 | 147 | 178 | 208 | 239 | 270 | 300 | 331 | 361 |
| **27** | 27 | 58 | 87 | 118 | 148 | 179 | 209 | 240 | 271 | 301 | 332 | 362 |
| **28** | 28 | 59 | 88 | 119 | 149 | 180 | 210 | 241 | 272 | 302 | 333 | 363 |
| **29** | 29 | 60 | 89 | 120 | 150 | 181 | 211 | 242 | 273 | 303 | 334 | 364 |
| **30** | 30 | | 90 | 121 | 151 | 182 | 212 | 243 | 274 | 304 | 335 | 365 |
| **31** | 31 | | 91 | | 152 | | 213 | 244 | | 305 | | 366 |

# APPENDIX 2

## JULIAN DAY CALENDAR FOR REGULAR YEARS (2013 AND 2014)

| | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 1 | 32 | 60 | 91 | 121 | 152 | 182 | 213 | 244 | 274 | 305 | 335 |
| **2** | 2 | 33 | 61 | 92 | 122 | 153 | 183 | 214 | 245 | 275 | 306 | 336 |
| **3** | 3 | 34 | 62 | 93 | 123 | 154 | 184 | 215 | 246 | 276 | 307 | 337 |
| **4** | 4 | 35 | 63 | 94 | 124 | 155 | 185 | 216 | 247 | 277 | 308 | 338 |
| **5** | 5 | 36 | 64 | 95 | 125 | 156 | 186 | 217 | 248 | 278 | 309 | 339 |
| **6** | 6 | 37 | 65 | 96 | 126 | 157 | 187 | 218 | 249 | 279 | 310 | 340 |
| **7** | 7 | 38 | 66 | 97 | 127 | 158 | 188 | 219 | 250 | 280 | 311 | 341 |
| **8** | 8 | 39 | 67 | 98 | 128 | 159 | 189 | 220 | 251 | 281 | 312 | 342 |
| **9** | 9 | 40 | 68 | 99 | 129 | 160 | 190 | 221 | 252 | 282 | 313 | 343 |
| **10** | 10 | 41 | 69 | 100 | 130 | 161 | 191 | 222 | 253 | 283 | 314 | 344 |
| **11** | 11 | 42 | 70 | 101 | 131 | 162 | 192 | 223 | 254 | 284 | 315 | 345 |
| **12** | 12 | 43 | 71 | 102 | 132 | 163 | 193 | 224 | 255 | 285 | 316 | 346 |
| **13** | 13 | 44 | 72 | 103 | 133 | 164 | 194 | 225 | 256 | 286 | 317 | 347 |
| **14** | 14 | 45 | 73 | 104 | 134 | 165 | 195 | 226 | 257 | 287 | 318 | 348 |
| **15** | 15 | 46 | 74 | 105 | 135 | 166 | 196 | 227 | 258 | 288 | 319 | 349 |
| **16** | 16 | 47 | 75 | 106 | 136 | 167 | 197 | 228 | 259 | 289 | 320 | 350 |
| **17** | 17 | 48 | 76 | 107 | 137 | 168 | 198 | 229 | 260 | 290 | 321 | 351 |
| **18** | 18 | 49 | 77 | 108 | 138 | 169 | 199 | 230 | 261 | 291 | 322 | 352 |
| **19** | 19 | 50 | 78 | 109 | 139 | 170 | 200 | 231 | 262 | 292 | 323 | 353 |
| **20** | 20 | 51 | 79 | 110 | 140 | 171 | 201 | 232 | 263 | 293 | 324 | 354 |
| **21** | 21 | 52 | 80 | 111 | 141 | 172 | 202 | 233 | 264 | 294 | 325 | 355 |
| **22** | 22 | 53 | 81 | 112 | 142 | 173 | 203 | 234 | 265 | 295 | 326 | 356 |
| **23** | 23 | 54 | 82 | 113 | 143 | 174 | 204 | 235 | 266 | 296 | 327 | 357 |
| **24** | 24 | 55 | 83 | 114 | 144 | 175 | 205 | 236 | 267 | 297 | 328 | 358 |
| **25** | 25 | 56 | 84 | 115 | 145 | 176 | 206 | 237 | 268 | 298 | 329 | 359 |
| **26** | 26 | 57 | 85 | 116 | 146 | 177 | 207 | 238 | 269 | 299 | 330 | 360 |
| **27** | 27 | 58 | 86 | 117 | 147 | 178 | 208 | 239 | 270 | 300 | 331 | 361 |
| **28** | 28 | 59 | 87 | 118 | 148 | 179 | 209 | 240 | 271 | 301 | 332 | 362 |
| **29** | 29 | | 88 | 119 | 149 | 180 | 210 | 241 | 272 | 302 | 333 | 363 |
| **30** | 30 | | 89 | 120 | 150 | 181 | 211 | 242 | 273 | 303 | 334 | 364 |
| **31** | 31 | | 90 | | 151 | | 212 | 243 | | 304 | | 365 |