# USE OF INFRARED THERMAL IMAGING FOR ESTIMATING CANOPY TEMPERATURE IN WHEAT AND MAIZE

**By**

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## ABSTRACT

Wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) are among the most important cereal crops around the world and as a result there is increasing demand for their production. Drought is limiting the production of wheat and maize in most parts of the world. It is important to develop a crop production system that can perform better under water limited conditions and can sustain the increasing population. Understanding the physiological basis of drought tolerance is necessary to improve genetic ability of crop for higher yield and water use efficiency. Canopy temperature has been used as one of the traits for identifying drought tolerant cultivars because it shows the relationship between plants, soil and atmosphere and has been recognized as an indicator of plant water status. Several remote sensing approaches have been developed to study stomatal conductance and determine water stress in plants. Among them, thermal imaging has been used to measure the canopy temperature and study plant water relationships. This study investigates the potential use of infrared thermal imaging for calculating crop canopy temperature and determining relationship between canopy temperature and yield. Furthermore, the genetic variation among wheat genotypes and maize hybrids in terms of canopy temperature under different water regimes was studied. Thermal images were acquired on several dates from the field of 20 different wheat genotypes grown under dryland and irrigated conditions in 2014/2015 wheat growing season at Bushland, Texas. Moreover, images were also taken from the field experiment of maize where five

different hybrids were grown under two ($I_{50}$ and $I_{100}$) irrigation regimes in 2015 maize growing season at Bushland, Texas. A handheld thermal camera was used to acquire thermal images and the images were processed using IR Crop Stress Image Processor Software. The software filters out the background soil from thermal image of the wheat and maize plots and gives the mean canopy temperature of the selected area in the image. Thus obtained canopy temperature was recorded and further analyzed.

In the wheat study, a significant difference ($P < 0.05$) in canopy temperature among wheat genotypes grown under dryland condition was found several times when measurements were taken. Similarly, a significant difference in canopy temperature among the maize hybrids was found under $I_{50}$ irrigation regime. However, in both the crops, consistent canopy temperature differences in wheat genotypes and maize hybrids were not observed under irrigated condition when the plants were having sufficient soil moisture to maintain transpiration. Canopy temperature of maize hybrids measured under $I_{50}$ irrigation regime was higher than in $I_{100}$ irrigation regime which gives an indirect indication of water status in soil.

A strong negative correlation ($P < 0.05$) was found between canopy temperature and above ground biomass across the wheat genotypes under dryland condition. Also, a similar relationship was observed between canopy temperature and grain yield across maize hybrids. Moreover, in the maize study, the hybrid with lower canopy temperature (averaged across all the measurement dates) had relatively higher yield under $I_{50}$ water regime. However, under fully irrigated condition, consistent correlation between canopy temperature and grain yield was not found. These results indicated that the genotypes that can maintain cooler canopies during water stress can produce higher yield. It is concluded that canopy temperature can be a good indicator of crop water status and may be used as a selection criterion in identifying drought tolerant genotypes under water-limited conditions. Infrared thermal imaging showed a potentially promising technique in studying the genotypic variation among wheat genotypes and maize hybrids thereby can be helpful to enhance breeding programs for drought tolerance of wheat and maize.

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## DEDICATION

TO MY BELOVED GRANDMOTHER

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# CHAPTER 1

# INTRODUCTION

With the increase in the world's population, it is certain that the demand for crop production will be increased in the near future. Crop production in coming years should be targeted in such a way that can satisfy the needs of the human population that is expected to grow to more than 9 billion by 2050 (Becker, 2015). In association with the goal to meet increasing food demand, there are several other challenges for crop production such as increased temperature, and the decrease in the availability of fresh water resources for irrigation leading to severe droughts in many parts of the world. The expansion in crop production will rely on the development of improved crop management techniques and better crop varieties (Miflin, 1999).

Wheat (*Triticum aestivum* L.) is one of the world's most important grains. It is also a major crop in the U. S. Southern Great Plains, including Texas High Plains (Howell et al., 1995b). In 2015, 55 Mt of wheat was produced by United States of which Texas produced 2.9 Mt (USDA-NASS, 2016).

Maize (*Zea mays* L.) is another most important crop in the world and is a major grain crop in the U. S. In 2015, total maize grain produced in U. S. was 326 Mt. In the same year, Texas produced 6.7 Mt where 5.06 Mt was from irrigated and 1.6 Mt from non-irrigated land (USDA-NASS, 2016).

Drought significantly affects wheat and maize production; the historic drought in 2011 reduced wheat yield by 47% as the production was just 1.3 Mt compared to a five-year average of 2.5 Mt in Texas (Anderson et al., 2012). As the drought progressed for a longer time, it had a significant impact on maize production as well. It caused a loss of 46% maize yield in 2011 as the production was just 3.47 Mt compared to a five-year average of 6.47 Mt (Anderson et al., 2012). In Texas High Plains, both wheat and maize are grown under wide range of water regimes (from full irrigation to reduced irrigation to rain-fed condition). Irrigation water is mainly supplied by the Ogallala Aquifer in this region which is declining at a fast rate because of the minimal recharge capacity and increased water withdrawal (Howell, 2001; Colaizzi et al., 2009). Decline in the water table coupled with unstable weather conditions have imposed limitations to crop yield and may continue in the coming days. There are higher chances that the farmers choose either limited irrigation, application of less irrigation water, or dryland crop production in the near future (Colaizzi et al., 2009). It is necessary to develop crop management practices that can produce better yield under limited water conditions and maintain production stability. Adoption of high yielding, water efficient, and drought tolerant cultivars is one way to reduce the production risk and maintain profitability under severe weather conditions (Hao et al., 2015).

Crop breeding has played a crucial role for improving yield by developing cultivars with better drought tolerant traits (Cattivelli et al., 2008). Moreover, breeders are always looking for ways to improve the genetic ability of the crop for yield and other agronomic and physiological traits. Yield, which is a major phenotypic selection criterion in plant breeding, is influenced directly and indirectly by several environmental, morphological, physiological, biochemical and metabolic processes (Jackson et al., 1996). Assessing the physiological attributes of crop growth is one of the important bases for minimizing drought stress. It helps to understand root development, water uptake, crop growth, and the physiological principles behind drought tolerance. This can reduce the risk of crop failure in dryland areas by improving the ability of crops to extract water from the deeper soil profile, decreasing the demand of water by the crops (improving water use efficiency), or by enhancing the ability of crops to survive longer periods without water (Cattivelli et al., 2008).

Interaction of plants with the surrounding environment through the exchange of water, energy, and carbon helps them to grow in varying environmental conditions (Costa et al., 2013). This interaction brings variation in plant physiological parameters such as stomatal conductance, transpiration, canopy temperature, leaf area index (LAI), and crop yield between the plants and crop cultivars. Among these, stomatal conductance and crop canopy temperature have been proposed as good indicators of plant water status (Idso et al., 1981; Jackson et al., 1981; Balota et al, 2007; Ehrler, 1973) and to compare cultivars with respect to drought tolerance (Ayeneh et al., 2002; Fischer et al., 1998). Stomatal conductance and regulation of leaf gas exchange plays key roles in determining water loss (transpiration) and leaf temperature (Jones, 2014). When the leaf transpires, a substantial amount of energy is required to convert liquid water into vapor, and this energy is consumed by evaporating water from the leaf which lowers the leaf temperature and thus cools it. When water becomes limiting in the soil profile, it results in stomatal closure which causes the reduction of transpiration. This lowers the amount of heat that is utilized while converting water into vapor and increases the leaf temperature (Jones et al., 2009). Measuring leaf temperature is crucial to study water status and physiological processes occurring in plants. There are several approaches to measure leaf gas exchange (porometry) and canopy temperature (thermometers) which are considered cumbersome (Zia et al., 2011). Also, the physiological response of a plant varies from leaf to leaf even on a single plant which make the measurements more complicated if we need to evaluate the water status of a crop in the field. Taking measurements on a large number of leaves is difficult and is a major limiting factor to the study crop water status and evaluating the genotypes in terms of water requirement in the field. These difficulties therefore warrant the use of remote sensing for monitoring physiological characteristics of crops which will provide instantaneous, non-invasive, and non-destructive information about crop status (Jones and Vaughan, 2010). Infrared thermal imaging is one of the remote sensing techniques commonly used for visualizing, diagnosing, and quantifying plant stresses (Jones and Schofield, 2008). The thermal camera collects the radiation emitted by the object and makes an electromagnetic image based on the temperature differences of the object. Thus, obtained images can be processed and over a hundred-thousand simultaneous temperature measurements can be obtained. Thermal imaging is primarily used to study plant water relations and it shows the ability to include large number of individual plants in a single image while calculating temperature measurements (Jones et al., 2009). One of the most important issues while analyzing the thermal imaging is to filter out the background soil from the image and get more precise canopy measurements. It is important to remove the errors caused by background soil and to reduce the loss of canopy data while filtering out the soil from the image. Also, the canopy temperature and the use of thermal imaging are significantly influenced by several factors including canopy color, leaf orientation, leaf morphology and other environmental factors such as air temperature, solar radiation, humidity, and wind speed. Eliminating the influence of background soil in canopy temperature and reducing the impact of these factors is important when using thermal imaging based canopy temperature measurements.

## OBJECTIVES

The overarching goal of this study was to investigate the use of thermal imaging for determining crop canopy temperature. Specific objectives were:

1. To study if the genotypes grown under different water regimes show significant differences in canopy temperature.
2. To study the relationship of canopy temperature with other crop parameters.
3. To study if the canopy temperature varies with level of irrigation.

The hypothesis for this study is that canopy temperature can be calculated from infrared thermal imaging and the obtained temperature is significantly correlated with grain yield and biomass of wheat and corn grown under different irrigation treatments.

# CHAPTER 2

# LITERATURE REVIEW

There are several physiological traits that are critical during plant growth and development and play a vital role in contributing yield. Canopy temperature, transpiration, stomatal conductance, photosynthesis are some of the physiological parameters directly associated with grain yield in wheat and maize production. These parameters help to understand the water exchange between the plants and the environment and define how sensitive is the growth and development of crop on the changing environmental conditions.

## 2.1. Physiological parameters

### 2.1.1. Stomatal conductance

Stomatal conductance is the measure of gas exchange from or into the leaf. It provides the estimate of carbon dioxide uptake and water loss through the leaf stomata. Stomata are the small pores found in the epidermis of plant leaves and they play a crucial role in controlling water and gas exchange. When the stomatal pores are closed water loss is reduced, so is the uptake of carbon dioxide. Stomatal conductance is responsible for regulating transpiration and leaf temperature in which these processes influence leaf photosynthesis response under different environmental condition (Cornish et al., 1991; Jones, 2014).

### 2.1.2. Transpiration

Transpiration is the loss of water from leaves and stem of plants (Jones, 2014). Plants absorb water from the roots and some portion of the absorbed water is used for plant growth and metabolism while the remaining is lost in the form of vapor by transpiration. It is an engine that pulls the water from the soil through the roots. Transpiration is positively associated with biomass and grain yield. Tolk and Howell (2003) found a positive relationship of evapotranspiration with grain yield and biomass produced in sorghum. When the evapotranspiration was 297 mm, sorghum produced 463 g $m^{-2}$ of yield and at a higher evapotranspiration rate of 612 mm the yield was 876 g $m^{-2}$. Moreover, transpiration also varies with the amount of water available in the soil. Rodriguez et al. (2005) found that the stomatal conductance, net photosynthetic rate and transpiration rate were lower in rainfed plots in comparison to well-irrigated plots. The highest stomatal conductance (0.28 mol $m^{-2}s^{-1}$), net photosynthetic rate (25.2 µmol $Co_2$ $m^{-2}s^{-1}$), and transpiration rate (3.9 µmol $H_2o$ $m^{-2}s^{-1}$) were found under well-irrigated condition.

### 2.1.3. Canopy temperature

Stomatal conductance and the amount of water that leaves the plant define the canopy temperature (Jackson, 1982). Specifically, the rate of transpiration from the leaf determines the temperature of plant canopy. When the leaf transpires, a substantial amount of energy is required to convert liquid water into vapor, and this energy is consumed by evaporating water from the leaf which lowers the leaf temperature and thus cools it. Thus, this process of converting water into vapor and loosing into atmosphere links canopy temperature with crop water stress and evapotranspiration (Colaizzi et al., 2012). When water becomes limiting in the soil profile, transpiration is reduced which reduces the amount of heat that is utilized while converting water into vapor and plant temperature increases (Jones et al., 2009). Continuous monitoring of canopy temperature can provide the measure of water leaving the plant which can be a good indicator of water status, water use, and metabolic functioning of plant (Colaizzi et al., 2012). The varying response of plants depending upon soil water status and the genotypic ability to withstand environmental conditions is one of the reasons for using canopy temperature to study soil plant relationships (Blum et al., 1989).

#### 2.1.3.1. Factors affecting canopy temperature

Determining crop water status and screening genotypes based on canopy temperature measurements in the field is a complex process because of the environmental factors that can influence the temperature. The differences in canopy temperature obtained between the treatments can be caused by many other factors than transpiration and stomatal conductance. Canopy temperature is significantly affected by several plant traits such as canopy size, canopy architecture, canopy color (Ferguson et al., 1973), root morphology, leaf orientation (Wallace and Cum, 1938; Balota et al., 2008), leaf morphology (Balota et al., 2008; Smith, 1978) and the atmospheric conditions such as ambient air temperature (Jackson et al., 1977), vapor pressure deficit (Jones, 2014), wind velocity, time of day (Balota et al., 2008; Pradhan et al., 2014), cloud cover (Pradhan et al., 2014) and soil water availability (Blum, 1989). Also, there is a temporal variation in environmental condition affecting the plant canopy temperature. Air temperature, soil temperature, humidity, cloud cover, wind speed, amount of solar radiation change regularly within a short period of time. These variations in the environment and all other factors influencing canopy temperature are needed to be taken care so that the measurements obtained from the canopy will have lower errors and the variation among the plants in regard to canopy temperature can be identified more precisely. Several attempts have been made to normalize the canopy temperature measurements to reduce the environmental impacts.  Jackson et al. (1977) developed ‘stress degree day’ (SDD) by subtracting air temperature measured at 150 cm above the soil surface from canopy temperature. This difference is also called as canopy temperature depression (CTD) and it is being used as an important tool to normalize the differences in environmental condition (Pinter et al., 1990; Pradhan et al., 2014). Although they accounted for the differences in air temperature, they did not account for differences in humidity and vapor pressure deficit over the time. Later on, in 1981, Idso et al. (1981) developed ‘crop water stress index’ (CWSI) to account for humidity and vapor pressure deficit by relating the observed canopy temperature to the temperature of non-stressed and non-transpiring crops under same environmental condition. Jones et al. (1996) extended the CWSI index and used completely wet and dry surface as a reference to normalize the measurements between environments. Karimizadeh and Mohammadi (2011) evaluated several drought indices to access drought tolerance of wheat genotypes under different environmental conditions. They planted eight wheat genotypes under different irrigation gradients, measured canopy temperature and calculated canopy temperature depression (CTD), stress susceptibility index (SSI), stress tolerance index (STI), tolerance index (TOL), mean productivity (MP) and geometric mean productivity (GMP). They found a significant positive correlation of CTD with YP, STI, TOL, MP, GMP which shows that these indices can be more effective in identifying high yielding genotypes under different irrigation regimes. Grant et al. (2006) suggested that if we could take the average temperatures of canopies containing several leaves then it might be more useful for reducing the error caused by plant traits and variation in environmental condition.

**2.1.3.2. Relationship between canopy temperature, stomatal conductance and yield**

Zia et al. (2013) found a negative correlation between canopy temperature and stomatal conductance which shows that a canopy with lower temperature indicates for higher transpiration and higher stomatal opening which thus can help to increase the yield. When canopy temperature was 33ºC, stomatal conductance was 0.11mol $m^{-2}s^{-1}$ and when the canopy temperature was lower (27ºC) then a higher stomatal conductance (0.28 mol $m^{-2}s^{-1}$) was found. This association was supported by the research conducted by Lu et al. (1998) on pima cotton and bread wheat grown under higher temperatures. They found a positive association of stomatal conductance with grain yield ($r = 0.93$) and lint yield ($r = 0.92$) in wheat and cotton respectively. Moreover, lower wheat grain yield (6800 kg $ha^{-1}$) was found under lower stomatal conductance (0.40 mol $m^{-2}s^{-1}$) and higher yield (8400 kg $ha^{-1}$) was found under higher stomatal conductance (0.65 mol $m^{-2}s^{-1}$). They hypothesized that with the increase in stomatal conductance canopy gets cooler and this principle favors yield in crops.

Dejonge et al. (2015) found a positive correlation ($R^2 = 0.89$) between canopy temperature and leaf water potential that was measured during mid-day at different growth stages of maize. Lobo et al. (2004) tried to correlate CTD, stomatal resistance, transpiration and leaf water potential. CTD was found to be negatively correlated with transpiration and leaf water potential and positively correlated with stomatal resistance. Cohen et al. (2005) measured leaf water potential by using pressure chamber and analyzed thermal images to calculate canopy temperature in the cotton field grown under different irrigation regimes. Leaf water potential was negatively associated (($R^2$ = 0.73) with leaf temperature in their results. Padhi et al. (2012) also found a positive association of canopy temperature with leaf water potential and a negative association with stomatal conductance. Feng et al. (2009) found that the wheat genotype which had lowest stomatal conductance and transpiration was warmest. Pinter et al. (1990) found a negative correlation ($r^2$ = 0.86) between leaf conductance and canopy temperature depression measured during midday. This suggests that warmer canopy temperatures are associated with lower transpiration and cooler canopies with higher conductance and higher transpiration. Their data also showed that the cultivars with the higher canopy temperature under low water treatment had lower stomatal conductance and lowest seasonal water use and they performed better when grown under deficit irrigation condition. Canopy temperature is negatively associated with grain yield (Mohammadi et al., 2012; Zia et al., 2013). Also, CTD which is the difference between canopy temperature and ambient temperature is positively correlated with grain yield (Reynolds et al., 1994; Amani et al., 1996; Fischer et al., 1998; Rashid et al., 1999; Ayeneh et al., 2002; Balota et al., 2007; Bahar et al., 2008; Karmizadeh and Mohammadi, 2011; Pradhan et al., 2014) under heat and drought stress conditions. Canopy temperature is also associated with different crop indices. Blum et al. (1989) found a positive correlation (r = 0.72) between drought susceptibility index and canopy temperatures across the genotypes which indicates that the genotypes under higher water stress condition had warmer canopies and suffered relatively greater yield loss.

#### 2.1.3.3. Differences in canopy temperature because of variation in soil water content

Canopy temperature is affected by soil water content and other metabolic activities of plants. Zhang et al. (2007) studied the relationship between canopy temperature and soil water content under different irrigation treatments in rice and found that the canopy temperature was higher when soil water content was lower. Palmer (1967) reported that the mean cotton leaf temperatures were higher for non-irrigated plants than those of the irrigated plants. Also, they found that, under irrigated condition the lower leaves of the canopy were cooler than the upper leaves; whereas under non-irrigated treatment lower leaves had approximately the same temperature as the upper ones. Sandhu and Horton (1978) found leaf temperatures of water stressed oats to be 4.0ºC warmer than plants that were well-watered. Zia et al. (2012) calculated the canopy temperature by processing thermal images taken from the field of winter wheat grown under five different irrigation treatments. They found that the canopy temperature is affected by soil water content where deficit irrigation treatment had higher canopy temperature than that of fully irrigated condition. In addition, Wanjura et al. (2004) found a higher canopy temperature in low watered cotton compared to highly watered cotton; a similar trend was reported in maize. Padhi et al. (2012) measured canopy temperature and soil water content for several days during cotton growth to study if canopy temperature is related with soil water content within the root zone. They found that canopy temperature was almost 7ºC higher when irrigation water was reduced from 50% to 85%. They also noted the same pattern in stomatal conductance where stomatal conductance was significantly higher when only 50% of the irrigation was reduced and it went on decreasing when the irrigation level was reduced. Furthermore, they found that the canopy temperature was negatively associated with soil water content within the root zone which indicates that when there is higher level of water in the soil profile then the plants can maintain transpiration reducing the canopy temperature and in the other hand if there is low soil water in the profile then transpiration is reduced and temperature of leaves will be higher. Supporting this result, they also found positive correlation between stomatal conductance and soil water content within the root zone.

#### 2.1.3.4. Canopy temperature and air temperature

Canopy temperature is influenced by the air temperature within the crop canopy and near the surface of the canopy (Tanner, 1963; Palmer, 1967). Leaf and canopy temperature can be warmer and cooler than the surrounding air depending upon the environmental factors upon which the plants are grown (Jackson, 1982). The temperature of well-watered canopies will be slightly below surrounding air whereas the canopy temperature of limited or low watered canopies will be slightly higher than the surrounding air depending upon whether the environment is warmer or cooler (Reicosky et al., 1980). Palmer (1967) calculated the differences between leaf temperature and air temperature to study the diurnal variation in leaf and boll temperatures grown under two soil moisture regimes in a semi-arid climate of Australia. Leaf temperature and air temperature were similar during early morning in both the irrigated and non-irrigated condition. During mid-day and early afternoon the temperature of non-irrigated plant leaves was 4ºC higher than the air temperature on both cooler and hotter days. Also, it was reported that the temperature of irrigated plants was higher than the air temperature only in cooler days but was less on hot or very hot days. Jackson et al. (1977) developed the stress degree day to detect plant stress by using thermometers for measuring leaf temperature and air temperature. According to this index, when the plants are well watered then canopy temperature is lower than the air temperature but if the canopy temperature is greater than the air temperature then the plants are drought stressed. Clum (1962) measured leaf temperature and air temperature by using thermocouples on potted plants grown in green house and open area. The amount of irrigation water was differentiated in the pot and tried to get different transpiration rates. Leaves were always warmer than the air by 5-10ºC. Olufayo et al. (1996) conducted a research to evaluate plant water stress by measuring canopy temperature in sorghum. They found that the canopy temperature of plants grown under deficit irrigation treatment was 7ºC higher than the air temperature but the difference was almost 0ºC under fully irrigated condition.

### 2.2. Remote sensing for plant science

Remote sensing is a technique to collect information about an object or phenomenon from the distance without making any physical contact with the object (Jones and Vaughan, 2010). The measurements of an object taken by using remote sensing tools are based on electromagnetic radiation emitted by the object. Light is reflected, absorbed or transmitted from the object and remote sensing is the measurement of the amount of reflected and emitted radiation at different spectral wavelengths (Costa et al., 2013). The measurements are usually recorded from a variety of platforms like satellite, airplanes, unmanned aerial vehicle, and handheld devices such as sensors, cameras and video recorders. Remotely taken measurements can be further processed and analyzed to understand the nature and properties of the surface as well as to interpret those data to get some meaning. Remote sensing makes the use of visible; near infrared and short-wave infrared sensors and these sensors detect the nature of radiation reflected from the surface of the object to gather the information about the object. The interaction of plants with radiant energy has made it possible to use remote sensing to study plant growth and development. Use of remote sensing to obtain information about plant or vegetation is a non-invasive methodology which is now commonly used for monitoring physiological characteristics of plants. Evaluating crop performance under different environmental conditions, assessing plant health, quantifying the effect of environmental and biological stresses on crop productivity, and predicting crop yield are some of the areas where remote sensing is being used (Hatfield et al., 1993).

### 2.2.1. Theory of infrared radiation and its use in determining canopy temperature

All objects emit radiation in the far-infrared region of the spectrum (3-100 µm) and the intensity of this radiation is the function of their surface temperature. If the temperature of the object is higher, then it will emit higher amount of radiation and if the temperature is lower, then it will emit lower radiation. This emitted radiation is called thermal infrared radiation (IR) radiation (Vadivambal and Jayas, 2010). Li et al. (2014) stated that the magnitude of this radiation is proportional to fourth power of the absolute surface temperature of the object. The instruments used to determine the temperature of the surface measures the radiation emitted from the target and relates this radiation R to the surface temperature $T_s$ by the Stefan-Boltzmann black body law given in the formula below

$$R = \varepsilon \sigma T s^4$$

Where, R is radiation energy per unit of time and area ($Wm^{-2}$), ε is the emissivity of the surface (when it is a black body ε=1 and for that of plants it is ε = 0.91 to 0.97), σ is Stefan-Boltzmann constant ($5.674 \times 10^{-8}$ $Wm^{-2}K^{-4}$).

There are several remote sensing tools that can capture the radiation emitted by the objects. In the field of agronomy and crop physiology, the development of devices that can measure the emitted thermal radiation made it possible to measure the canopy temperature. Previously, thermocouples and mercury thermometer were commonly used to measure leaf temperature. It was cumbersome process to measure the temperature of individual leaf to determine the temperature of plant and the measurement of a single leaf could not indicate that transpiration is a major cause of cooling. Moreover, temperature of the upper leaves of plant differs from the lower leaves (Waggoner and Shaw, 1952) because of the variation of light in sunlit and shaded leaves. Thus, these associated problems while measuring leaf temperature made a way for using remote sensing tools to measure crop canopy temperature. Monteith and Szeicz (1962) and Tanner (1963) were among the earliest researchers to use remote sensing for determining leaf temperature. Monteith and Szeicz (1962) used radiometers to measure the radiant energy emitted by the surface and determined the temperature of plants and bare soil. Tanner (1963) used infrared thermometry for determining the leaf temperature under different water regimes. His data suggested that plant temperature can provide a valuable qualitative index to determine plant water status and detect water stress in plants. After that, several researchers have used airborne thermal scanners to measure canopy temperature and determine water stress in the field (Bartholic et al., 1972; Heilman et al., 1976; Zia et al., 2013).

### 2.2.2. Remote Instruments to measure canopy temperature

The most commonly used remote sensing tools to measure canopy temperature are infrared thermometer (IRTs) which is also called as thermometry and thermal imaging (thermography). These techniques are found to be very useful to determine various physical and biological stresses in plants, estimating soil water status and planning irrigation scheduling (Mahan and Yeater, 2008; Vadivambal and Jayas, 2010). Mahan and Yeater (2008) threw emphasis on the advantages of thermometry to measure canopy temperature in the field. They said that the IRTs are affordable, data can be transferred remotely without the use of wires and are easier to use in field. Supporting Mahan and Yeater (2008), Hatfield (1990) said that IRT provides rapid and accurate data of foliage temperature that can be used for assessing plant stress. He further stated that this methodology poses some limitations like it covers only small area in the field and there are higher chances of interference of radiations from the soil background. He suggested for refinements to be made in this technique. Leinonen and Jones (2004) said that infrared thermometers usually have a finite angle of view so there are some possibilities of getting infrared signals from the background soil and those signals can be included in the acquired thermal signal. This generally happen when the soil is not fully covered by the canopy and the thermometer captures the radiation emitted from the soil. Moreover, thermometers can only cover certain portion of the plots in the field and can take account of few data points which sometimes may not be sufficient to characterize crop water stress. Wanjura et al. (2004) measured canopy temperature of cotton using infrared thermometer and thermal scanner and found that the temperature measurements from thermometer were higher than that of scanner. According to them, this was caused because of more soil being viewed within the canopy perimeter by the thermometer than scanner. IRTs are also limited by the number of measurements that can be taken in a given period of time under changing environmental condition. Thermal imaging is another technique that captures the radiations emitted by the objects and is being highly used in the field of agriculture. Thermal cameras that are used in thermal imaging capture the differentiated radiation patterns and form visible images of the objects that can be further processed and analyzed. It has been considered as more advantageous than thermometry in terms of higher precision and larger coverage. Thermal imaging can take into account over a hundred-thousand simultaneous discrete measurements covering a larger portion in the plots (Ishimwe and Ahmed, 2014). Hackl et al. (2012) compared the plant temperature measured by using thermal imaging and infrared thermometry. They found comparable results from both the methods when there was a dense crop stand of wheat and stated that these methods can be applied for quick and easy measurement of plant temperatures. They kept a higher emphasis on the advantages of thermal imaging over thermometry in a way that thermography offers opportunities for further processing of images taking account of larger portion of the plots. During processing of images there are chances of excluding the non-plant material (background soil) from the image which can add the precision on the final data measurements. Jackson (1982) reviewed different aspects of measuring canopy temperature and pointed out that even in thermal imaging the background soil exposed by incomplete canopies can have a problem while determining canopy temperature. Actually, the sensors in this condition will observe bare soil, vegetative soil, shaded region, and totally sunlit region in the plots and will take into account all these different temperature readings while creating an image. Making an accurate selection and determining the actual temperature is a challenge. Moller et al. (2007) suggested to combine thermal images and color digital images during analysis to exclude the influence of background soil and improve the canopy temperature measurements. For taking thermal images, there are hand held thermal cameras from which we can take the images very easily for a smaller region. But for larger areas, airborne thermal scanners are being used.

### 2.2.3. Use of thermal imaging

#### 2.2.3.1. Thermal imaging as a tool for monitoring plant stress

Padhi et al. (2011) conducted a research to test if thermal imaging can be used to distinguish soil water deficit in cotton fields by applying different irrigation treatments. They suggested that thermal imaging can be used to access the soil water deficit condition in cotton fields. Leinonen and Jones (2004) and Cohen et al. (2005) combined thermal imagery and visual imagery to estimate the canopy temperature and to identify water stress in grape vines and cotton. They also suggested some of the advantages of thermal imaging. They said that this method can cover large number of leaves in the plants and take into account of several data points in a very less time. Also, if the images are properly analyzed using appropriate software, then the impact of background soil can be discarded and the errors in leaf temperature measurements can be minimized. Pou et al. (2014) conducted a research on matured grape vines to explore the possibility of using thermal imaging to monitor plant stress. Grant et al. (2007) used thermal imaging to detect stress responses in grapevine under different irrigation regimes. They found that thermal imaging can distinguish irrigated and non-irrigated plant canopies and they also noted a distinction between plants between deficit irrigation treatments.

Moller et al. (2006) also investigated the use of thermal imaging to monitor water stress in grapevine in Israel. Thermal and visible images were taken from the grapevine vineyard that had three irrigation treatments (mild, moderate and severe stress). Images were taken on four days at midday with FLIR thermal imaging system and a digital camera. They suggested that if thermal and visible imaging is merged together and images are processed then it would give precise measurements on crop water status and stomatal conductance. Jones et al. (2002) also studied the use of infrared thermography for monitoring stomatal closure in the field using grapevine for their experiment. It was indicated that the water relations of grapevine canopies can be studied by using infrared thermography. To make this methodology more precise it is necessary to avoid the inclusion of non-leaf material in the analysis of the images. Avoiding non-leaf material can be done either by selecting appropriate areas in the canopy plots or by using dry and wet threshold temperatures to define the range outside which temperature values are rejected. They further emphasized the potential advantages of thermal imaging. Thermography allows the semi-automated analysis of large areas of canopy for studying stomatal behavior of plants with much more effective replication than those which could be achieved by porometry. Also, thermal imaging and image analysis allow automated correction of images like the elimination of pixels representing sky or soil. Furthermore, they concluded that thermal imaging have the potential for getting measurements that are best suited for comparative studies because of the potentially high precision within-image comparisons. Zia et al. (2013) measured the canopy temperature of 150 maize genotypes grown under well waters and water stressed condition by using thermal imaging. IRBIS-PROFESSIONAL-3 software was used to process the thermal images and digital images were merged to differentiate the rows of appropriate genotypes. It was found that the temperature measured on the same day of genotypes grown under water stressed condition was 1-2°C higher than the genotypes grown under well water condition. This difference increased with the crop growth and reached around 5-6°C on 97 DAS. Gardner et al. (1981) measured canopy temperature of corn grown under seven different irrigation treatments at midday throughout the growing season. They found a canopy temperature difference of 7°C between stressed and non-stressed plants. Also, the midday temperature of sunlit leaves of non-stressed and moderately stressed plants was generally 1–2°C below air temperature where as in severely stressed plants the canopy temperature was as much as 4.6°C above air temperature. They suggested that corn plants can be under water stress and still be cooler than air temperature unless they are severely stressed. Millard et al. (1978) as cited by Jackson (1982) used an airborne thermal scanner to measure the temperature of a wheat crop canopy in Phoenix, Arizona. They found that the temperature of stressed plots was around 8ºC above air temperature which was measured at 1.5m and that of irrigated plots was around 6ºC lower than surrounding air temperature. It was concluded that thermal imagery can be used to distinguish the effect of different irrigation treatments on plants. Bartholic et al. (1972) used thermal scanner to determine the temperature of cotton canopy grown under different irrigation regimes and observed the differences of almost 6ºC between the most stressed and least stressed plots. Leinonen and Jones (2004) combined thermal and visible imagery for estimating canopy temperature and identifying plant stress in grape vines. Greenhouse and field experiment were conducted and plants were grown subjecting to different irrigation treatments consisting of fully irrigated condition and rainfed condition. They took thermal images and visible images and processed those images by overlaying the corresponding pixels into one another. From the image they classified different objects such as background soil, non-green parts, sunlit leaves, and shaded leaves to extract the final temperature. A higher temperature variance of shaded canopy than sunlit canopy was observed. Moreover, they also found that the plants grown under rainfed condition had higher temperature than fully irrigated plants. These, results show that infrared thermal imaging can be used as one of the techniques to study the water status in the soil. Zia et al. (2012) assess crop water status of winter wheat by thermography under different irrigation regimes in North China Plain. They subjected four different irrigation levels (100%, 50%, 16%, and no-irrigation). Thermal images and digital images were taken and merged to differentiate the canopy cover with background soil. Crop water stress index (CWSI) was calculated and it was found that the CWSI was higher in non-irrigated condition then fully irrigated condition which shows that thermography can be used to differentiate the stress levels in the field.

#### 2.2.3.2. Use of thermal imaging as a tool for genotype evaluation

To evaluate the performance of a genotype it is necessary to understand and assess the plant traits such as growth, development, physiological characteristics, yield, tolerance, adaptation and resistance of plants to certain biotic and abiotic stress. Moreover, there is a complex gene × environment interaction which makes the evaluation of crop cultivar grown in the field even more difficult. Hanson and Nelson (1980) stated that the genotype evaluation and screening method should be rapid, accurate, can handle large number of samples within a short period of time, can be used early in the season and non-destructive. Canopy temperature is being used as an efficient method to monitor the plant response to water stress which is the basis for evaluating different genotypes. Canopy temperature measurements are considered to be useful in developing drought resistance or drought tolerant varieties. It can be an indirect selection criterion for improving genetic gains in wheat genotypes for heat and drought adaptation (Mohammadi et al., 2012). Rashid et al. (1998) investigated the use of canopy temperature measurements as a screening tool for drought tolerance in spring wheat by conducting field experiments in 1992 and 1993. Canopy temperature of 12 different spring wheat genotypes grown under two irrigation levels was measured. A difference in canopy temperature between the genotypes grown under both the irrigation treatments in both years was reported. Some varieties had consistently lower temperature while some other had consistently higher temperature under moisture stressed condition on different days when canopy temperature was measured. Similar results were found under irrigated condition as well. In a research conducted by Guendouz et al. (2012), a significant difference in canopy temperature among the genotypes was found under well-watered and water stressed condition. They also found a significant correlation between canopy temperature and grain yield and suggested that canopy temperature can be used in screening for developing tolerant varieties. Blum et al. (1989) stated that under water stress condition wheat genotypes with relatively lower mid-day canopy temperatures were found to have relatively better water status. Canopy temperature difference of 0-2ºC was observed by Hackl et al. (2012) between the wheat cultivars grown under different water regimes. Pinter et al. (1990) studied the use of canopy temperature in screening wheat genotypes for water use and yield characteristics by growing six spring wheat cultivars under well-watered and deficit irrigation regimes. They found some differences in canopy temperature among the cultivars grown under irrigated condition. Although, the differences were small under well-watered condition, they said that this information could be used to evaluate the performance of genotypes under deficit irrigation. Some of the warmer varieties grown under irrigated condition performed better when grown under water stress condition. The differences in canopy temperature among the genotypes show that the regular comparison of canopy temperature between the genotypes can provide additional selection criteria during breeding for drought tolerance. Thermal imaging which measures canopy temperature may be a potential method to evaluate the performance of genotypes grown under different environmental conditions (Winterhalter et al., 2011). It can be used as an easy, rapid, non-destructive screening method to understand the phenotypic variations of breeding populations for future genetic analysis (Prashar et al., 2013). Romano et al. (2011) investigated the use of infrared thermography for high throughput phenotyping of tropical maize genotypes. They took thermal images of 92 different maize genotypes grown under fully irrigated condition and water stressed condition during anthesis and blister stages. They found a significantly lower canopy temperature of genotypes that were under fully irrigated condition compared to genotypes grown under water stressed condition. They also found a significant difference in canopy temperature between the genotypes grown under water stressed condition. Their result showed that the genotypes having lower canopy temperature are better adapted to drought conditions producing relatively higher grain yield. They concluded that thermography can be potentially useful in genotype screening process in maize. Zia et al. (2013) investigated the use of thermal imaging to identify maize genotypes that can tolerate water stress. Three hundred tropical and subtropical maize hybrids that differ on maturity under well watered and water stressed conditions were evaluated. They used a high resolution (384×288 pixels) thermal camera (VarioCAM) to take the thermal images using a wide angle lens. A significant difference in canopy temperature between early and late maturing variety at the end of vegetative growth stage and blister stage was observed. Moreover, they found a difference of 5-6ºC in between the two genotypes that is highly stressed and one that is less stressed under water stressed condition and around 1-2ºC under fully irrigated condition. Furthermore, they found a negative correlation between canopy temperature and grain yield and suggested that thermal imaging can be used as a fast technique to monitor water stress of large number of genotypes during anthesis stage. Chaerle et al. (2006) investigated the combine use of thermal and chlorophyll fluorescence imaging to study the spatial and temporal heterogeneity to determine leaf transpiration and photosynthesis in the crop field. They suggested that this technique can be used for selection for stomatal or photosynthesis cultivar as well as can be applied for screening stress tolerance cultivars.

#### 2.3.2.3. Time of taking thermal images

There are different principles regarding how and when to measure canopy temperature that can be used for genotype selection and stress monitoring process (Printer et al., 1990). The first principle states that temperature measurements should be taken when there is less water content in the soil. The reason is; if the plants are capable of transpiring in a higher rate under low soil moisture condition then they are capable of maintaining relatively higher growth and yield. This principle has been verified by some of the research experiments (Gardner et al., 1986). The second principle is that the temperature measurements should be taken under well watered conditions. The reason for this is that when the plants have higher temperature under this condition then it means they are transpiring less and saving water in the soil profile which can be used later during reproductive stage and have better chances of getting higher yields. Printer et al.

(1990) found that the genotypes of pearl millet and winter wheat with higher canopy temperature under well-watered conditions used less amount of water for growth which helped them to produce relatively higher yields. Also, they said that the warmers genotype under fully irrigated condition can perform better when grown in non-irrigated condition. Hatfield et al. (1987) also found similar kind of results in their research on cotton. The strains which were warmer earlier in the season used low soil water and remained cooler in the latter stage of crop growth. These principles are the basis for screening varieties for drought stress. On the other side, it is also considered that the plants that can maintain cooler canopy throughout the growing season might have deeper root system and are capable of pulling water from the deeper soil profile (Kaman et al., 2011). Also, some of the genotypes can have higher leaf water content and can maintain lower canopy temperature and higher yield thereby improving water use efficiency (Silva et al., 2007). Because of the strong negative correlation between grain yield and canopy temperature, it can be said that lower canopy temperature can be one of the factors influencing grain yield (Pradhan et al., 2014).

It is very important to determine the optimum time of taking thermal images considering the stage of crop, time of day and weather conditions. In most of the studies, canopy temperature was measured around midday (Printer et al., 1990; Reynolds et al., 1984). Zia et al. (2012) in their study took thermal images hourly to study the effect of the time of day on image acquisition and found that midday can be the most appropriate time to take thermal measurements because of the highest canopy temperature and lowest stomatal conductance during solar noon and said that this will help to find the greatest difference between the treatments. Wanjura et al. (2003) measured canopy temperature throughout the day and found a larger variation in canopy temperature between the treatments form 1200 to 1600 hours in the afternoon. Pradhan et al. (2014) analyzed the canopy temperature measurements taken throughout the day and found that 1100-1300 and 1600 hours are the best time for measuring canopy temperature. Balota et al. (2007) tried to determine optimal measurement times for canopy temperature in relation to growth stage, time of day, and weather for the Texas High Plains environment. They found that the best times to measure canopy temperature is around 0900 in the morning and 1300 in the afternoon. They also noted a poor correlation between canopy temperature depression (CTD) and other parameters when the measurements were taken during low solar radiance, high wind speed and rain events.  The following figure (Figure 2.1) explains the time where genotypes showed differences in canopy temperature. It shows that the differences in treatments with regard to canopy temperature can be found during 1100-1600 hours of a day. Although, canopy temperature differences are seen most of the times during the day, it is suggested to take thermal images close to solar noon because of the differences in canopy temperature between the sunlit and shaded leaves (Jones et al., 2002).

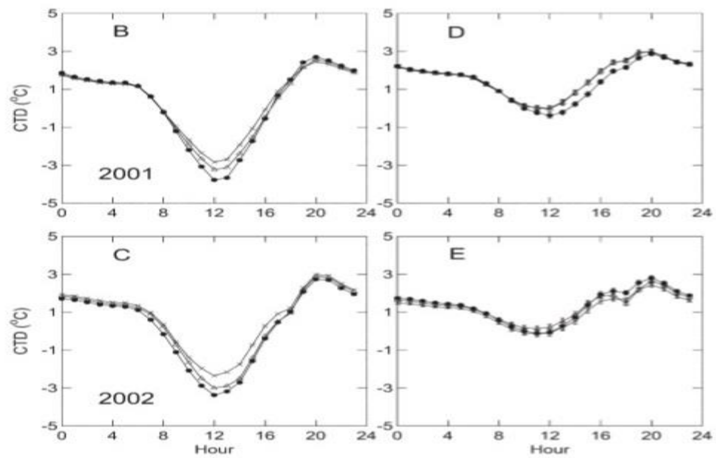



Figure 2.1. Diurnal canopy temperature depression (CTD) trends for three closely related wheat lines grown under (B-C) dryland and (D–E) irrigated conditions at Bushland, TX (Balota et al., 2007).

Regarding the appropriate crop growth sage of taking thermal images, Zia et al. (2013) recommended to take the measurements during grain filling stage of maize as the difference in canopy temperature between the genotypes was found to be clearer. They also suggested that blister stage is also critical for determining grain yield in maize and measurements can be during this period as well. Feng et al. (2009) took measurements for canopy temperature, stomatal conductance and transpiration during kernel filling to maturity in wheat.  Pradhan et al. (2014) reported that the best time for taking thermal measurements is during grain filling stage of wheat.

# CHAPTER 3

# MATERIALS AND METHODS

## 3.1. 2014/2015 Wheat Experiment

### 3.1.1. Description of Study Area

The field experiment was conducted at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas (35º11'N, 102º06'W, and elevation 1170 m) during the 2014-2015 wheat growing season. The soil type was Pullman clay loam soil (fine, mixed, thermic Torrertic Paleustoll: USDA classification). Climate in Bushland is semi-arid with erratic rainfall and high temperatures during summer causing higher evaporative demands. The precipitation during the growing season was 524 mm, and the average maximum and minimum temperature during the growing season was 17.4ºC and 6.2ºC, respectively.

Table 3.1. Summary of monthly temperature for the 2014-2015 winter wheat growing season at Bushland, Tx

| | Temperature | |
|---|---|---|
| Month | Maximum | Minimum |
| | ºC | ºC |
| October | 23.6 | 6.7 |
| November | 13.6 | -3.1 |
| December | 10.6 | -4.3 |
| January | 6.9 | -5.8 |
| February | 11.4 | 3.4 |
| March | 16.2 | 7.8 |
| April | 22.6 | 12.9 |
| May | 22.3 | 15.4 |
| June | 29.2 | 22.7 |

Source: U. S. Climate data

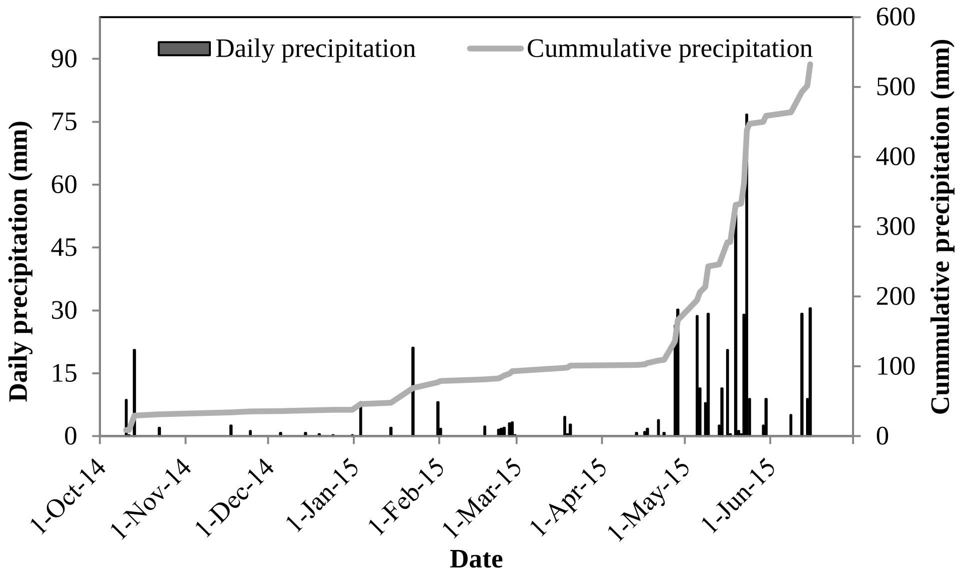



Figure 3.1. Daily and cumulative precipitation during the 2014/15 wheat growing season

### 3.1.2. Experimental Materials and Design

Twenty different winter wheat genotypes (Table 3.2) were planted under both irrigated and dryland conditions on 2 October and 7 October, 2014, respectively. The two soil water regimes were located in two different fields. Irrigation was carried out several times with linear sprinkler irrigation system in the irrigated plots. The experimental design was a randomized complete block design with three replications. Seeding rate was 67 kg/ha for dryland and 100 kg/ha for irrigated plots. The plot size was 4.6 m × 1.52 m (7 $m^2$) dryland and 3 m × 1.52 m (4.6 $m^2$) for irrigated plots while the row spacing for all of the plots was 18 cm. There were seven rows per plot in both conditions.

Table 3.2. Wheat genotypes used in this study with their pedigree

| Name | Year of release | Pedigree |
|---|---|---|
| TAMW-101 | 1971 | KS56761/Bison (=TX65A1682) (CI 15324) |
| TAM105 | 1979 | Short wheat/Sturdy composite bulk selection |
| TAM110† | 1996 | TXGH12588-105=(TAM 105*4/Amigo*4//Largo) |
| TAM111 | 2003 | TAM 107/TX78V3620/CTK78/3/TX87V1233 |
| TAM112† | 2005 | 105*4/Amigo*4//Largo) |
| TAM114 | 2014 | TAM 111/TX98A0050 (=N87V106//TX86V1540/TAM 200) |
| TAM304 | 2007 | TX01D3232=TX92U3060/TX91D6564 (=X95U104-P66) |
| TAM113 | 2010 | TX02A0252=TX90V6313//TX94V3724(TAM-200 BC41254-1-8-1-1/TX86V1405 |
| TX99A0153-1† | Not released | Ogallala/TAM-202 |
| Dumas | 2000 | WI90-425/WI89-483 |
| PlainsGold Byrd | 2011 | CO06424=TAM 112/CO970547-7 |
| Jagalene | 2001 | Abilene/Jagger |
| Hatcher | 2005 | Yumar/PI372129//TAM-200/3/4*Yumar/4/KS91H184/Vista |
| Winterhawk | 2007 | 474S10-1/X87897-26//HBK0736-3 |
| Iba | 2012 | OK93P656-RMH3299/OK99621 F4:11 |
| Endurance | 2004 | HBY756A/´Siouxland`//´2180` |
| Duster | 2006 | OK93P656H3299-2C04=WO405D/HGF112//W7469C/HCF012 |
| Billings | 2009 | OK03522=N566/OK94P597 F4:14 |
| Jagger | 1994 | KS82W418/Stephens (=KS84063-9-39-3) (PI 593688) |
| Fuller | 2006 | KS00F5-14-7=BULK SELN |

†The genotype has 1AL. 1RS rye translocation.

### 3.1.3. Thermal measurements

#### 3.1.3.1. Thermal image acquisition

A handheld thermal camera, FLIR ThermaCam (model HS45S) with a spatial resolution of 320 × 240 and a wide angle lens with a Field of View (FOV) of 68º, was used to take thermal images. This camera captures the radiation emitted by the object and forms an image within a very short period of time (ten seconds).

Images were taken between 12:00 and 13:30 in dryland and between 14:00 and 15:30 in irrigated plots to minimize the influence of solar angle on the canopy. A two meter ladder was used to take the images in order to capture the canopy and the height between the plant and the camera was maintained constant throughout the growing season (Figure 3.2). In order to reduce the atmospheric (air temperature, solar radiation, humidity) variation between the first plot and the last plot to measure, the duration of taking images was minimized by taking images of two plots at the same time keeping the ladder in the alley in between the plots. Images were taken several times during the crop growing season considering several growth stages. In dryland, images were taken from 186 DAP (between jointing and booting) to 232 DAP (gran filling), while in the irrigated condition, between 188 DAP (jointing) to 226 DAP (grain filling) in 7 to 12 day intervals depending upon atmospheric and soil moisture conditions (Table 3.3). Images were not taken when it was too windy or cloudy and when the field was too wet.

Table 3.3. Days of image acquisition during the wheat growing season

| Date | Days After Planting (DAP) | Crop growth stage |
|---|---|---|
| | Dryland | |
| 09 April, 2015 | 186 | Between jointing and booting |
| 20 April, 2015 | 197 | Boot stage |
| 29 April, 2015 | 206 | Heading and anthesis |
| 12 May, 2015 | 218 | Grain filling |
| 18 May, 2015 | 224 | Grain filling |
| 27 May, 2015 | 232 | Grain filling |
| | Irrigated | |
| 17 April, 2015 | 188 | Jointing |
| 1 May, 2015 | 201 | Boot stage |
| 12 May, 2015 | 212 | Heading and anthesis |
| 18 May, 2015 | 218 | Grain filling |
| 27 May, 2015 | 226 | Grain filling |

Figure 3.2. Taking thermal images of wheat plots

#### 3.1.3.2. Processing the thermal images

ThermalCAM Researcher Pro 2.8 SR-1 (FLIR Systems, Inc., Boston, MA) software was used to convert the thermal JPEG format images to FLIR Public file (.fpf) format. The converted (.fpf) file was then uploaded into IR Crop Stress Image Processor Software which was developed was David Verbree (2012) to post process the thermal images. This software filters out the background soil from the image on the basis of temperature differences between plant canopy and background soil. When the temperature of the plant material is significantly different than the temperature of soil material then by the use of clustering algorithms, the software filters out the soil automatically. After filtering out the soil, the software calculates the average canopy temperature taking into account numerous canopy pixel points from the plant material in the image. Furthermore, it also gives the standard deviation, minimum temperature, maximum temperature, and number of canopy pixels that were selected and included, while calculating the average canopy temperature.

During the processing of image in the software, a rectangular portion of the plot was selected from the image leaving the border in all the sides and the data were recorded only from the selected portion. The software then removed the soil material from the image and gave the canopy temperature reading of the selected rectangular portion (Figure 3.3).

**Image taken by normal camera**

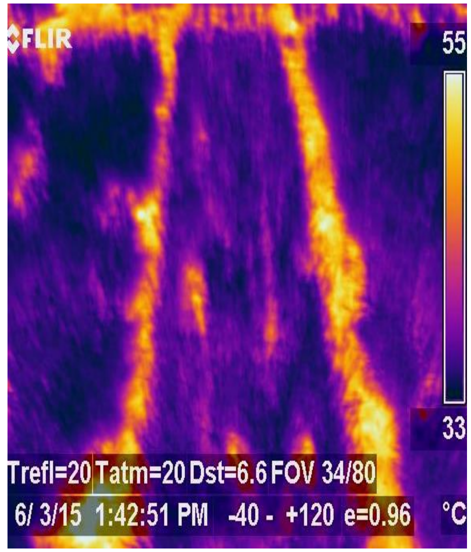
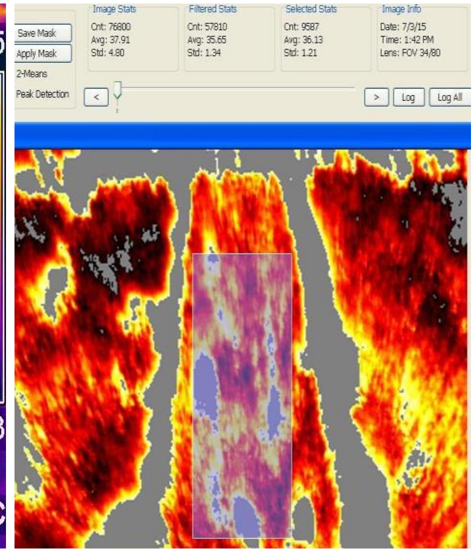
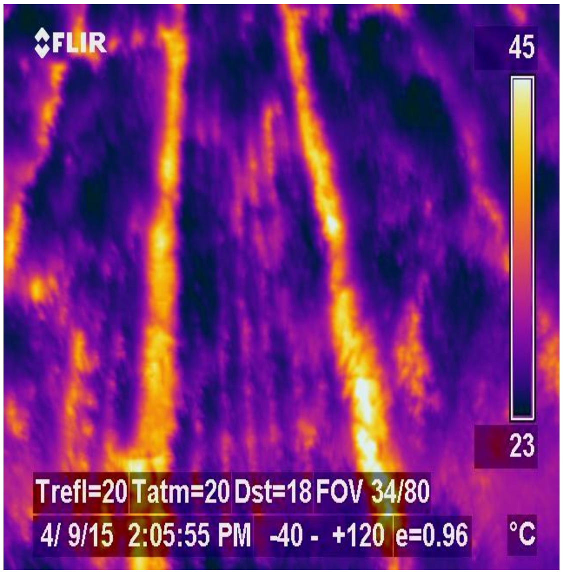


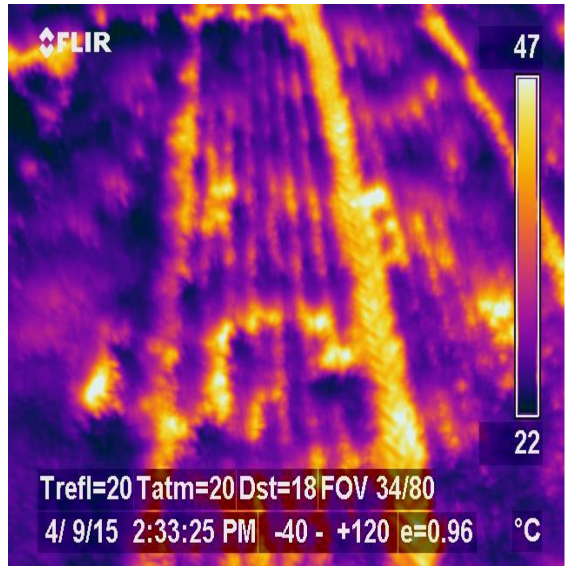

**Image taken by thermal camera**



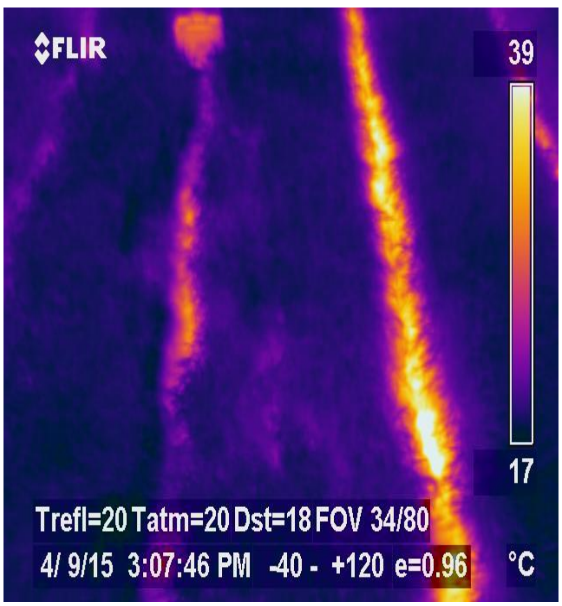

**Soil separated from the plot during image processing**

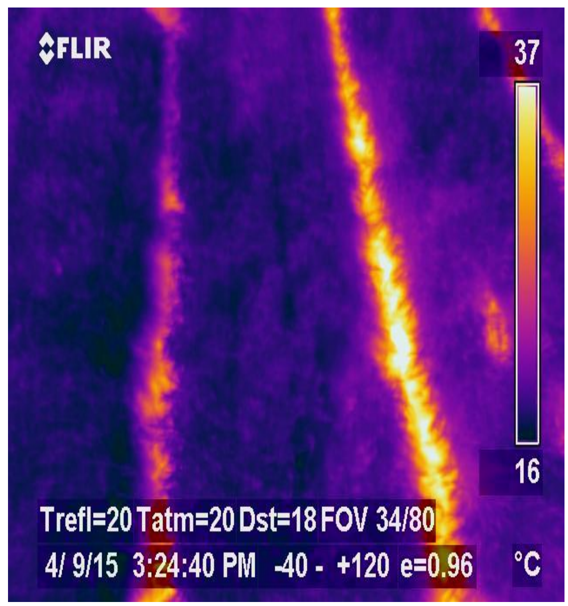
Figure 3.3. Processing the thermal images




**A. TAM111- Dryland** **B. Dumas- Dryland**




**B. TAM111- Irrigated** **D. Dumas- Irrigated**

Figure. 3.4. Thermal images taken on same date under dryland (A-B) and irrigated condition (C-D)

#### 3.1.3.3. Infrared Thermometer (IRTs) Measurements

The canopy temperature was also measured using SmartCrop wireless IRTs (Smartfield Inc., Lubbock, TX, www.smartfield.com). The main objective of using IRTs in this study was to compare the canopy temperature measurements taken by thermal camera and IRTs as IRTs are widely used to measure canopy temperature and CTD. IRT sensors were installed on mid-April in two replications in both the dryland and irrigated fields. A base unit was also installed near the study area to collect and store the data from all the 40 sensors in each water regime. The sensors were positioned about 30 cm above the canopy and were facing downwards with an angle of 45º. All sensors were installed parallel to rows so that they collect the radiation emitted by the surface (Figure 3.5). These sensors record data every minute and report the average every 15 minutes to the base station. The base station located near the field also records the ambient air temperature with the help of sensor in the same manner as IRTs. The data were collected from April 17 until May 24, 2015. But for this study, data were used only from the respective days and time when thermal images were taken.

Figure 3.5. IRT sensors in the field

### 3.1.4. Other Plant Parameters

To evaluate the genotypes and to study the canopy temperature relationship, other crop growth parameters such as leaf chlorophyll content and plant biomass were measured.

*Leaf chlorophyll content*

Leaf chlorophyll measurements were taken using a portable chlorophyll meter (SPAD -502, Minolta Camera Co. Ltd., Japan). In each plot, readings were taken from four fully expanded flag leaves and all the values were averaged for a single value for each plot. The same sampling method was used in both the dryland and irrigated water regimes, and measurements were taken during anthesis stage of crop growth.

*Biomass*

Above ground biomass was collected at anthesis; 50 cm of one row was cut at ground level from each plot. For each plot, stems and heads were separated and dried at 60ºC for 72 hours. The total weight was expressed on gram per $m^2$ basis.

*Yield*

Yield of both the dryland and irrigated plots were not harvested because of severe damage (Figure 3.6) caused by hailstorm. Plots were severely lodged and the heads shattered.

Figure 3.6. Wheat plots lodged and damaged by hailstorm

### 3.1.5. Statistical Analysis

Statistical analysis was done using the SAS version 9.3 (Statistical Analysis System Institute, Cary, NC, USA). Analysis of variance (ANOVA) was performed using the General Linear Model and mixed model to compare differences among the genotypes under dryland and irrigated conditions. Least significant values at P=0.05 were used to compare means for each parameter among the 20 wheat genotypes.  Correlation was used to study the relationship between different parameters.

## 3.2. 2015 Maize Study

### 3.2.1. Description of the Study Area

The field experiment was conducted at the Texas A&M Agrilife Bushfarm, Bushland, Texas (Lat. 35º11'N, Long. 102º06'W; elevation 1170 m above mean sea level) during the 2015 maize growing season. The soil type was Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll: USDA classification). The precipitation during the growing season was 514 mm, and the average maximum and minimum temperature during the growing season was 28.6ºC and 21.8ºC, respectively.

Table 3.4. Summary of monthly temperature for the 2015 maize growing season at Bushland, Tx

| | Mean Temperature | |
|---|---|---|
| Month | Maximum | Minimum |
| | ºC | ºC |
| June | 29.2 | 22.7 |
| July | 31.1 | 24.6 |
| August | 30.8 | 23.8 |
| September | 30.3 | 22.8 |
| October | 21.8 | 15.4 |

Source: U. S. Climate data

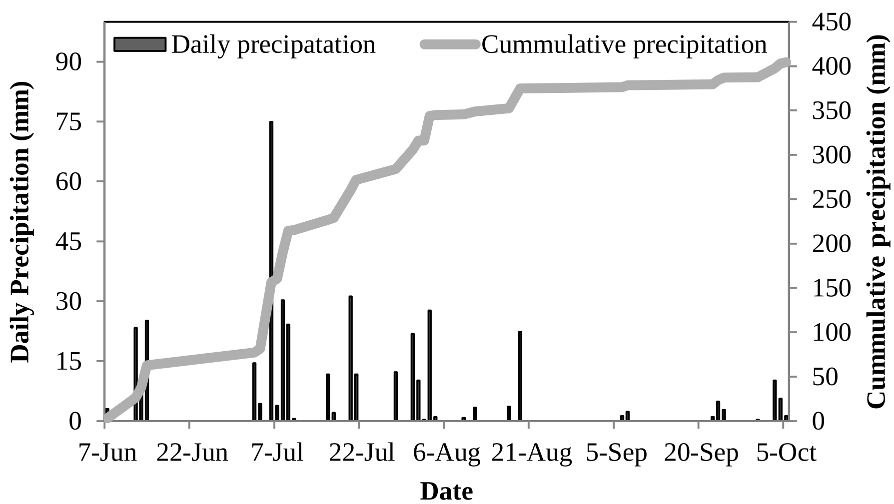



Figure 3.7. Daily and cumulative precipitation during the maize growing season in 2015 (US Climate data)

Table 3.5. Amount of irrigation applied during the maize growing season

| Date | Days after planting (DAP) | Amount of irrigation (mm) |
|---|---|---|
| | **$I_{100}$** | |
| 11-Aug | 66 | 81 |
| 18-Aug | 73 | 37 |
| 24-Aug | 79 | 30 |
| 4-Sep | 90 | 63 |
| 11-Sep | 101 | 31 |
| 18-Sep | 108 | 42 |
| | Total | 286 |
| | **$I_{50}$** | |
| 12-Aug | 67 | 42 |
| 18-Aug | 73 | 21 |
| 19-Aug | 74 | 20 |
| 4-Sep | 90 | 43 |
| | Total | 126 |

### 3.2.2. Experimental Materials and Design

The experimental design was a split-plot design with four replications. Irrigation was the main plot factor with hybrid as a sub-plot factor. Irrigation treatment consisted of two different water regimes, 100% ($I_{100}$) and 50% ($I_{50}$) of the expected ET requirements, but due to technical problems with the irrigation system, both treatments were moderately stressed in early stages. The varietal treatments had five different hybrids. Once the irrigation system was established, furrow irrigation was applied several times during the growing season to maintain target soil water level as determined by neutron moisture meter. The total irrigation water applied for $I_{100}$ and $I_{50}$ were 286 mm and 126 mm respectively.

Five different hybrids that differ in their drought tolerance characteristics were planted on 6 June, 2015 (Table 3.6). Among them, hybrid 33D53AM is considered as drought susceptible and N74R is considered as drought tolerant. The field had a total of

40 experimental plots (2×5×4) and each plot comprised of four rows, 0.7m wide and 9.14 m long. Each plot had four rows with spacing of 0.76m.

Table 3.6. Maize hybrids used in this study with their agronomic details

| Name | Maturity |
|---|---|
| 33D53AM | 115 |
| N74R | 114 |
| N75H | 115 |
| P1151AM | 113 |
| TAM | 115 |

### 3.2.3. Measurements

#### 3.2.3.1. Thermal image acquisition

As in the wheat study, handheld thermal camera, FLIR ThermaCam (model HS45S) with a spatial resolution of 320 × 240 and a wide angle lens with a Field of View (FOV) of 68º was used to take thermal images. Images were taken during the midday hours starting from 13:00 to 14:00 using a ladder (Figure 3.8). Usually it took 40 minutes to one hour to take the images on both the water regime. It is assumed that the weather condition does not have a major effect on taking thermal images because of short time interval in taking images. Images were taken on cloud free days when the sky was clear several times during the crop growing season representing several growth stages. They were taken on different dates starting from 39 DAP (late vegetative stage) to 89 DAP (grain filling stage) at 7-15 day intervals on both the water regimes (Table 3.7). In order to study the effect of irrigation level on canopy temperature, images were taken when the upper layer of the soil was dry after irrigation water was applied. Usually, a 2-3 day interval was maintained between irrigation application and image acquisition.

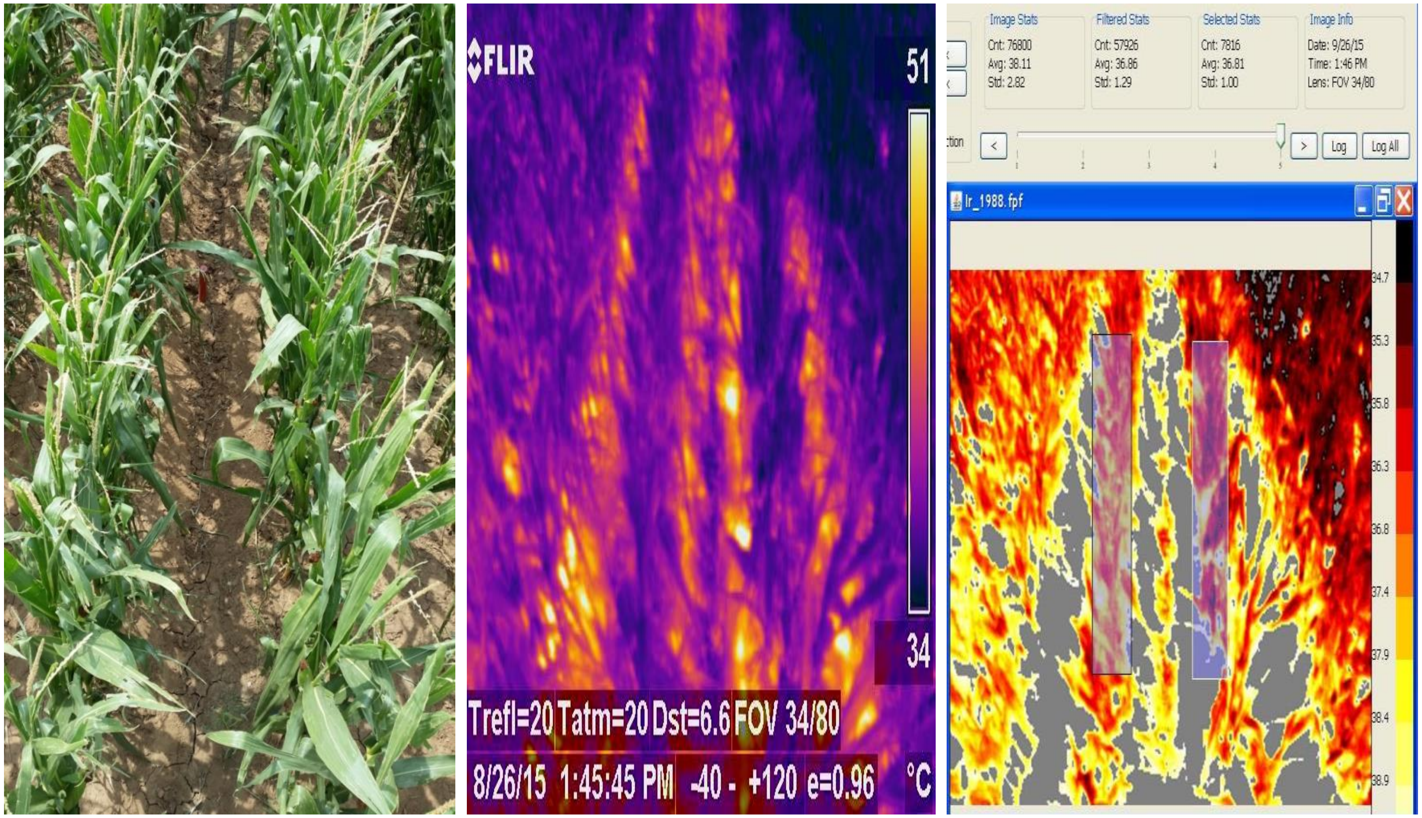

Figure 3.8. Thermal image acquisition of maize plots

Table 3.7. Dates of image acquisition during the maize growing season

| Date | Days After Planting (DAP) | Crop growth stage |
|---|---|---|
| 15 July, 2015 | 39 | Vegetative stage |
| 24 July, 2015 | 48 | Vegetative stage |
| 28 July, 2015 | 52 | Tasseling stage |
| 5 August, 2015 | 60 | Silk stage (R1) |
| 22 August, 2015 | 77 | Milk stage (R3) |
| 26 August, 2015 | 81 | Milk stage (R4) |
| 3 September, 2015 | 89 | Dough stage (R5) |

### 3.2.3.2. Processing the thermal images

As in the wheat study, ThermalCAM Researcher Pro 2.8 SR-1 (FLIR Systems, Inc., Boston, MA) software was used to process the thermal images. To obtain temperature data from the image, two rows were selected in the image leaving the bordered two rows. Individual rows from the plot were selected to avoid the shading of plants in between the rows if there was any in the image (Figure 3.9-C). The software filtered out the background soil that was in between the plants and in between the rows. For each of the plots, the selection of rows was made similar by selecting similar number of pixels from two rows in the image. Average, minimum and maximum canopy temperature, and standard deviation was then recorded in the excel sheet.




**A. Image taken by normal camera**

**B. Image taken by thermal camera**

**C. Image processing-soil separated from the image**

Figure 3.9. Thermal image processing of maize plots

#### 3.2.3.3. Other measurements

*Climatic data*

To record the ambient air temperature, a base station was installed at the edge of the field as in wheat study.

*Biomass*

Above ground biomass was collected during harvest of the crop. Six plants from central two rows of each plot were harvested for biomass. To determine the dry biomass, these plants were separated into stover and ears. After grain was threshed off the ears, the cobs and stems were dried at 70ºC until they reached a constant weight. This biomass and grain yield was used to calculate the harvest index and to study the relationship of above ground biomass with canopy temperature. Harvest index was calculated as the ratio of the grain weight to the total above ground plant biomass.

*Yield*

$I_{50}$ plots were harvested on 30 September, 2015 and fully irrigated plots were harvested on 12 October, 2015. Ears were harvested from a total of 6 m length of central two rows in which 3 m was harvested from each row. Yield was adjusted to 15.5% moisture for reporting.

### 3.2.4. Statistical Analysis

Statistical analysis was done using the SAS version 9.3 (Statistical Analysis System Institute, Cary, NC, USA). Analysis of variance (ANOVA) was performed using the General Linear Model (GLM) to compare differences among the genotypes under dryland and irrigated conditions. The hybrid, irrigation treatment and their interaction was considered as fixed effects and replication was considered as random effect. Least significant values at P=0.05 were used to compare means for each parameter. Correlation was used to study the relationship between different parameters.

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1. 2014/2015 Wheat Study

### 4.1.1. Canopy temperature variation among wheat genotypes under dryland condition

Under dryland condition, significant differences in canopy temperature among the genotypes were not observed during the early growth stage of wheat (Table 4.1). However, significant differences were detected on 218 DAP, 224 DAP and 232 DAP when the crop reached anthesis, and grain filling stage. In 218 DAP, TAM304 had the highest canopy temperature of 21.1ºC and TAM111 had the lowest canopy temperature of 19.6ºC. In 224 DAP, the highest mean canopy temperature was found in Dumas (24.4ºC) and the lowest was found in Jagalene (23.0ºC). In 232 DAP, Iba had the lowest temperature of 26.9ºC and TAM304 had the highest temperature of 28.5ºC. Moreover, if we consider all the days when thermal images were taken then, similar ranking of cultivars occurred when TAM304, TAMW-101 and Dumas were the warmest while TAM111, TAM114 and PlainsGold Byrd were the coolest. The canopy temperature averaged across all the measurement dates also showed a similar trend. These results are in agreement with the study done by Pradhan et al. (2014) in which they found the canopy temperature of TAM111 to be lower throughout the growing season. It was 0.9ºC cooler than other genotypes (TX86A8072, TX86A5606). But, in case of Dumas, they noted a lower canopy temperature which is the opposite of what was found in this study.

One of the reasons that these genotypes behaved differently under similar growing conditions might be because of the variation in the genotypic composition among the genotypes. TAM111 and TAM114 have a similar genetic makeup and were released as drought tolerant varieties by TexasAgrilife Research (Xue et al., 2014). Similarly, PlainsGold Byrd was released by Plains Gold from Colorado as one of the drought tolerant variety. These varieties might have the ability to maintain transpiration and remain relatively cooler in comparison to other varieties. A different behavior was found in Jagalene in this study; it had relatively higher temperature during early growth but became cooler in the later stage of crop growth. This behavior is similar to what Hatfield et al. (1987) reported in their study in which they found that the genotypes with higher canopy temperature early in the season became cooler during the later growth stage. This variety was also released as a drought tolerant variety by Syngenta for semiarid regions. One of the reasons for this appearance may be because this cultivar uses less water early in the season due to less transpiration and saves water for later reproductive phase which makes the genotype cooler later in the growing season. This difference in seasonal canopy temperature variation depicts the differential drought tolerance mechanisms between the TAM varieties and non-TAM varieties which might be because of differences in genetic composition. Moreover, the drought tolerant varieties may have compact and deeper root systems in comparison to drought susceptible cultivars, which help them to pull water from deeper soil profile and maintain cooler canopy temperatures either throughout the crop growing season or in some phase of growth (Manschadi et al., 2006). Thus, it shows that the behavior of plants to tolerate periodic drought is either due to preventing water loss early in the season or by maintaining a consistent supply of water to the plants. On the other hand, cultivars Dumas, TAM 105, TAM304, and TAMW-101 were comparatively warmer and were considered drought susceptible by several researchers. TAM304 and TAM105 are considered to perform better under irrigated conditions but not under dryland condition by Texas Agrilife Research when they were first released. Xue et al. (2014) reported that TAM105 and Dumas had higher yield reduction during drought and were considered susceptible to limited water conditions. The reason might be because these varieties may not have the potential to capture water from the soil and maintain transpiration as other genotypes resulting into higher canopy temperature. Also, a canopy temperature difference of 1.5ºC to 2.7ºC at different days was found between the warmer and cooler genotypes (Table 4.1). Although, the differences between the genotypes is small these data shows that thermal imaging can be used to identify the genotypes that behave differently under limited water condition in terms of canopy temperature.

Table 4.1. Mean Canopy temperature of wheat genotypes calculated from thermal images taken at different days under dryland condition

| | Canopy temperature (ºC) | | | | | |
|---|---|---|---|---|---|---|
| Genotypes | 186 DAP | 197 DAP | 206 DAP | 218 DAP | 224 DAP | 232 DAP |
| Billings | 25.9 | 23.9 | 24.0 | 20.1 | 23.5 | 27.5 |
| Dumas | 25.8 | 22.7 | 23.7 | 20.7 | 24.0 | 28.0 |
| Duster | 24.2 | 23.0 | 23.0 | 19.8 | 23.3 | 27.4 |
| Endurance | 23.8 | 23.1 | 22.9 | 20.1 | 23.4 | 27.2 |
| Fuller | 24.8 | 22.7 | 22.7 | 20.5 | 23.6 | 28.5 |
| Hatcher | 25.8 | 23.2 | 24.2 | 20.5 | 23.5 | 27.9 |
| Iba | 23.9 | 21.8 | 22.1 | 20.1 | 23.3 | 26.9 |
| Jagalene | 24.2 | 23.0 | 23.1 | 20.2 | 22.9 | 27.0 |
| Jagger | 24.1 | 23.0 | 23.3 | 20.2 | 23.5 | 27.9 |
| PlainsGold Byrd | 23.7 | 21.3 | 22.6 | 19.9 | 23.0 | 27.1 |
| TAM105 | 24.3 | 22.9 | 23.5 | 20.7 | 24.1 | 28.2 |
| TAM110 | 23.6 | 21.8 | 23.2 | 20.5 | 24.3 | 28.5 |
| TAM111 | 23.2 | 20.1 | 22.6 | 19.6 | 23.0 | 27.4 |
| TAM112 | 24.2 | 21.8 | 23.6 | 21.0 | 24.3 | 27.7 |
| TAM113 | 24.4 | 22.8 | 22.5 | 20.1 | 23.4 | 27.7 |
| TAM114 | 23.7 | 21.0 | 23.8 | 20.3 | 23.3 | 27.2 |
| TAM304 | 24.4 | 22.8 | 23.5 | 21.1 | 24.2 | 28.5 |
| TAMW-101 | 25.0 | 21.6 | 24.0 | 21.0 | 24.3 | 28.4 |
| TX99A0153 | 24.4 | 21.4 | 23.2 | 20.2 | 23.3 | 27.9 |
| Winterhawk | 25.3 | 24.5 | 23.3 | 20.2 | 23.3 | 27.2 |
| **Mean** | 24.4 | 22.4 | 23.2 | 20.3 | 23.6 | 27.7 |
| **CV (%)** | 4.7 | 7.11 | 3.31 | 2.55 | 1.89 | 1.91 |
| **LSD (0.05)** | NS | NS | NS | 0.9 | 0.7 | 0.9 |
| **P-Value** | 0.21 | 0.23 | 0.12 | 0.05 | 0.0002 | 0.0002 |

### 4.1.2. Canopy temperature variation among genotypes under irrigated condition

Under irrigated condition, the wheat genotypes showed significant differences in their canopy temperature only once at 218 DAP (Table 4.2) which represents anthesis stage of crop development. The highest mean canopy temperature was from Jagger (24.4ºC) and the lowest was from TAM111 (23.0ºC). On other days there was no significant difference between the genotypes. This can be because of sufficient supply of water throughout the growing season. Moreover, there was no significant difference in canopy temperature between the genotypes even when the temperature was averaged across all measurement days. These results are in opposite of what Pinter et al. (1990) reported from their field experiment that was conducted in Arizona. They found significant differences in canopy temperature between the wheat genotypes when grown under irrigated condition.

Table 4.2. Mean canopy temperature of wheat genotypes calculated from thermal images taken at different dates under irrigated condition

| | **Canopy temperature (ºC)** | | | | |
|---|---|---|---|---|---|
| Genotypes | 188 DAP | 201 DAP | 212 DAP | 218 DAP | 226 DAP |
| Billings | 19.2 | 23.9 | 18.7 | 23.7 | 28.5 |
| Dumas | 17.9 | 23.1 | 18.4 | 23.7 | 29.2 |
| Duster | 17.8 | 23.8 | 18.6 | 23.6 | 26.7 |
| Endurance | 18.7 | 24.3 | 18.7 | 23.5 | 28.8 |
| Fuller | 17.8 | 23.5 | 18.2 | 24.0 | 28.8 |
| Hatcher | 17.5 | 24.2 | 18.4 | 23.9 | 28.9 |
| Iba | 18.4 | 24.0 | 18.5 | 23.7 | 28.4 |
| Jagalene | 17.4 | 23.8 | 18.1 | 23.4 | 28.4 |
| Jagger | 18.5 | 23.9 | 18.4 | 24.4 | 28.8 |
| PlainsGold Byrd | 17.9 | 25.0 | 17.9 | 23.1 | 28.5 |
| TAM105 | 17.6 | 23.2 | 18.6 | 23.7 | 29.1 |
| TAM110 | 18.0 | 23.9 | 18.4 | 23.5 | 29.4 |
| TAM111 | 17.7 | 24.3 | 18.6 | 23.0 | 29.3 |
| TAM112 | 18.5 | 23.9 | 18.5 | 23.9 | 29.5 |
| TAM113 | 19.0 | 23.9 | 18.8 | 24.1 | 29.1 |
| TAM114 | 18.1 | 24.0 | 18.0 | 23.9 | 29.5 |
| TAM304 | 18.6 | 24.2 | 18.3 | 24.3 | 28.9 |
| TAMW-101 | 18.7 | 23.3 | 19.5 | 23.6 | 29.0 |
| TX99A0153 | 17.8 | 23.1 | 18.4 | 23.7 | 28.8 |
| Winterhawk | 18.5 | 23.5 | 19.0 | 23.7 | 29.2 |
| **Mean** | 18.2 | 23.8 | 18.5 | 23.7 | 28.8 |
| **CV (%)** | 3.82 | 3.16 | 3.73 | 1.78 | 3.08 |
| **LSD (0.05)** | NS | NS | NS | 0.7 | NS |
| **P-value** | 0.118 | 0.34 | 0.75 | 0.04 | 0.18 |

### 4.1.3. Canopy temperature measured by thermal camera (TC) and infrared thermometer sensors (IRTs) under dryland and irrigated condition

Canopy temperatures calculated from thermal images were compared with the measurements taken from infrared thermometers. For this purpose, data obtained on the same day and same time from 20 genotypes under dryland and 15 genotypes under irrigated field with two replications were used. There was no significant difference in canopy temperature obtained from thermal imaging and infrared thermometers in all of the days when measurements were taken under both the irrigated and dryland conditions (Figure 4.1). However, temperature obtained from IRTs was slightly higher than that taken from thermal camera; 0.3-1.3ºC in dryland and 0.8-2.8ºC in irrigated condition. IRTs may have captured the radiation emitted from the soil which made the canopy temperature measurements appear higher. Wanjura et al. (2004) also observed higher average canopy temperature from infrared thermocouples than thermal scanner and concluded that this can be caused by more soil being viewed by the thermometers than thermal scanners. The difference in average canopy temperature measured by the two sensors was 0.2ºC under high water cotton, 3.2ºC under low water cotton and 0.6ºC under high water corn. Leinonen and Jones (2004) also stated the possibility of capturing infrared signals from the soil by IRTs making the temperature measurements higher. Hackl et al. (2012) also found the slight differences in maize canopy temperature taken by thermography and thermometry and said the different viewing angles and soil influences might be the reason for the differences. The difference in canopy temperature as measured from thermometry and thermography was 0-5ºC. These results indicate that the canopy temperature measured from the small area of crop canopy by infrared thermometers are comparable to those obtained from larger area using thermal camera when the leaf cover is sufficient to mask the soil background.

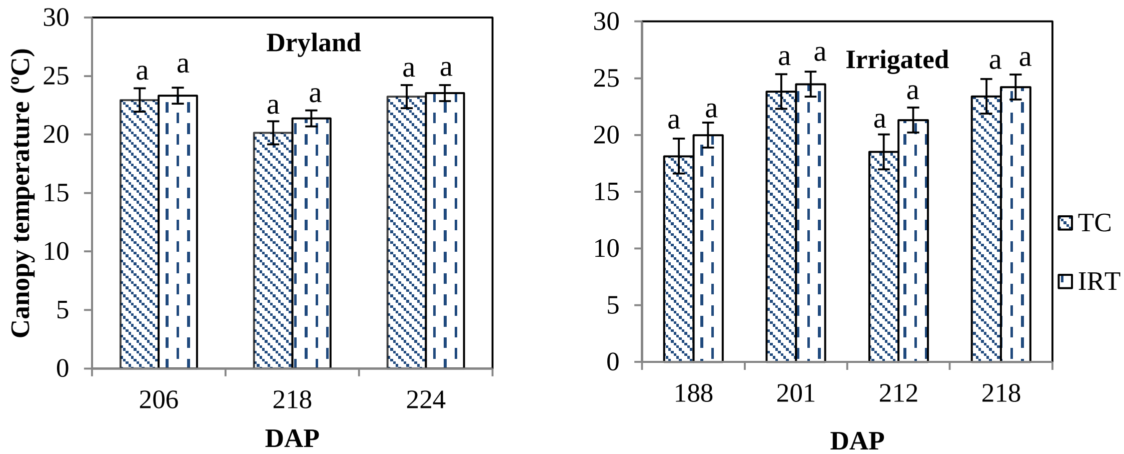



Figure 4.1. Mean canopy temperature of wheat genotypes measured by thermal camera (TC) and infrared thermometers (IRTs). Vertical bars represent standard error

### 4.1.4. Canopy temperature and air temperature

The average canopy temperature of 20 genotypes under dryland and irrigated condition was compared with the air temperature obtained during the period of image acquisition. In dryland condition, the mean canopy temperature of 20 genotypes as obtained from thermal images was 1.3 to 4.2ºC higher than the air temperature measured at the same time when thermal images were taken (Figure 4.2a). These results are in agreement with the results of Pradhan et al. (2014) who also found a higher canopy temperature of 1ºC to 9ºC than the surrounding air at different measurement days under dryland condition in their research that was also conducted in Bushland, Texas. It can be assumed that, because of limited water under dryland, plants could not maintain transpiration and got warmer and the canopy temperature became higher than the surrounding air. Moreover, similar results were reported by Balota et al. (2008) in which canopy temperature was 1.7ºC to 3ºC higher than the air temperature. However, inverse results were obtained by Karimizadeh and Mohammadi (2011) in which they found that the canopy temperature of rain-fed wheat was lower than air temperature. Under irrigated condition, canopy temperature was mostly lower or similar to air temperature (Figure 4.2b). During early stage of growth, the canopy temperature was almost 4ºC lower than the air temperature but, as the season proceeded, the difference became lower and the temperature of wheat canopy became similar to air temperature. This indicates that, when the plants have enough moisture in the soil, they will be able to maintain transpiration and, with the depletion of soil moisture; plants get stressed and the canopy temperature becomes higher than the air temperature. Balota et al. (2008) and Karimizadeh and Mohammadi (2011) also found similar results in irrigated wheat in which canopy temperature was lower than air temperature. Moreover, Balota et al. (2008) found a difference of 0-2ºC and Karimizadeh and Mohammadi (2011) found a difference of 0-4.5ºC between canopy temperature and air temperature. In a similar kind of study with different level of reduced irrigation treatments (T50 to T85), Padhi et al. (2011) found that, in all of the water levels, air temperature was higher than the average canopy temperature in wheat by 3ºC to 10ºC. This suggests that the reduction in soil moisture leads to an increase in the temperature of plants and if the stress becomes severe then the temperature of canopies become higher than the air temperature.

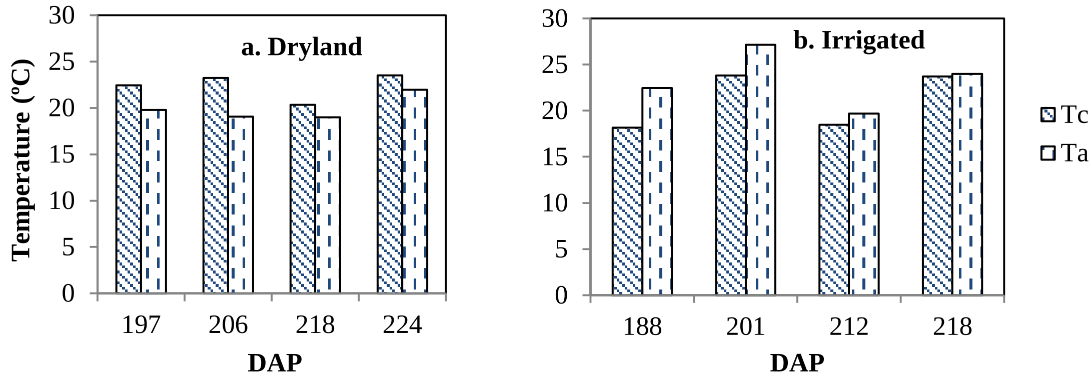



Figure 4.2. Canopy temperature ($T_c$) and air temperature ($T_a$) at different days under dryland and irrigated conditions

#### 4.1.5. Above-ground biomass and leaf chlorophyll (measured during anthesis stage) variation among wheat genotypes under dryland condition

As shown in Table 4.3, there was no significant difference among the genotypes in terms of biomass under dryland condition. However, PlainsGold Byrd had the highest biomass (1084.4 g $m^{-2}$) and the lowest was from TAMW-101 (556.4 g $m^{-2}$).

As shown in Table 4.3, the 20 wheat genotypes showed significant difference in their leaf chlorophyll content at anthesis under dryland condition. The highest mean value of leaf chlorophyll recorded was for Iba (52) and the lowest was from TAMW-101(43) and TAM304 (43).

Table 4.3. Summary statistics of biomass (g $m^{-2}$) and leaf chlorophyll content measured at anthesis stage of wheat genotypes under dryland condition

| Genotypes | Biomass (g $m^{-2}$) | Leaf Chlorophyll |
|---|---|---|
| Billings | 576.7 | 49 |
| Dumas | 628.3 | 49 |
| Duster | 858.8 | 49 |
| Endurance | 676.1 | 47 |
| Fuller | 869.7 | 44 |
| Hatcher | 581.8 | 47 |
| Iba | 731.8 | 52 |
| Jagalene | 808.9 | 49 |
| Jagger | 805.6 | 45 |
| PlainsGold Byrd | 1084.4 | 46 |
| TAM105 | 635.5 | 47 |
| TAM110 | 820.6 | 48 |
| TAM111 | 830.0 | 49 |
| TAM112 | 737.0 | 47 |
| TAM113 | 625.7 | 45 |
| TAM114 | 730.0 | 48 |
| TAM304 | 679.5 | 43 |
| TAMW-101 | 556.4 | 43 |
| TX99A0153 | 860.9 | 45 |
| Winterhawk | 626.4 | 49 |
| **CV (%)** | 26.24 | 5.6 |
| **LSD (0.05)** | 319.3 | 4 |
| **P-value** | 0.18 | 0.02 |

### 4.1.6. Above-ground biomass and leaf chlorophyll variation (measured at anthesis) among wheat genotypes under irrigated condition

As shown in Table 4.4, there was a significant difference among the genotypes in terms of biomass under irrigated condition. PlainsGold Byrd had the highest biomass (1543.5 g $m^{-2}$) and the lowest was from Endurance (832 g $m^{-2}$).

There was a significant difference among the 20 different wheat genotypes on leaf chlorophyll content where Iba (49) and Jagalene (49) had the highest leaf chlorophyll content and the lowest was from PlainsGold Byrd (40).

Table 4.4. Summary statistics of biomass (g $m^{-2}$) and leaf chlorophyll content measured at anthesis stage of wheat genotypes under irrigated condition

| Genotypes | Biomass (g $m^{-2}$) | Leaf Chlorophyll |
|---|---|---|
| Billings | 1077.9 | 48 |
| Dumas | 1010.4 | 48 |
| Duster | 1053.8 | 45 |
| Endurance | 832.8 | 45 |
| Fuller | 1161.3 | 44 |
| Hatcher | 1156.6 | 43 |
| Iba | 1113.8 | 49 |
| Jagalene | 1225.9 | 49 |
| Jagger | 1096.6 | 47 |
| PlainsGold Byrd | 1543.5 | 40 |
| TAM105 | 1473.0 | 43 |
| TAM110 | 934.1 | 42 |
| TAM111 | 1060.5 | 45 |
| TAM112 | 1455.4 | 43 |
| TAM113 | 1436.8 | 43 |
| TAM114 | 1350.6 | 48 |
| TAM304 | 1133.1 | 45 |
| TAMW-101 | 1085.6 | 46 |
| TX99A0153 | 1153.4 | 45 |
| Winterhawk | 1099.5 | 46 |
| **CV (%)** | 16.18 | 7.57 |
| **LSD (0.05)** | 420 | 5.64 |
| **P-value** | 0.01 | 0.06 |

### 4.1.7. Relationship between canopy temperature and above ground biomass

The Pearson's correlation analysis indicated an association between canopy temperature and above ground biomass. Above ground biomass harvested at anthesis stage was correlated with the canopy temperature measured during the same stage (206 DAP under dryland and 212 DAP under irrigated condition). A significant negative relationship was obtained under dryland condition (Table 4.5). Under irrigated condition the relationship was found to be negative but not significant ($r = -0.15$; $P > 0.05$). Several researchers have found that canopy temperature is associated with grain yield in wheat under dryland condition (Balota et al., 2008; Pradhan et al., 2014). It indicates that the lower canopy temperature might be associated with higher biomass production in wheat. Moreover, higher biomass may have contributed to a larger transpiration area of the canopy, resulting in lower canopy temperature.

Table 4.5. Pearson's correlation coefficient (r) between biomass (harvested at anthesis) and canopy temperature (measured during anthesis) under dryland and irrigated water regime. a) All 20 genotypes, b) TAM genotypes c) other genotypes

| Water regime | r | *p*-value |
|---|---|---|
| **Dryland** | | |
| a. All 20 genotypes | -0.55 | 0.01 |
| b. TAM genotypes | -0.32 | 0.46 |
| c. Other genotypes | -0.64 | 0.03 |
| **Irrigated** | | |
| a. All 20 genotypes | -0.30 | 0.52 |
| b. TAM genotypes | -0.15 | 0.23 |
| c. Other genotypes | -0.69 | 0.02 |

Table 4.6. Pearson's correlation coefficient (r) between biomass (harvested at anthesis) and canopy temperature measured on various days after planting (DAP) under dryland and irrigated water regimes

| Days after planting (DAP) | r | *p*-value |
|---|---|---|
| **Dryland** | | |
| 186 | -0.14 | 0.25 |
| 197 | -0.21 | 0.09 |
| 206 | -0.55 | 0.01 |
| 218 | -0.12 | 0.34 |
| 224 | -0.11 | 0.40 |
| 232 | 0.04 | 0.76 |
| **Irrigated** | | |
| 188 | -0.09 | 0.61 |
| 201 | -0.03 | 0.85 |
| 212 | 0.30 | 0.16 |
| 218 | 0.17 | 0.35 |
| 226 | 0.19 | 0.32 |

### 4.2. 2015 Maize study

### 4.2.1. Biomass, yield and yield components

The effect of hybrid and water regime on biomass, grain yield, harvest index, kernel weight and kernel number was studied. A significant effect of water regime was found in grain yield, harvest index, kernel weight and kernel number and final biomass (Table 4.7). Averaged across the hybrids, all of these variables increased as the amount of irrigated water increased from $I_{50}$ to $I_{100}$ (Table 4.8; Figure 4.3). These results are consistent with the results reported by Howell et al. (1995a), Colaizzi et al. (2011) and Hao et al. (2015). When the crop faces water deficit situation during reproductive stage then it can cause pollination failure leading to a reduced number of kernels and grain yield (Roth et al., 2013). This might be one of the reasons for having lower values for yield determining variables under reduced irrigation treatment compared to fully irrigated plots. However, similar impacts of drought have been seen in this study under both the irrigation treatments in which the grain yield, kernel number and kernel weight values are comparatively lower. There was a technical problem with the irrigation system during vegetative stage and irrigation was not applied until tasseling stage which might have caused moderate stress in plants under both treatments, resulting in relatively lower yield than those reported by Hao et al. (2015). They obtained higher values for yield and yield components except harvest index than those found in this study. Averaged across hybrids and years, under $I_{50}$ irrigation, yield was 7.35 Mg ha$^{-1}$, biomass was 14.8 Mg ha$^{-1}$, harvest index was 0.51, kernel weight was 195 mg kernel$^{-1}$, and kernel number was 3971 kernels m$^{-2}$. Under $I_{100}$ irrigaton level; yield (13.9 Mg ha$^{-1}$), biomass (28.89Mg ha$^{-1}$), harvest index (0.61), kernel weight (308 mg kernel$^{-1}$), and kernel number (4925 kernels m$^{-2}$) was found. Another reason for lower yield and yield components in this study might be due to the damage caused by hail during early vegetative stage resulting in crop stress. Results show that kernel number is much affected by water stress in which the number of kernels per square meter under $I_{50}$ was reduced by 32% as compared to $I_{100}$ and kernel weight was reduced by 29%. The final grain yield was reduced by 42% when the supply of water was reduced from $I_{100}$ to $I_{50}$. Hao et al. (2015) also found a similar yield reduction in their experiment in 2012 but reported a yield reduction of about 37% in 2013 which might be because of mild weather and high rainfall during critical growth period in 2013 growing season in comparison to 2012. Furthermore, as the result of this study indicated, they also reported that the yield loss from $I_{100}$ to $I_{50}$ was due to the reduction in kernel weight and kernel number. Moreover, a significant reduction in harvest index and biomass was found in $I_{50}$ plots which indicate that the final yield loss under reduced water level is because of lower harvest index and biomass as well. Reduced number of kernels, lower kernel weight, reduced biomass and lower harvest index under $I_{50}$ contributed to yield loss under reduced irrigation level.

Table 4.7. Analysis of variance of maize grain yield, biomass, harvest index, kernel weight, and kernel number as affected by water regime and hybrid

| Effect | d. f. | Grain yield | Biomass | Harvest index | Kernel weight | Kernel number |
|---|---|---|---|---|---|---|
| Water regime (WR) | 1 | 0.0072 | 0.0056 | 0.0030 | 0.0088 | 0.0146 |
| Hybrid (H) | 4 | <0.0001 | 0.8618 | <0.0001 | <0.0001 | 0.0009 |
| WR × H | 4 | 0.3736 | 0.3249 | 0.0066 | 0.0677 | 0.3888 |

Table 4.8. Summary statistics of maize biomass, and yield components as affected by water regimes and hybrid

| Water regime | Hybrid | Biomass† (Mg ha$^{-1}$) | Harvest† Index | Kernel weight† (mg kernel$^{-1}$) | Kernel number (kernels m$^{-2}$) |
|---|---|---|---|---|---|
| $I_{50}$ | 33D53AM | 9.67 | 0.46b | 166c | 2333a |
| | N74R | 11.90 | 0.53a | 256a | 2344a |
| | N75H | 10.92 | 0.46b | 207b | 2308a |
| | P1151AM | 11.12 | 0.57a | 219b | 2414a |
| | TAM | 12.37 | 0.35c | 225b | 1561b |
| | Mean | 11.20B | 0.47B | 214B | 2192B |
| $I_{100}$ | 33D53AM | 16.46 | 0.61b | 235b | 3944a |
| | N74R | 15.20 | 0.64ab | 294a | 3272b |
| | N75H | 15.72 | 0.61b | 297a | 2988bc |
| | P1151AM | 17.12 | 0.65a | 293a | 3595a |
| | TAM | 15.36 | 0.54c | 299a | 2416c |
| | Mean | 15.98A | 0.61A | 284A | 3243A |

†Biomass, harvest index, and kernel weight are calculated on the basis of dry weight.
For each water regime on each column means followed by same lowercase letters are not significantly different at the 0.05 probability level based on LSD test.
On each column means following the same uppercase letters are not significantly different at 0.05 probability level based on LSD test.

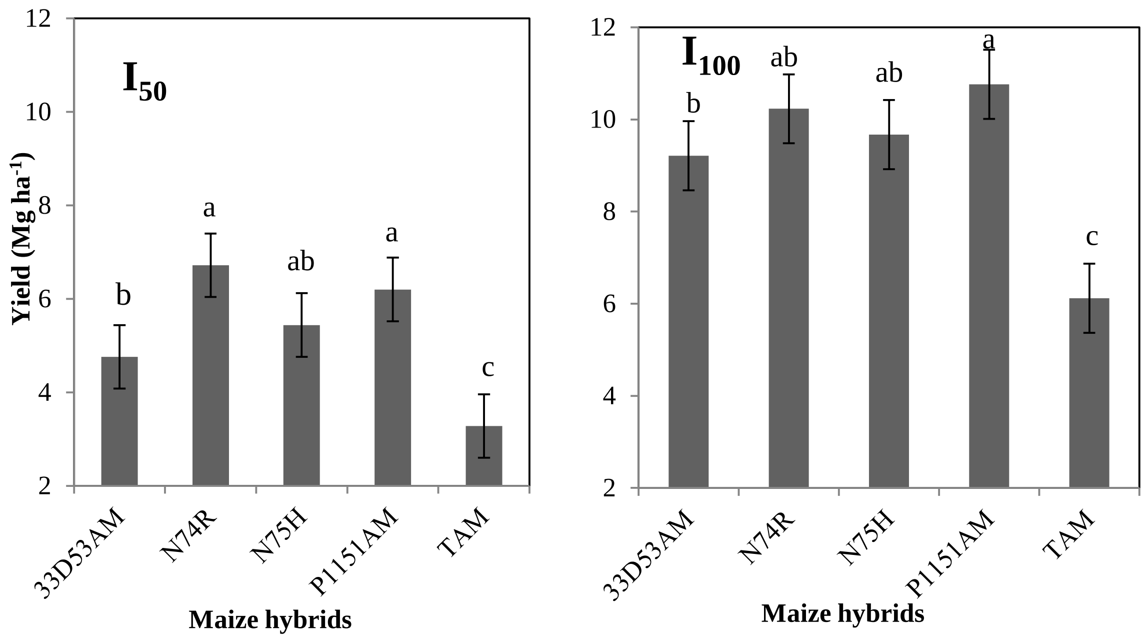



Figure 4.3. Grain yield variation among five maize hybrids grown under $I_{50}$ and $I_{100}$ irrigation regimes. Grain yield was calculated based on 15.5% moisture.
Vertical bars represent standard error. Means with different letters are significantly different at $P < 0.05$.

Also, there was a significant effect of hybrid on grain yield, harvest index, kernel weight and kernel number (Table 4.7). Comparing the five hybrids under $I_{50}$ water regime, N74R had highest kernel weight (256 mg kernel$^{-1}$) and highest yield (6.72 Mg ha$^{-1}$) but P1151AM had the highest kernel number (2414 kernels m$^{-1}$), highest harvest index (0.57) and the grain yield which was 6.20 Mg ha$^{-1}$. TAM hybrid had significantly lowest kernel number (1561 kernels m$^{-1}$), kernel weight (224.6 mg kernel$^{-1}$), harvest index (0.35) (Table 4.8) and grain yield (3.28 Mgha$^{-1}$) (Figure 4.3). Under $I_{100}$ irrigation regime, 33D53AM had highest kernel number (3944 kernels m$^{-1}$) but the lowest kernel weight (235 mg kernel$^{-1}$). TAM hybrid had the lowest kernel number (2416 kernels m$^{-1}$) and highest kernel weight (299 mg kernel$^{-1}$) (Table 4.8). P1151AM had the highest harvest index (0.65) and highest grain yields (10.76 Mg ha$^{-1}$) whereas TAM hybrid had the lowest harvest index (0.54) and lowest grain yield (6.12 Mg ha$^{-1}$) (Table 4.8; Figure 4.3). Evaluating the performance of maize hybrids under different irrigation treatment has provided an opportunity to compare the drought tolerance ability of genotypes. Among the five hybrids, N74R had a lower yield reduction (34%) and 33D53AM had more yield reduction (48%) when the supply of water is reduced from 100% to 50%. These results indicate that N74R can perform better under reduced irrigation than other four hybrids. A significant water regime × hybrid interaction was found on harvest index indicating that the impact of differentiating the water level is different on different hybrids. For example, 33D53AM had 14% lower harvest index than N74R under $I_{50}$ water regime but under $I_{100}$ water regime the value was 4%. Moreover, under $I_{100}$ water regime, harvest index was more than 0.6 (0.61-0.65) in all of the hybrids except TAM hybrid (Table 4.8) which is generally higher than those reported by Colaizzi et al. (2011); Hao et al. (2015). The highest value of harvest index as reported by Hao et al. (2015) was 0.61 and by Colaizzi et al. (2011) was 0.55.

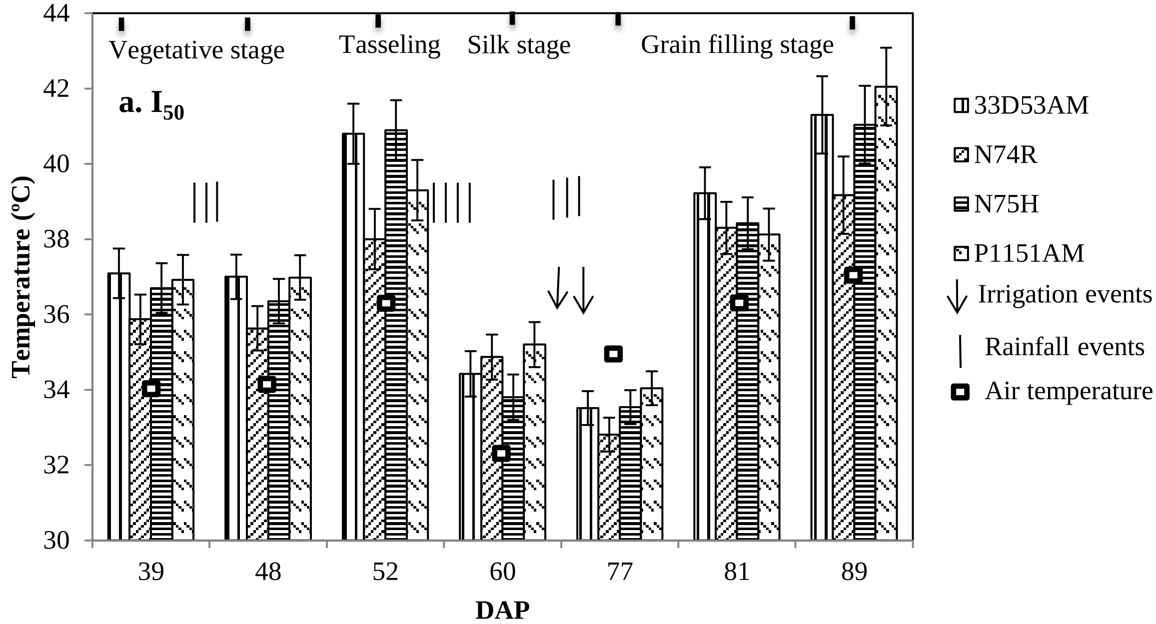
As TAM hybrid was a silage variety it has not been included in further canopy temperature analysis.

**4. 2. 2. Canopy temperature**

Averaged across hybrids, a significant effect of irrigation level on canopy temperature was found (Table 4.9). There was no significant difference in canopy temperature between the irrigation regimes at the beginning of the season. However, as different levels of irrigation water were supplied a significant effect of irrigation level was seen on canopy temperature after 60 DAP**.** Canopy temperature was significantly higher under $I_{50}$ water regime compared to $I_{100}$ water level (Figure 4.5). Romano et al. (2011) also reported similar variation in canopy temperature in which the maize genotypes under water stressed condition were 5ºC warmer than irrigated genotypes. The mean canopy temperature of five hybrids under $I_{50}$ water regime ranged from 33ºC to 41ºC while the canopy temperature of those same hybrids under fully irrigation level was from 32ºC to 37ºC after irrigation. One of the reasons for having lower canopy temperatures under a fully irrigated water regime may be because of higher water level in the soil under $I_{100}$ irrigation compared to $I_{50}$ irrigation level. This relationship between soil water content and canopy temperature variation has been explained by Padhi et al. (2011). They found a negative correlation between canopy temperature and soil water content. A canopy temperature difference of 1ºC, 5ºC and 4ºC between $I_{50}$ and $I_{100}$ irrigation level was found on 77 DAP, 81 DAP and 89 DAP respectively. These results are in close agreement with the findings of Zia et al. (2012). They have reported a canopy temperature difference of about (2-5ºC) between well-watered and water stressed maize hybrids. Under $I_{100}$, irrigation was applied on 79 DAP and the water in the soil profile was depleted at a faster rate as the crop was on grain filling stage. The results showed an increase in canopy temperature in the consecutive days after the irrigation was applied. When there is increase in surrounding air temperature and decrease in soil water content, transpiration is reduced which increased the mean canopy temperature of hybrids even under $I_{100}$ irrigation level from 32ºC on 81 DAP to 36ºC on 89 DAP (Figure 4.5). Under, $I_{50}$ water regime, irrigation was applied on 73 DAP and there was an increase in canopy temperature in consecutive measurement dates from 33ºC on 77 DAP to 40ºC on 89 DAP (Figure 4.5).

Table 4.9. Analysis of variance of maize canopy temperature measured in different dates as affected by water regime, hybrid, and days after planting (DAP)

| Effect | d. f. | P > F |
|---|---|---|
| Water Regime (WR) | 1 | 0.0112 |
| Hybrid (H) | 3 | 0.0005 |
| Days After Planting (DAP) | 6 | <.0001 |
| WR×H | 3 | 0.2005 |
| WR×DAP | 6 | <.0001 |
| H×DAP | 18 | 0.2172 |
| WR×H×DAP | 18 | 0.7088 |



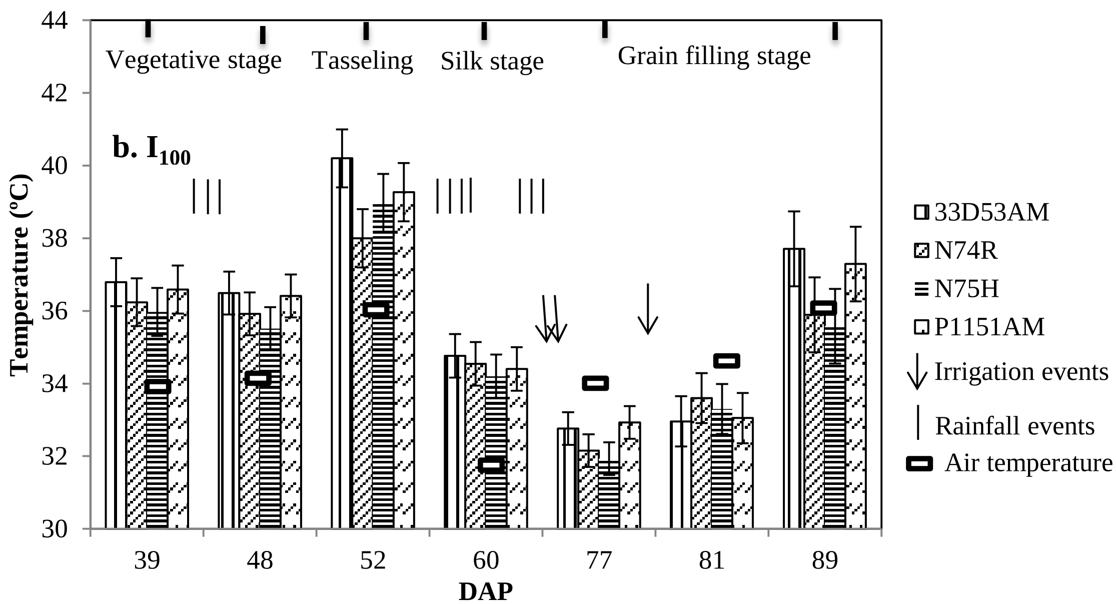




Figure 4.4. Canopy temperature variation under a. $I_{50}$ and b. $I_{100}$ water regimes. Vertical bars represent standard error

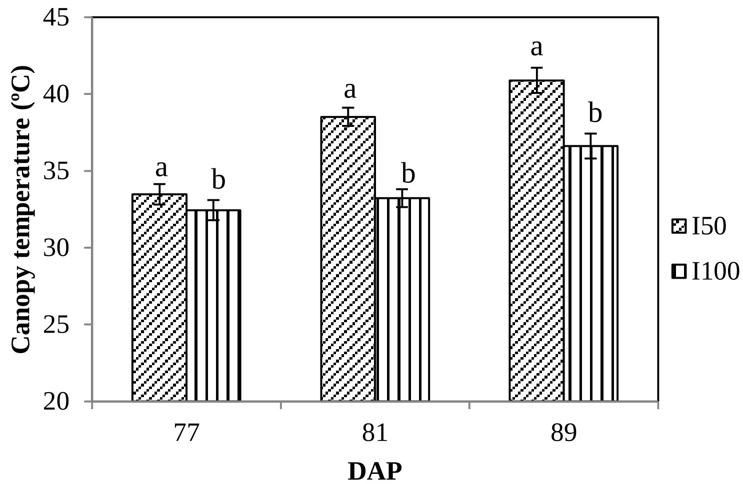



Figure 4.5. Relative canopy temperature (averaged across hybrids) under $I_{50}$ and $I_{100}$ water regime at different days after planting (DAP) after different level of irrigation was applied. Vertical bars represent standard error. Means with different letters are significantly different at $P < 0.05$.

Comparing the hybrids, as shown in Table 4.9, there was a significant effect of hybrids on canopy temperature. Among the four hybrids, 33D53AM had the highest and N74R had the lowest canopy temperature on most of the days under $I_{50}$ water regime (Figure 4.4a). A consistent variation in canopy temperature between the hybrids was found throughout the growing season when measurements were taken. Hybrids followed a consistent ranking most of the times in terms of canopy temperature, 33D53AM being the highest followed by P1151AM, N75H, and N74R (Figure 4.4a). Small differences of about 1-3ºC between the hybrids were found during the measurement times. The data also showed that the difference in canopy temperature between the hybrids increased in consecutive days after irrigation is applied. The difference on 77 DAP was 1.52ºC and it increased to 2.58ºC on 89 DAP as the water content in the soil profile is reduced. There can be a difference in water uptake and leaf transpiration between the hybrids which caused the difference in canopy temperature. The clear difference in canopy temperature during different stages shows the degree of water stress development between the hybrids which can be used as an indicator to differentiate the ability of hybrids to withstand water stress and perform better under drought condition.

Under, $I_{100}$ irrigation regime, 33D53AM and P1151AM had higher canopy temperature and N74R and N75H had the lower canopy temperature until 60 DAP (Figure 4.4b) and the difference in canopy temperature between the hybrids was 1-2ºC as in $I_{50}$ water regime. But after irrigation was applied, there was no significant difference in canopy temperature between the hybrids. Moreover, all the hybrids had similar temperature as long as there was enough soil moisture in the soil. The difference in canopy temperature was less than 1ºC between the hybrids on 81 DAP which was two days after irrigation. As the interval between the day of temperature measurements and the day of irrigation is increased the difference between the hybrids became higher. On 77 DAP (four days after irrigation) it was around 1.2ºC and on 89 DAP (10 days after irrigation) it was 2.25 ºC. These results are in close association with what Zia et al. (2013) has reported.

There was no significant interaction between water regime and hybrid, hybrid and days after planting (DAP), and water regime, hybrid and days after planting. However, a significant interaction between water regime and days after planting (DAP) was found which is presented in figure 4.5.

### 4.2.3. Canopy temperature and air temperature

Canopy temperature obtained from four hybrids under both the irrigation regime was compared with the air temperature (Figure 4.4). Canopy temperature of all the hybrids under both the $I_{50}$ and $I_{100}$ irrigation regime was higher than the air temperature before the irrigation was applied. The difference between canopy temperature and air temperature was around 3-5ºC during this time. As the irrigation water was supplied, canopy temperature was lower than the surrounding air under both the irrigation regimes until the plants were not stressed. As the water in the soil profile declined, canopy temperature became higher than air temperature. Under $I_{50}$ irrigation regime, hybrids were cooler than surrounding sir at 77 DAP. However, they again became warmer than surrounding air on 81 DAP and 89 DAP. The difference between air temperature and canopy temperature during this time was higher (4-5ºC). Moreover, canopy temperature of hybrids under $I_{100}$ irrigation regime remained lower on 77 DAP and 81 DAP which might be because of water available in the root zone as this field was irrigated on 73 DAP and 79 DAP. Furthermore, as the soil moisture depleted in the consecutive days, on 89 DAP canopy temperature of N74R and N75H was still lower than air temperature but 33D53AM and P1151AM were warmer than the surrounding air. These results indicate that the canopy temperature in maize is largely governed by the moisture available in the soil more than air temperature. However, air temperature effects transpiration and cause the change in canopy temperature (Jones, 2014).

**4.2.4. Grain yield and canopy temperature**

The relationship between canopy temperature and grain yield is presented in Table 4.10. A significant negative association was found between grain yield and canopy temperature measured during gain filling stage when the measurements obtained from $I_{50}$ and $I_{100}$ irrigation regimes were combined. However, there was no such strong association when correlation analysis was done separately. Figure 4.6. shows the variation in canopy temperature averaged across all the measurement dates and grain yield under $I_{50}$ irrigation regime. N74R had a lower canopy temperature and higher yield among the four hybrids. This might be due to the efficient root system or higher root density (Kaman et al., 2011) which helped plants to extract more water from the soil and maintain transpiration resulting into lower canopy temperature and higher yield. The negative correlation of grain yield and canopy temperature found in this study has been reported by several researchers in wheat (Alderfasi and Morgan, 1998; Balota et al., 2008; Zia et al., 2012; Pradhan et al., 2014) and maize (Zia et al., 2013). It indicates that lower canopy temperature might be one of the several reasons for higher yield in corn hybrids.  N74R had the lower yield reduction and comparatively lower canopy temperature under $I_{50}$ irrigation regime. This indicates that N74R can be one of the hybrids that can perform better under limited water condition and can be considered as having drought tolerant characteristics. Among the four different stages, grain filling stage was found to have a strong association between canopy temperature and grain yield. This suggests that grain filling stage can be an important stage to take thermal measurements for comparing the performance of maize hybrids which is in accordance with the findings of Romano et al. (2011).

Under fully irrigated condition, strong and consistent relationship was not observed between canopy temperature and grain yield. This might be because of inconsistent variation in canopy temperature among the hybrids.

Table 4.10. Pearson's correlation coefficients (r) between grain yield (Mg ha$^{-1}$) and canopy temperature measured on various days after planting (DAP). Four maize hybrids, two water regimes

| Canopy temperature | | | |
|---|---|---|---|
| | $I_{50}$ and $I_{100}$ combined | $I_{50}$ | $I_{100}$ |
| DAP | r | r | R |
| 39 | -0.10 | -0.21 | 0.14 |
| 48 | -0.1 | -0.05 | 0.04 |
| 52 | -0.1 | -0.08 | 0.15 |
| 60 | 0.11 | 0.23 | 0.08 |
| 77 | -0.45** | 0.16 | 0.27 |
| 81 | -0.73*** | -0.33 | 0.32 |
| 89 | -0.57*** | -0.04 | 0.13 |
| Mean | -0.52** | -0.01 | 0.18 |

**Correlation coefficient significant at the 0.01 probability level

***Correlation coefficient significant at the 0.001 probability level

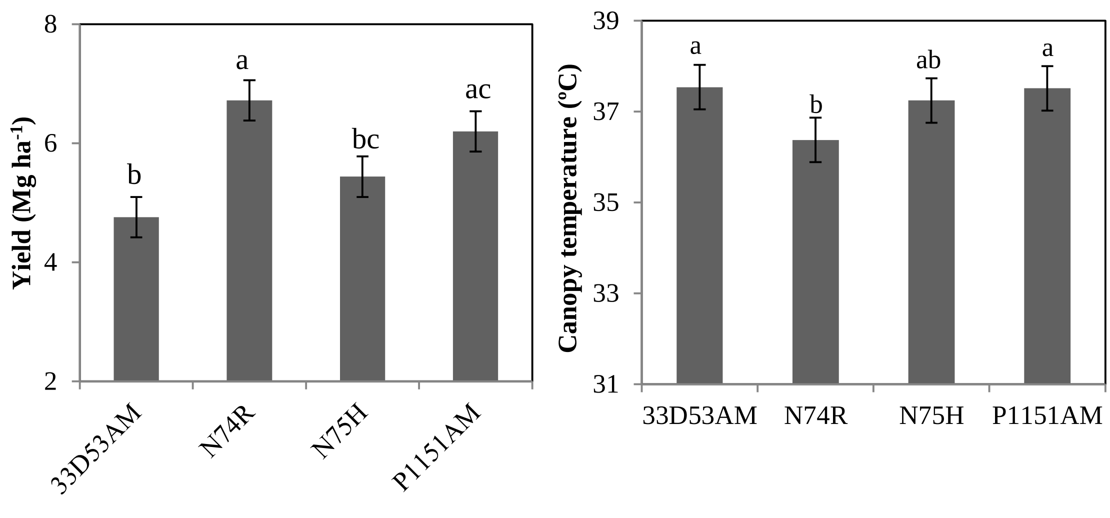



Figure 4.6. Grain yield and canopy temperature (averaged across seven different measurement days) under $I_{50}$ water regime. Vertical bars represent standard error. Means with different letters are significantly different at $P < 0.05$

# CHAPTER 5

# CONCLUSION

This study demonstrates the use of a remote sensing technique (infrared thermal imaging) for measuring crop canopy temperature. Thermal images taken from wheat and maize experiments were processed using IR crop stress image processor software and the canopy temperature was determined. Thus obtained canopy temperature was used to assess the water stress in plants.

In wheat study, significant difference in canopy temperature among the 20 different wheat genotypes under dryland condition was obtained on different measurement days. Some of the genotypes remained relatively warmer while some remained consistently cooler throughout the growing season. Different behavior was found in some of the cultivars in which they had higher canopy temperature early in the season during the vegetative stage and then became cooler during reproductive stage. It shows that these genotypes might have the ability to save water for future use and produce higher yield by reducing transpiration in their early growth stage. However, under irrigated condition significant difference in canopy temperature among the wheat genotypes was not found.

In maize study, significant difference in canopy temperature among the maize hybrids was observed under water limited condition ($I_{50}$ water regime) when the plants were stressed. Canopy temperature was not significantly different among the maize hybrids under fully irrigated condition ($I_{100}$ water regime). Moreover, canopy temperature of hybrids grown under reduced irrigation level ($I_{50}$) was significantly higher than those grown under fully irrigated treatment ($I_{100}$) after irrigation was applied and differentiated. This clearly indicates that thermal imaging can be potentially useful in differentiating water status in the soil on the basis of canopy temperature.

Above-ground biomass of wheat collected at anthesis under dryland condition had a strong negative correlation with canopy temperature. Also, the grain yield of maize was negatively associated with canopy temperature measured at several dates representing reproductive and grain filling stages. The negative correlation of canopy temperature with biomass of wheat and maize grain yield suggests that the cooler canopy under water stress environment might be one of the reasons for higher yield and better drought tolerance. The strong negative association among canopy temperature, biomass and yield has opened a way for further investigation of the physiological bases of canopy temperature and its relationship with other crop parameters. Cultivars having relatively lower canopy temperature and higher yield indicate that they have advantages either in their transpiration behavior or root architecture. Further investigations should include root growth dynamics to further enhance the use of canopy temperature to study water stress in plants. Although the mechanism resulting in the variation of canopy temperature looks more complicated, these results indicate the potential use of thermal imaging and canopy temperature analysis for studying genotypic variability in terms of drought tolerance and better water use efficiency.

In this study, images were taken by thermal camera using a ladder and those images were used to calculate the canopy temperature. Although, attention was given to reduce the time interval of taking images, it did take a little more time while moving the ladder from one plot to another when large number of plots were considered. This might have influenced the measurements because of variations in the angle of view and continuous changes in environmental conditions. Use of automated techniques such as unmanned aerial vehicles (UAVs), or boom lifts is suggested for image acquisition of large number of plots within smaller time intervals in order to avoid the influence of changing environmental conditions during measurement. Moreover, development and use of high throughput thermal imaging techniques with an appropriate method to process and analyze the thermal images can help plant breeders with screening and identifying genotypes that are more tolerant to drought stress. Also, it is important to combine high throughput phenotyping mechanisms with the high throughput genotyping approach to identify the fundamental basis of drought tolerance. Understanding gene by environmental interaction is necessary to obtain accurate information for analyzing the performance of a particular genotype in a certain environment.

In conclusion, thermal imaging can be a potential technique to measure canopy temperature and study the plant-water relations. Also, there are some limitations of using thermal imaging for field phenotyping and genoptye screening in breeding programs. It is important that the canopy coverage is sufficient to mask the soil underneath the canopy or the effect of background soil on temperature measurements can be removed by using certain image processing software. Also, canopy coverage, weather conditions, growth stage, water status, time of the day, and length of time in taking thermal images are some of the crucial factors that are always needed to be considered before taking thermal measurements.

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