MICROCLIMATE AND TRANSPIRATION EFFICIENCY IN DRYLAND CROPS IN RELATION TO PLANTING GEOMETRY, GROWTH STAGE, AND CULTIVAR

By

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ABSTRACT

Cultivar selection, planting geometry, and plant population are the key factors determining grain sorghum yields in water deficit areas. When soil resources such as water are non-limiting, uniform cropping will provide the greatest efficiency in light interception and photosynthesis, but when resources are limiting, non-uniform treatment of the land or the crop can be an advantage. A 2-yr sorghum (*Sorghum bicolor* L. Moench) greenhouse study was conducted to investigate whether clump geometry (three plants clustered) improves microclimate within crop canopy when plants are grown under varying water levels. Plants were grown at two geometries (clump and conventional evenly spaced planting; ESP), two water levels (high and low representing well-watered and drought condition), and three soil surface treatments (lid covered, straw-mulched, and bare surface). Air temperature and relative humidity (RH) within the plant canopy were measured every five minutes at different growth stages. Mean vapor pressure deficits (VPDs) within the clumps were consistently lower than those for ESPs, indicating that clumps improved the microclimate. Clumps had significantly higher harvest index (HI) compared to ESPs (0.48 vs. 0.43), which was largely due to clumps having only 0.4 tillers per plant compared to 1.2 tillers per plant for ESPs. Grain yield was not different between clumps and ESPs. However, results suggest that improved microclimate was likely a reason for clumps producing significantly higher grain yields in previous studies reported in the literature.

Corn (*Zea mays* L.) field studies were conducted in Gruver (Gruver field study, GFS) and Bushland (Bushland field study, BFS), Texas to compare plant canopy temperature, within canopy VPD, grain yield, yield components, and water use efficiency (WUE) for clump (3 plants clustered) and ESP geometries with the same plant populations. At different growth stages for both studies, thermal images were taken for calculating canopy temperature, and temperature and relative humidity within the plant canopy were measured. As a whole, canopy temperatures were significantly lower for clumps compared to ESPs, and mean VPDs within the clumps were consistently lower than those for ESPs, indicating that clumps improved the microclimate. WUE and grain yield showed mixed results, but HI was significantly higher for clumps than that for ESPs in both studies (0.56 vs. 0.54 in GFS and 0.48 vs. 0.45 in BFS). In GFS, plants were grown under three water levels (high, medium, and low). With decreasing irrigation level, canopy temperature and VPD increased and aboveground biomass, grain yield, and HI decreased. Corn plants with medium irrigation level had the highest WUE (1.83 kg m^{-3}) compared to plants at high (1.34 kg m^{-3}) and low (1.22 kg m^{-3}) irrigation levels. Results suggest that growing corn in clumps may be a useful strategy under semi-arid climatic conditions because they improved microclimate, reduced number of tillers, and increased HI with comparable grain yield compared to conventional ESP.

Transpiration efficiency (TE) is an important physiological trait in plants for maintaining soil moisture longer and producing high yield with limited water supply. In contrast to other major food crops, little is known about the sorghum TE and its dynamics in relation to environmental VPD. Two simultaneous studies in each of the greenhouse and plant growth chamber were conducted to compare sorghum TE at different growth stages, and to determine the effects of VPD on TE. Plants were grown using lid covered boxes and harvested at six-leaf stage (S1), flag leaf stage (S2), grain filling stage (S3), and grain maturity stage (S4). For all studies, shoot biomass increased linearly with cumulative water used in transpiration. Root biomass increased up to S3 and remained constant thereafter, but shoot biomass as well as shoot: root (S:R) ratio increased consistently from S1 through S4. The overall mean VPDs and shoot transpiration efficiency (TE_{shoot}) for different growth stages were similar within each study. VPDs were different from one study to the other. When data from all studies were combined, ET_{shoot} showed an inverse linear relationship with crop growing period VPD, suggesting that TE decreases as the crop growing period VPD increases.

The yield of wheat (*Triticum aestivum* L.), one of the major crops grown in the Texas High Plains, is mainly affected by drought. Under drought conditions, TE is often considered an important determinant of plant growth and grain yield, which may differ from one cultivar to the other. A greenhouse wheat study was conducted to compare TE among six wheat cultivars namely, Triumph 64 and Scout 66 (released during 1960s), TAM W 101 and TAM 105 (released during 1970s), and TAM 111 and TAM 112 (released after 2000). Plants were grown at high and low water levels with four replications and harvested before anthesis at 62 days after planting. Aboveground dry matter showed a significant linear relationship ($P < 0.0001$, $R^2 = 0.93$) with cumulative water used during the crop growing period. On average, wheat plants produced ~2.8 kg of aboveground dry matter per cubic meter of water use. WUE was not significantly different among the cultivars, but there was a trend that the older cultivars had higher WUEs. Plants growing at high water had significantly higher WUE (2.40 kg m^{-3}) and leaf chlorophyll (55) than those at low water level (2.15 kg m^{-3} WUE, and 52.6 chlorophyll).

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ABBREVIATIONS

ANOVA	analysis of variance
BFS	Bushland field study
CST	Central Standard Time
CT	canopy temperature
DAP	days after planting
DM	dry matter
ESP	evenly spaced planting
ET	evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FC	field capacity
GC	growth chamber
GFS	Gruver field study
GH	greenhouse
GY	grain yield
HI	harvest index
HIT	high irrigation treatment
LAI	leaf area index
LCC	leaf chlorophyll content
LIT	low irrigation treatment
LRWC	leaf relative water content

LSD	least significance difference
Mg	megagram
MIT	medium irrigation treatment
PAW	plant available water
PET	potential evapotranspiration
R:FR	red to far red light ratio
RH	relative humidity
S:R	shoot to root ratio
SAS	statistical analysis system
SVP	saturated vapor pressure
TEb	biomass transpiration efficiency
TEg	grain transpiration efficiency
TR	transpiration ratio
UNEP	United Nations Environment Programme
VPD	vapor pressure deficit
WUEb	biomass water use efficiency
WUEg	grain water use efficiency

CHAPTER I

INTRODUCTION

1.1 Agriculture in the Texas High Plains

The Texas High Plains is one of the most productive agricultural regions in the world. Favorable growing conditions, fertile soils, and irrigation water from the Ogallala Aquifer have allowed the Texas High Plains to become an important food and fiber production region in the United States (U.S.) (Weinheimer et al., 2013). Water scarcity and drought are the major constraints for agricultural production in many parts of the world (Badr et al., 2012; Huang et al., 2002; Rosegrant and Cline, 2003), and this is also true for the Texas High Plains. The climate of the area is semiarid, where more than 50% of all cultivated farmland is under dryland production (Baumhardt and Salinas-Garica, 2006). Declining water tables (Nativ and Smith, 1987) and volatile fuel costs will likely cause some irrigated land to return to dryland production (Musick et al., 1990). The impact of drought is usually severe in dryland farming areas because precipitation amounts in drylands are considerably less than the potential evapotranspiration (PET) (FAO, 2004; Stewart and Peterson, 2015).

The Texas High Plains is characterized by limited growing season precipitation of 200 - 300 mm (8 - 12 in) (Weinheimer et al., 2013), high evaporative demand due to high solar radiation, temperature, wind speed, and vapor pressure deficit (Stewart and Burnett, 1987; Krishnareddy et al., 2006). The primary source of groundwater is the Ogallala

Aquifer, which spans about 450,000 km^2 (173,746 mi^2) of South Dakota, Wyoming, Colorado, Nebraska, Kansas, Oklahoma, Texas, and New Mexico, and is one of the largest freshwater aquifer in the world (Colaizzi et al., 2008). More than 90% of the withdrawals from the aquifer are for agricultural irrigation (Colaizzi et al., 2009). The natural recharge rate in the Central and Southern High Plains of the Ogallala Aquifer region is low, ~11.00 mm yr^{-1} (0.43 in yr^{-1}) (Scanlon et al., 2010) while the withdrawal rates are higher. As a result, water levels in the aquifer are rapidly depleting (McGuire, 2004; Roberts et al., 2007; Colaizzi et al., 2009). There is a possibility of decreasing agricultural crop yields by 70% in the dry regions of the U.S., mainly due to the soil water shortage (Boyer, 1982).

More than 25 crops are commercially produced in the Texas High Plains (Weinheimer et al., 2013). Grain sorghum (*Sorghum bicolor* L. Moench), corn (*Zea mays* L.), and wheat (*Triticum aestivum* L.) are some of the important cereals grown under irrigated as well as dryland conditions. Sorghum (also called milo) is a drought-tolerant and water-use-efficient crop grown in semiarid tropical and subtropical environments (Blum, 2004; Rooney, 2004). It is a widely grown dryland crop in the southern Great Plains (Stewart, 2006). Though sorghum is used primarily as a feed grain for livestock in the U.S., it is regarded as a dietary staple food for people in more than 30 countries. Based on production, sorghum was the fifth most important cereal crop in the world after corn, rice (*Oryza sativa* L.), wheat, and barley (*Horedeum vulgare* L.) in 2013 (FAOSTAT, 2016). In 2013, the crop was grown on approximately 42.12 M ha (104.08 M ac) with total production of 61.38 M Mg (67.66 M ton) worldwide (FAOSTAT, 2016).

Corn, a major irrigated summer crop in the Texas High Plains (Musick et al., 1990), is one of the most important ingredients in human diets. In addition, the crop is widely used as animal feed and to produce biofuel. Though corn plants are relatively tolerant to water deficits during the vegetative growth and seed ripening stages (Doorenbos and Kassam, 1979), drought is one of the major threats limiting grain yield (Lobell et al., 2008). In 2013, the crop was grown on approximately 184.2 M ha (455.2 M ac), with total production of 1,016.7 M Mg (1,120.7 M ton) worldwide (FAOSTAT, 2016).

Wheat, the most widely cultivated crop in the world, is a major crop in the Texas High Plains for grain and forage production (Musick et al., 1994; Howell et al., 1997). Over the centuries, wheat evolved into a plant that can: 1) tolerate cold, 2) survive and produce in rocky, shallow soil, yet be genetically capable of greater yields in better habitats, and 3) mature under conditions of limited moisture (Smith, 1995). In 2013, the crop was grown on approximately 218.46 M ha (539.92 M ac), with total production of 713.18 M Mg (786.15 M ton) worldwide (FAOSTAT, 2016).

1.2 Problem Statement

In water deficit areas, the main pathways for enhancing water use efficiency (WUE) are to increase the biomass production per unit of water, reduce losses of water, and reallocate available water to higher priority uses (Zhang et al., 1998; Howell, 2001). Cultivar selection, planting geometry, and plant population are the key factors that determine grain yield when crops are grown under water limiting conditions. Manipulating planting geometry plays a crucial role in increasing the WUE when crops are grown under dryland environments (Stewart and Burnett, 1987). Reducing plant populations, modifying row spacing, and using skip row configurations are some of the strategies that have been adopted by growers for better utilization of plant available soil water (Larson and Vanderlip, 1994). These methods help conserve some soil water for use by plants during flowering and grain filling growth stages. In comparison, conventional methods often deplete soil water reserves before the plants reach the reproduction stage resulting in low yield or total crop failure (Fukai and Foale, 1988; McLean et al., 2003; Routley et al., 2003). However, decreased plant population might reduce WUE, because it exposes more leaf area per plant to the environment. Moreover, in case of sorghum and corn, low plant populations commonly trigger tiller formation due to perception of high red: far-red (R:FR) light ratio at the base of the plants. Excessive tiller formation often occurs with sorghum at low plant populations under favorable water and fertility conditions because of excess photosynthate production. In dryland production, tillers use water and nutrients, but often produce little or no grain, and hence, negate the expected benefit of having low plant density (Stewart, 2009). Growing three to four plants in clumps is a strategy based on the rationale that it will increase plant competition resulting in less use of water, nutrients, and sunlight, and the vegetative mass will be reduced mainly because of less tillering (Stewart, 2009).

When soil resources such as water are nonlimiting, uniform cropping will provide the greatest efficiency in photosynthesis, but when resources are limiting, nonuniform treatment of the land or the crop can be an advantage (Loomis, 1983). Previous studies suggested that planting grain sorghum and corn in clumps improved the grain yield and harvest index (HI) by reducing vegetative growth at the early growth stage hence, leaving a portion of soil water for reproductive and grain filling stages (Bandaru et al., 2006;

Kapanigowda et al., 2010a; Mohammed et al., 2012). Growing plants in clumps changes the canopy architecture, which may influence the microclimate within crop canopy, but it is not well studied. An understanding of the relationship between the microclimate, and plant growth and grain yield is extremely important to recommend better agronomic practices, especially when crops are grown under semiarid climatic conditions.

1.3 Objectives

Exploring alternative planting methods for production stability as well as agricultural sustainability in the semiarid Texas High Plains, the overarching objective was to compare microclimate within plant canopy, grain yield, and yield components between clump and conventional evenly spaced planting (ESP) geometries at different water and soil surface treatments.

The primary objective was to compare the canopy temperature and within canopy vapor pressure deficit (VPD), leaf area or leaf area index (LAI), tiller number, aboveground biomass, grain yield, harvest index (HI), and water use efficiency (WUE) between growing sorghum and corn plants in clumps and the same number of individually spaced plants in rows, called ESP.

The second objective was to compare the transpiration efficiency (TE) and shoot: root (S:R) ratio for grain sorghum harvested at different growth stages (six-leaf, flag leaf, grain filling, and grain maturity), and to determine VPD effects on TE.

The final objective was to compare the TE among six wheat cultivars namely, Triumph 64 and Scout 66 (released during 1960s), TAM W 101 and TAM 105 (released during 1970s), and TAM 111 and TAM 112 (released after 2000 at vegetative growth.

CHAPTER II

REVIEW OF LITERATURE

2.1 Dryland Agriculture

Dryland agriculture has been practiced for millennia and is an important supplier of the world's grain such as wheat, grain sorghum, and millet. The North American Region covering Canadian Prairies and the Great Plains of the U.S., the Pacific Northwest and Southwest of the U.S., and parts of the intermountain areas are classic examples of a great food producing dryland areas (Cannell and Dregne, 1983). In many cases, dryland farming and rainfed farming are used interchangeably, but they are vastly different. Rainfed farming includes dryland farming, but dryland farming is generally practiced in regions where lack of moisture limits crop and/or pasture production to part of the year (Stewart et al., 2006).

Various definitions have been used to delineate the dry farming areas. Hargreaves (1957) mentioned that dry farming may be generally defined as agriculture without irrigation in regions of scantly precipitation. Higbee (1958) states that dry farming is an agriculture dependent on rain and snow; it generally implies farming carried on under the handicap of low rainfall. According to UNEP (1997), drylands have a ratio of average annual precipitation to potential evapotranspiration (PET) of less than 0.65 and annual precipitation of less than 600 mm (24 in). Koeppe and Long (1958) mentioned that the minimum rainfall for producing a crop in the dry regions is 250-350 mm (10-14 in) in winter rainfall areas, and 500 mm (20 in) in summer rainfall areas. Duley and Coyle (1955) state that the annual precipitation in dryland areas is generally low, about 200 to 500 mm (8-20 in). However, the use of total rainfall as a general definition is misleading, because the evaporative index varies considerably even within the same region. For instance, a given amount of precipitation in the northern states of the North American semiarid region may be sufficient for crop production, but in the southwestern states, where the average temperature is much higher and the growing season is longer, the same amount would be inadequate (Cannell and Dregne, 1983).

Dryland agriculture may constitute the world's largest biome and is indispensable for food production, which covers approximately 47% of the Earth's land surface (UNEP, 1997; Schimel, 2010). It forms the habitat supporting many plant and animal species and microorganisms, and provides much of the world's grain and livestock (Koohafkan and Stewart, 2008).

Substantial amounts of water are needed for evapotranspiration (ET) and to a large extent, crop yields are determined by the growing season ET. Seasonal precipitation in dryland areas is not adequate to meet the ET requirement, which eventually results in poor crop yields (Greb et al., 1967; Adams et al., 1976). Successful cropping in drylands in the U.S. Southern Great Plains depends on plant available water stored in the soil profile at time of planting to supplement the growing season precipitation (Stewart, 2006). Therefore, one of the most effective ways to utilize available water and improve WUE is to alter the balance between evaporation and transpiration (Cooper et al., 1987). This is done to increase plant transpiration and decrease evaporation from the soil surface as much as possible.

Soil water between field capacity (FC) and permanent wilting point (PWP) is available to the growing plants. When the soil water reaches the wilting point, plants cannot extract water, but the remaining water in the soil can evaporate. To return the soil back to FC, first the amount of water lost below the wilting point must be added, and then the plant available water (PAW) (Stewart and Peterson, 2015). The PAW in soil not only controls the physical environment of plant roots, but may also affect soil chemical and biological conditions (Asgarzadeh et al., 2014). Conserving soil water and making it available to the plants, especially during the reproduction and grain filling growth stages is one of the most challenging aspects of crop production in dryland farming. Stewart and Burnett (1987) stated that dryland farming emphasizes water conservation in every practice throughout the year.

Zero tillage (no-till), surface mulch, and summer fallowing in dryland areas are common practices for conserving precipitation in the soil and increasing WUE. The conserved soil water can help in meeting crop demand at least for the germination and early stand crop establishment. Though water available in soil may not be sufficient to fully meet crop requirements for the production of acceptable yield, it can help ensure a certain yield and protect growers from complete yield loss (Li et al., 2012). Ridge (1986) found that summer fallow enhanced yield stability without reducing the overall productivity of the system. However, summer fallowing is not free of critics (Peterson et al., 1993; Unger, 2001). According to Li et al. (2012), during the fallow period, the bare soil surface was subjected to severe wind and water erosion. Power (1990) and Rasmussen and Collins (1991) reported that fallowing often resulted in a decline in soil organic matter content, especially when used with intensive tillage. There was also a considerable loss of large amounts of water through evaporation (Zhang and Wu, 1994; Peterson et al., 2012).

Irrigation is the most important water use sector accounting for about 70% of the global freshwater withdrawals and 90% of consumptive water uses (Siebert et al., 2010), which alone can increase yields of most crops by 100 to 400% (FAO, 2007). Growing staple food crops and non-food crops, raising livestock and aquaculture requires large amounts of water (FAO, 2012b). Although the declining availability of fresh water has become a worldwide problem, it is more severe in arid and semi-arid regions, where irrigation depends mainly on groundwater resource (Chauhan et al., 2008). Depleting ground water tables and meager precipitation combined with low spring temperatures are the major constraints on crop production in drylands (Rockstrom et al., 2007; Liu et al., 2009; Wang et al., 2009). Hence, in drylands, the yields of a number of crops are likely to decrease (Lobell et al., 2008). Improved management techniques, better-adapted cultivars, crop insurance programs, suitable tillage practices, advances in soil and water conservation methods, and other changes have increased production stability in dryland agriculture during the past few decades. How long that relative stability will continue is an unanswerable question, given our imperfect knowledge of atmospheric processes (Cannell and Dregne, 1983).

2.2 Grain Sorghum Physiology

Grain sorghum, a crop with the C_4 photosynthesis pathway is a member of the Poaceae family. Morphologically, it looks similar to corn, but it produces more tillers and more finely branched roots than corn. It is an upright, annual plant grown in a summer season. Sorghum leaf blades are flat, stems are rigid, and there are no creeping rhizomes.

Sorghum can grow in low fertile land with moderately acidic to highly alkaline soils, but it is best adapted to fertile and well-drained soils at a pH between 6.0 and 6.5. It is not tolerant of frost, shade and prolonged water logging condition (Clark, 2007; FAO, 2012a; Undersander, 2003).

Sorghum is one of the most versatile crops, capable of growing well under contrasting climatic conditions. It is one of the more adaptable crops for the rainfed and dryland regions because of its ability to remain dormant under adverse conditions and resume growth after drought (Unger, 1994). Under water stress conditions, it has the potential to delay vegetative growth and resume the growth when soil moisture conditions improve (Bennett et al., 1990). Sorghum produces heads over a longer time period because tillers develop over several weeks. Consequently, short periods of drought do not seriously damage pollination and fertilization. In a long drought, sorghum produces fewer and smaller heads, but they are rarely without grains (Carter et al., 2013). Despite its ability to tolerate drought, a lack of water during the reproduction and grain-filling stages causes significant yield loss. Craufurd et al. (1993) reported that water stress during booting and flowering stages resulted in grain yield reductions of up to 85%.

Sorghum is a short-day plant. For short-day plants, basic vegetative phase consists of two stages, namely the juvenile stage (temperature dependent) and inductive stage (photoperiod dependent). Sorghum plants were found to be insensitive to photoperiod in juvenile stage (up to 14-21 d after emergence) (Karande et al., 1996). But, for inductive stage, flowering of tropical varieties was delayed by longer than 11.1-12.6 h d^{-1} and reproductive stage was started when day length became shorter than 12 h (Shinde et al., 2013).

Sorghum is a self-pollinating plant having a loose and open panicle of short, few-flowered racemes. Glumes vary in color from red or reddish brown to yellowish and are at least three quarters as long as the elliptical grain. The grain is predominately red or reddish brown (Kearney and Peebles, 1969; Barkworth, 2003). Seed components are endosperm (82%), embryo (12%), and seed coat (5-6%). Though both corn and sorghum have a C_4 photosynthetic pathway, sorghum can tolerate hot and dry conditions better than corn, so it is quite popular among the farmers in dryland areas (UK, 2010). The number of chromosomes in sorghum is $2n = 20$.

2.3 Corn Physiology

Corn is a plant belonging to the family of grasses, Poaceae, and follows the C_4 photosynthetic pathway. It is a tall, determinate, monoecious, annual crop. Like sorghum, corn stems are rigid and there are no creeping rhizomes. Corn grows in a wide range of soils, but deep fertile soils rich in organic matter and well-drained soils having soil pH in the range of 7.5 to 8.5 are the most preferred ones (Tripathi et al., 2011). The major environmental factors influencing corn yields are daily maximum and minimum temperatures, humidity, soil quality, wind movement, day length, light intensity, and pest and disease complex (Brown and Darrah, 1985).

As a short-day plant, corn does not respond to photoperiod until the end of the juvenile stage during which only vegetative growth occurs. When the inductive stage starts, it becomes sensitive to photoperiod. For instance, increasing photoperiod delays tassel initiation in corn (Kiniry et al., 1983; Ellis et al., 1992).

Having separate male and female inflorescences on a single stem, corn is a cross pollinated plant. Flowers are in pairs and each pair is called a spikelet, which is enclosed by two bracts. Two smaller bracts enclose three stamens. The female inflorescences are lower down on lateral branches. One plant may produce up to four ears, but generally only one or two of them reach full maturity. Depending on the variety, the kernels are arranged in 8 to 20 rows along the length of the cob. The kernel is composed of a germ (embryo + cotyledon), an endosperm, and a pericarp, which forms a hard seed coat around the exterior of the kernel (Ngo-Samnick, 2012).

Corn produces large, narrow, opposite leaves, borne alternatively along the length of the stem. All corn varieties follow the same general pattern of development, although specific time and interval between stages and total number of leaves developed may vary between varieties, seasons, time of planting, and location (Ngo-Samnick, 2012). The usual spread of corn roots is about 1.25 m (4.10 ft) and the depth of many of the roots can be 1.6 m (5.2 ft) with some approaching 2.0 m (6.5 ft) (Waldern, 1983). The number of chromosomes in corn is $2n = 20$.

2.4 Wheat Physiology

Photosynthesis in wheat is mediated by the Calvin cycle (C_3 pathway) (Evans, 1975). Wheat plants may reach 2.0 m (6.6 ft) in height but the modern semi dwarf cultivars are usually less than 1.0 m (3.3 ft) depending on the moisture, fertility, day length, and genetic makeup. Wheat is grown over a wide range of moisture and temperature conditions. The main wheat regions of the world lie between 30º and 55º in the North Temperate Zone and 25º and 40º in the South Temperate Zone, in areas where annual precipitation ranges from 30 to 144 cm (12 to 57 in) (Nuttonson, 1955). For the most satisfactory growth and development of grain, a cool and moist growing season followed by a sunny day and warm ripening period of 6-8 weeks with a mean temperature of 18-19ºC (64-66ºF) is necessary (Percival, 1921).

The development of a wheat plant is keyed to the development of stem nodes and the expansion of internodes. All leaves, adventitious roots, and tillers arise from buds associated with crown or stem nodes. The first visible roots are the seminal, or seedling roots, that appear shortly after germination. Additional roots called nodal, coronal or adventitious, arise from nodes within the crown, the crown being the meristematic region where the shoot and root meet (Smith, 1995). Although wheat is normally a self-pollinated plant, natural cross-pollination occurs in 1 to 4% of total flowers (Garber and Quisenberry, 1923).

Vernalization and photoperiod responses provide the bases for the wide adoptability of wheat. Vernalization response is recognized as acceleration of development following the exposure of low temperature, which is perceived directly by the apex once the seed starts imbibition process or even during seed development in the mother plant (Purvis, 1961). The vernalization response is believed to take place in the shoot apex, even in excised shoot apices of wheat. Junges (1959) suggested that 3ºC (37ºF) was the most effective temperature for vernalization of winter wheat but 10ºC (50ºF) for spring wheat.

Regarding the photoperiod response, wheat is a long-day plant. Many wheat cultivars are photoperiod sensitive. In more arid and/or hotter areas of production, cultivars may be photoperiod insensitive in order to initiate reproduction solely on temperature. Such non-photoperiodic cultivars would likely initiate productive growth too early in more northern areas of the U.S. and therefore be more susceptible to frost damage (Smith, 1995). The wheat genome is made up of a basic set of 7 (i.e. x = 7, 14, 21 chromosomes in its reproductive cells) resulting in somatic cell nuclei, 2n, with 14 (diploid), 28 (tetraploid), or 42 (hexaploid) chromosome.

2.5 Corn and Sorghum Response to Soil Moisture Availability

When water is limited, supplemental irrigation (if available) helps to reduce the severity of water stress experienced by crops grown in both arid and semi-arid climates. While adopting dryland farming, it is important to understand and quantify crop water-yield relationships as influenced by the methods of planting, plant population, and planting geometry to optimize WUE and crop yields.

Corn, a major irrigated summer crop in the Texas High Plains is a water demanding crop. Until an optimum number of plants per unit area is reached, increasing plant population usually increases corn yields (Lutz et al., 1970). Optimum plant population is determined by the availability of soil moisture (Karlen and Camp, 1985), nitrogen fertilizer, and other environmental factors (Al-Kaisi and Yin, 2003).

Corn is sensitive to water deficit conditions and other environmental stresses, especially during the reproduction stage (Bryant et al. 1992; Otegui et al., 1995; Pandey et al., 2000). Rainfall distribution greatly influences maximum yields, especially for the three-week period centered on tasseling (Brown and Darrah, 1985). During the reproduction period, water stress has more effect on the timing of silk emergence than on tassel development and pollen shed. Under hot and dry environmental conditions, the tassel may develop and shed pollen before the ear and silk formation has been completed resulting in poor pollination. One day of moisture stress within a week after silking can result up to 8% yield loss (KSU, 2007) (Figure 1).

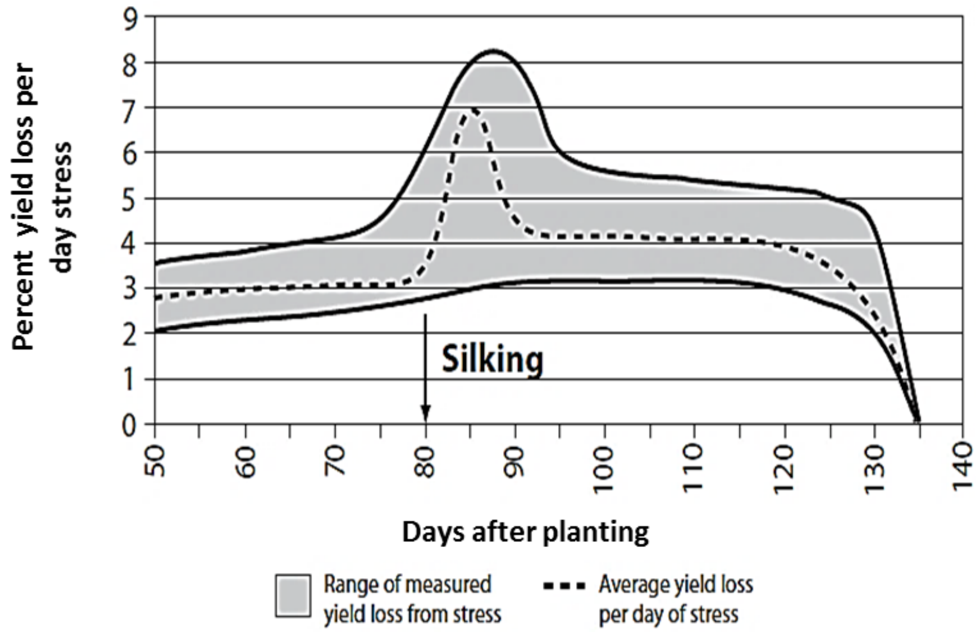

Figure 1. Corn yield loss due to one day of moisture stress after silking (KSU, 2007)

Corn can be grown successfully where the mean daily temperature is about 30ºC (86ºF). The crop is seldom grown where the mean temperature is less than 19ºC (66ºF). Extremely high temperature can be injurious to corn, especially when accompanied by soil moisture deficient. It is well known that corn needs more moisture during the time of tasseling and pollination, although the period of kernel filling is almost as important (Stomayor-Rios and Weibel, 1984). Water stress has been shown to reduce corn canopy height (Gavloski et al., 1992; Traore et al., 2000), leaf area index (LAI) (Bryant et al., 1992; Traore et al., 2000), and root growth (Jama and Ottman, 1993).

Claassen and Shaw (1970) observed that water stress before or during silking and pollination reduced kernel number, while stress during or after silking reduced kernel weight. Newell and Wilhelm (1987) studied root growth in corn in eastern Nebraska and found that dryland and deficit-irrigated corn had relatively greater root length than the fully irrigated corn. Studies also have suggested that corn yield is just a linear function of seasonal transpiration or ET and the effect of water stress on corn yield will depend on the magnitude in which stress affects seasonal ET (Stone, 2003; Klocke et al., 2004; Payero et al., 2006).

In contrast, grain sorghum, a summer crop grown under similar agronomic conditions to corn, is a drought tolerant crop (Muchow, 1989; Camargo and Hubbard, 1999; Bloom, 2004; Rooney, 2004) and has an ability to yield well under rainfed or water-limited conditions (Muchow, 1989). With the development of early maturing hybrids and cultivars, sorghum may be grown in areas with average annual precipitation as low as 380 mm (15 in). Studies suggest that its drought resistance is associated to a dense and prolific root system that is capable of extracting soil water deep in the soil profile (Wright and Smith, 1983; Singh and Singh, 1995). Further, it has an ability to maintain stomatal opening at low levels of leaf water potential through osmotic adjustment (Ludlow et al., 1990; Girma and Krieg, 1992), and can delay reproductive stage under water stressed conditions (Wright et al., 1983). Relatively shorter growth duration of sorghum also contributes to its ability to escape drought (Farre and Faci, 2006). Sorghum, as compared to corn, has a slow production of leaf area so that early in the season before canopy closure it loses less water. Also, sorghum tends to have a lower leaf photosynthesis rate and stomatal conductance so that the water loss rate for sorghum may be less than corn (Sinclair and Weiss, 2010). Therefore, sorghum can be an alternative crop to corn in areas where irrigation water supply is limited (Berenguer and Faci, 2001). However, a certain amount of water is required to establish the plant and allow adequate vegetative development to support potential yield without actually realizing any grain yield. Although this minimal level is dependent on environmental demand, it is probably in the range of 15-18 cm (6-7 in) of available water in the U.S. Great Plains (Hanks, 1974).

Farre and Faci (2006) studied corn and sorghum in northeast Spain with sprinkler irrigation system. Corn yield was superior to sorghum under well-irrigated conditions, but sorghum out-yielded corn under moderate to severe water deficit with higher aboveground biomass, harvest index (HI), and WUE. They found that sorghum had a greater ability to extract water from deeper soil profile. Singh and Singh (1995) studied water response of sorghum and corn on a sandy loam soil in Hisar, India and found that dry matter yield was not significantly different between corn and sorghum. However, sorghum was superior to maize under water deficit conditions with more water extraction from the sub-soil (45-135 cm [18-53 in]) compared to corn, which extracted more water from the topsoil (0-45 cm [0-18 in]). Stone et al. (1996) conducted a study over 14 years in Tribune, Kansas to establish the yield vs. water application relationships of corn and grain sorghum and found that as the total irrigation amount increased from 100-200, 200-300, and 300-400 mm (4-8, 8-12, and 12-16 in), corn out-yielded sorghum at total irrigation amounts of 345 mm (14 in) and above. They suggested that if grain mass is the major consideration, grain sorghum is a better choice than corn at less than 206 mm (8 in) of irrigation, whereas corn is a better choice than sorghum at more than 206 mm of irrigation.

2.6 Wheat Response to Soil Moisture Availability

A wheat plant is not highly drought-resistant and cannot survive long periods of drought. It does, however, adjust to moisture stress by producing smaller cells as the result of which the height of the clum, the size of the leaves, and the size of the stomatal opening are reduced. The potential yield of wheat can only be obtained under well-watered conditions (Evans, 1975). Under drought conditions, grain number per ear and grain weight are the most important factors determining yield. In drylands, maximum yields cannot be realized as there is a linear relationship between yield of a cultivar of wheat and the severity of drought (Fischer and Maurer, 1978).

Water stress in wheat at spike initiation causes the greatest reduction in yield (Day and Intalap, 1970). Fischer and Slatyer (1973) found that the most sensitive stage was 15 days before anthesis. Drought in the vegetative stage reduces the number of heads (tillers). Drought at flower formation results in reduced grain number, while drought at later stages results in reduced kernel size, because the number of grains has already been established (Asana et al., 1958). Under semiarid Great Plains in the U.S., good yields are obtained in most years when the soil is wet to a depth of 90 cm (3 ft) at the time of seeding (Army and Hide, 1959). The effect of water stress at various growth stages on grain yield reduction in wheat with heading and booming as the most critical stages are presented in Figure 2 (Brackle, 1980; cited by Kirkham and Kanemasu, 1983)

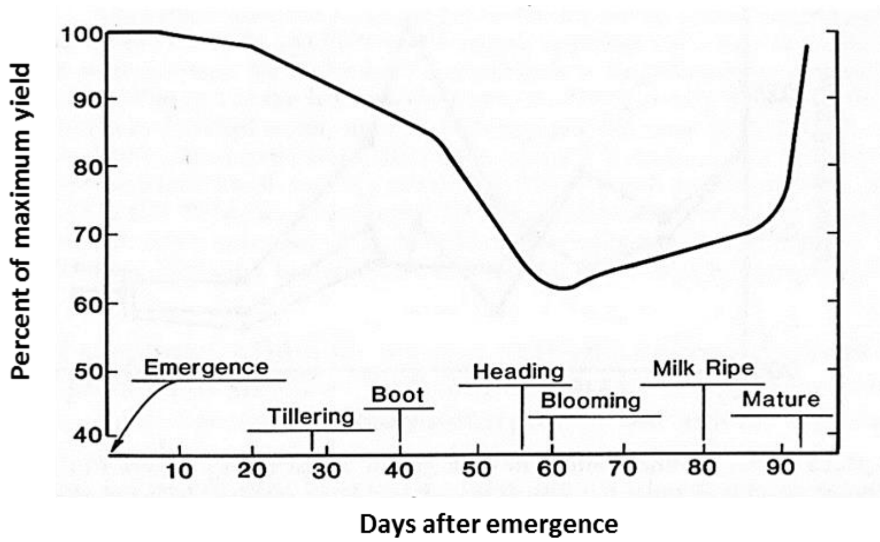

Figure 2. The effect of water stress at various growth stages on grain yield reduction in wheat (Brackle, 1980; cited by Kirkham and Kanemasu, 1983).

2.7 Planting Geometry

Producers continually search for agronomic methods that help to increase crop yields and reduce the cost of production, or a combination of both. Manipulating planting geometry, and increasing or decreasing of row spacing and plant population in the field have been practiced over the decades. Availability of resources such as water and nutrients often determine the selection of planting geometry for a specific area and crop.

Evenly spaced planting

In the conventional evenly spaced planting (ESP), growers practice different row-spacing and plant population intending to improve crop yields. Row-spacing plays a vital role in crop growth and development from various aspects. Narrow row-spacing in corn suppressed weed growth due to smothering effect compared with wider row-spacing (Dwyer et al., 1991). Narrow row-spacing in corn also had higher radiation use efficiency (RUE) and this characteristic especially during grain filling stage contributed to higher dry matter accumulation (Tollenaar and Aguilera, 1992). Studies on narrow row-spacing have resulted inconsistent results in crop yields. Widdicombe and Thelen (2002) studied the effect of row width of 76, 56, and 38 cm (30, 22, and 15 in) and five plant densities ranging from 56,000 to 90,000 corn plants ha^{-1} (~22,000 to 36,000 plants ac^{-1}) at six locations of the Northern Corn Belt. The highest plant density coupled with narrow-row spacing had the highest grain yield with slightly increased grain test weight. Fulton (1970) in Canada also found that under the adequate soil moisture conditions, higher plant densities (54,362 plants ha^{-1} [22,000 plants ac^{-1}]) produced higher yields than lower densities (39,536 plants ha^{-1} [16,000 plants ac^{-1}]) in corn, and rows spaced at 50 cm (20 in) produced higher yields than rows spaced 100 cm (40 in) apart.

Shapiro and Worthmann (2006) conducted corn field experiments for three years comparing the effects of 76 vs. 51 cm (30 vs. 20 in) row-spacing with three plant densities, and four N rates. Plant N concentration and biomass and grain yield were not affected by plant density, but decreasing row spacing from 76 to 51 cm (30 to 20 in) resulted in 4% more grain yield. In contrast, after studying the spacing effect in corn at six locations across Iowa over three years, Farnham (2001) reported that corn grown in 76 cm (30 in) row spacing produced higher yields (10.5 Mg ha^{-1} [4.7 ton ac^{-1}]) than that grown in 38 cm (15 in) rows (10.3 Mg ha^{-1} [4.6 ton ac^{-1}]). Bean and Gerik (2005) reported higher yields of corn planted in 1.0 m (40.2 in) rows than that planted in 76 and 51 cm (30 and 20 in) rows in the Texas Panhandle. However, Rutger and Crowder (1967) evaluated three hybrids of corn in New York at 46 cm (18 in) and 92 cm (36 in) spacing with the same plant population of 86,500 plants ha^{-1} (35,000 plants ac^{-1}) and reported that row spacing did not affect corn silage yields.

Berenguer and Faci (2001) studied sorghum yields at four planting densities (146,000, 180,000, 220,000, and 300,000 plants ha^{-1} [59,000, 73,000, 89,000, and 121,000 plants ac^{-1}]) under variable water supply in Spain. The plant densities did not significantly affect aboveground dry matter, grain yield or harvest index, which was mainly because a greater tiller production, a greater number of grains per panicle, and a higher weight of grains compensated for the smaller number of plants per square meter of the lower plant densities. Some other studies also have reported no effects from reductions in row spacing (Westgate et al., 1997; Porter et al., 1997; Van-Roekel and Coulter, 2012).

Clump

Planting three to four plants in clumps is based on the rationale that growing plants in clumps will increase plant competition, thereby resulting in less use of water, nutrients, and sunlight by the plants and there will be less vegetative growth, mainly because of less tillering. This will leave more water for use by the plants during the reproduction and grain filling growth stages and result in higher grain yields (Stewart, 2006). Clump planting of sorghum and corn has been shown to improve grain yields, reduce tillering, change plant architecture, and increase harvest index in the central and southern High Plains (Bandaru et al., 2006; Mohammed et al., 2012; Kapanigowda et al., 2010a; Krishnareddy et al., 2009; Haag, 2013).

Bandaru et al. (2006) compared clump (3 plants $clump^{-1}$) vs. ESP in the Texas Panhandle continuously for three years and in Tribune, Kansas for one year under dryland conditions. Results showed that planting grain sorghum in clumps reduced tiller formation to about one per plant compared to about three per plant for ESPs. Grain yields were increased by clump planting by as much as 100% when yields were in about 1.00 Mg ha^{-1} (0.45 ton ac^{-1}), 25 to 50% in the 2.0 to 3.0 Mg ha^{-1} (0.9 to 1.3 ton ac^{-1}) range, and there was a slight decrease when yields exceeded 6 Mg ha^{-1} (2.67 ton ac^{-1}).

Krishnareddy et al. (2009) evaluated clump (4 plants clump^{-1}) vs. ESP in grain sorghum with the same plant population of 5.3 plants m^{-2} in the Texas Panhandle. Because of perception of lower red: far-red (R: FR) light ratio for clumps, they produced fewer tillers (< 1 tiller plant^{-1}) compared to ESPs (2 tillers plant^{-1}).

Kapanigowda et al. (2010a) evaluated corn planted in three plants per clump (102 cm [40 in] apart) vs. ESP (34 cm [13 in]) in the Texas Panhandle. Corn was seeded at 3.9 plants m^{-2} and grown with three water treatments, 0 (dryland), 75 and 125 mm (0, 3, and 5 in) of applied irrigation water. They reported that clumps produced significantly fewer tillers but greater grain yield and harvest index compared with ESPs. Reduced early vegetative growth and LAI was also recorded in clumped plants. In the same location, Kapanigowda et al. (2010b) evaluated sorghum planted in four plants per clump (75 cm [30 in] apart) vs. ESP (19 cm [7 in] apart). The targeted plant population was 7 plants m^{-2}. Similar results (reduced tillers, increased grain yield, and HI) as of Kapanigowda et al. (2010a) were reported.

Mohammed et al. (2012) evaluated dryland corn geometries (three plants clump^{-1} with 1 m [39 in] apart, four plants clump^{-1} with 1.33 m [52.36 in] apart, and ESP with 33 cm [13 in] apart in the Texas Panhandle at different planting densities of 2.96 and 3.96 plants m^{-2} and found that clumps reduced LAI at the vegetative growth stage by 5-14% and increased harvest index by 5-10% than ESPs. Grain yields were not significantly higher for clumps but increased number of productive ears and kernel mass was recorded.

Haag (2013) studied five planting geometries in corn and grain sorghum: conventional, clump (3 plants clump^{-1}), cluster, plant-one skip-one (P1S1), and plant-two skip-two (P2S2) in Tribune, Kansas. Each geometry had three planting densities (3.0, 4.0, and 5.1 plants m^{-2}). Results of the study showed that clump planting consistently maximized the number of kernels per plant. Light interception at silking was highest for clump and conventional geometries. In the lowest yielding year, grain water use efficiency (WUEg) was highest for clump and P2S2. Across-years, corn yields were maximized when planted in clumps at low or intermediate plant density. In case of sorghum, clump, cluster, or conventional geometry resulted in similar levels of aboveground biomass, grain yield, biomass water use efficiency (WUEb) and WUEg.

Chim et al. (2014) studied corn 1, 2, and 3 seeds per hill using interrow spacing of 16, 32, and 48 cm (6, 12, and 18 in) , respectively in Oklahoma, and found that on average, normalized difference vegetative index (NDVI) and intercepted photosynthetically active radiation (IPAR) increased with number of seeds per hill and decreased with increasing plant spacing. Further, in three of four site-years, planting 1 or 2 seeds per hill, 16 cm (6 in) apart, increased grain yield by an average of 1.15 Mg ha^{-1} (0.51 ton ac^{-1}), when compared to placing 2 to 3 seeds per hill, every 48 cm (18 in).

Reddy et al. (2015) evaluated three planting geometries namely clump (3 plants adjacent to each other), cluster (3 corn or 6 sorghum plants in clusters), and ESP in a greenhouse. The effect of plant geometry on transpiration efficiency (TE) and grain yield was not statistically significant, but there was a clear trend that the closer the plants were to each other, the greater the TE and grain yield.

Besides ESP and clump, growers in drylands also practice skip-row configuration. This method will conserve some water in the skipped area for use by plants during flowering and grain filling stages, because under conventional spacing, soil water reserves are often depleted before plants reach the reproductive stage resulting in low yield or total crop failure (Fukai and Foale, 1988; McLean et al., 2003; Routley et al., 2003). Drought conditions late in the season when water requirements are high is likely result in premature crop senescence. This drought late in the season can have especially devastating effects on HI and crop yield since early crop senescence limits grain development and the production of harvestable yield (Sinclair and Weiss, 2010). Skip-row planting is expected to be most effective where soil has high water-holding capacity and can therefore conserve significant amounts of water for use during flowering and grain filling stages (Abunyewa et al., 2010). Vigil et al. (2008) reported that skip-row configurations in corn and grain sorghum offered an average of 0.38 Mg ha^{-1} (0.17 ton ac-1) advantage in grain yield over conventional row spacing when studied across 11 site-years at Colorado and Kansas. Lyon et al. (2009) conducted 23 field trials across the central Great Plains from 2004 through 2006 to quantify the effect of various skip-row planting patterns and plant populations on grain yield in dryland corn. In trials where skip-row planting patterns resulted in increased grain yields compared to the ESPs, the mean grain yield for the ESPs was 2.76 Mg ha^{-1} (1.23 ton ac^{-1}). In those trials where skip-row planting resulted in decreased grain yield compared to the ESPs, the mean yield was 8.47 Mg ha^{-1} (3.78 ton ac^{-1}). They suggested skip-row planting if yields are expected to fall between 4.71 and 6.27 Mg ha^{-1} (2.10 and 2.80 ton ac^{-1}), and ESPs for areas with yield potentials of greater than 6.27 Mg ha^{-1} (2.80 ton ac^{-1}).

2.8 Microclimate and Vapor Pressure Deficit

The existence of microclimates has long been recognized. It is the climatic environment of a very small area, which differ from the macroclimate because of uneven topography or differences in plant cover (Croker, 1956). Within the area of one macroclimate there may exist a whole series of microclimates, some of which may differ sufficiently to be of ecological importance. According to Geiger (1965), microclimate is the suite of climatic conditions measured in localized areas near the earth's surface. Owonubi (1975) defined microclimate as the prevailing distribution of various quantities such as temperature, water vapor, wind speed, radiation, and carbon dioxide (CO_2) near the ground. Different scholars (Owonubi, 1975; Brunig and Sander, 1983; Stigter, 1984, Harris and Natarajan, 1987) have studied the manipulation of microclimate in vrious intercropping systems, and have found lower temperature under the crop canopy, especially due to shading. Geiger (1942; cited by Croker, 1956) found that the climate near the ground differed from the macroclimate because of the effect of the ground and the presence of a plant cover.

The microclimate within a crop canopy is influenced by the canopy architecture of a particular crop, and may be strikingly different from the climate of the surrounding environment. Even emerging seedlings will alter the climate near the soil surface by reducing air movement and shading the ground (Arnon, 1975). As plants grow, the extremes in temperatures of the soil surface are reduced. The canopy microclimate may be cooler and more humid than the atmosphere above the crop. Leaf temperatures in sunlight may be higher than the air temperature in day and lower than the air temperature in night (Arnon, 1975).

Vapor pressure deficit (VPD) is the difference between the amount of moisture present in the air and how much moisture the air can hold when it is saturated (Prenger and Ling, 2009). The maximum water holding capacity of the air (dew point) increases with temperature. VPD is one of the most important environmental variables to which stomata respond (Addington et al., 2004). High temperature and low humidity induce leaf water stress when the uptake of water through the root system is inadequate to cope with high transpiration rates (Grange and Hand, 1987). Atmospheric evaporative demand and crop transpiration increase with increasing atmospheric VPD (Sinclair and Bennett, 1998).

The environmental conditions in a field can greatly influence crop physiology and yield. An increase in VPD from 1 to 1.8 kPa determines the major reduction in plant growth in several crops and this is because an increasing VPD can cause an inhibition of photosynthesis (Hoffman, 1979; Bunce, 1984). For example, the photosynthetic CO_2 exchange rates decrease during the afternoon as compared to the morning (Rawson et al., 1978; Singh et al., 1987; Hirasawa and Hsiao, 1999).

Because of the low vapor pressure in the arid regions, the VPD is high, and hence, the higher loss of water through stomata. According to Sinclair and Weiss (2010), grown in a 2 kPa VPD of average transpiration environment, C_4 crops use about 220 g of water to produce 1 g of biomass. In comparison, C_3 crops use about 330 g of water to produce 1 g of biomass. Wright et al. (1994) found positive associations between TE and total biomass produced in drought environments. Plants that follow C_4 photosynthetic pathway had higher TEs, about twice than those with the C_3 pathway (Fischer and Turner, 1978; Turner, 1993). The C_4 plants tolerate higher temperature and can be grown in the warmer seasons of the year. Their higher TE can result in higher yields compared to C_3 plants with the same amount of rainfall and irrigation. So, C_4 crops are preferable in drylands for producing biomass.

VPD is the primary factor that controls the rate of water loss through the stomata (Sinclair, 2009). As the VPD increases, guard cells lose high amounts of water in the form of vapor, which reduces water supply to the epidermal cells and guard cells. This decreases turgor pressure inside the cells. Stomata generally respond by partially closing (Lange et al., 1971; Farquhar et al., 1980; Eamus et al., 2008) to limit transpiration and eventually conserve water from excessive loss (Sinclair et al., 2005; Kholova et al., 2010). As reported by Oren et al. (1999), such phenomena may frequently occur around midday, which prevents extreme dehydration and physiological damage to the plants.

To cope with drought and stress, plants have evolved several adaptive strategies (Borrell et al., 2006; Araus et al., 2008). Conservative water use early in the growing season is one of those adaptations that make water available for the plants later in the growing season (Richards and Passioura, 1989; Sinclair et al., 2005; Messina et al., 2011). Gholipoor et al. (2010) found substantial intra-specific variability in the sensitivity of stomatal response to changes in VPD (1.6 to 2.7 kPa) for 17 sorghum genotypes in Manhattan, Kansas. This trait (stomatal response to VPD) helps to limit transpiration rate to a constant value when the VPD is high and contributes to increase grain yield (Sinclair et al., 2005).

2.9 Transpiration Efficiency and Transpiration Ratio

Transpiration can be defined as the loss of water from the aerial parts of plants in the form of vapor (Kramer, 1983). Transpiration efficiency (TE), an indispensable phenomenon associated with drought tolerance of plants (Mian et al., 1998), is the amount of aboveground biomass (kg dry matter) per unit of water transpired (m^3) (Fischer, 1979; Kemanian et al., 2005; Xin et al., 2009). TE is affected significantly and variably by plant canopy architecture, and leaf anatomy (i.e. thickness of leaf, density of stomata, and mesophyll cell size and position) and leaf activity (stomatal conductance; Zheng et al., 2015). A high TE trait could either enable plants to delay the water stress symptoms by conserving soil water until the next rain, or produce more biomass from the same amount of available soil moisture, or a combination of both (Xin et al., 2008).

Various experiments conducted with different crop species have shown a strong positive correlation between cumulative transpiration and plant dry matter accumulation (Tanner and Sinclair, 1983; Walker, 1986). Reported TE values vary from 3.65 to 3.91 (Bolger and Turner, 1998), 3.2 to 5.7 kg m^{-3} for barley (Kemanian et al., 2005), 1.8 to 4.7 kg m^{-3} for rice (Haefele et al., 2009), 4.7 to 7.1 kg m^{-3} for sorghum (Xin et al, 2009), and 2.9 to 4.5 kg m^{-3} for oat (Ehlers, 1989; Ehlers and Goss, 2003).

In general, plants with the C_4 photosynthesis pathway are more efficient in water use than plants with the C_3 photosynthesis pathway (Bacon, 2004). However, within each species, differences in TE occur (Hammer et al., 1997; Tanner and Sinclair, 1983; Mortlock and Hammer, 1999). Under dryland environments, enhancing TE is likely to have a large impact on improving grain yield in crops including sorghum (Xin et al., 2008).

Drought stress is the single most important factor affecting crop production and yield stability in many regions of the world (McWilliam, 1986). Improving the TE could minimize the effect of drought and improve the food security in drylands because improving the TE means maximization of crop production per unit amount of water use (Turner et al., 2001). To bring the crops to maturity within an available supply of water, Loomis (1983) proposed three strategies: 1) ensuring that a large proportion of available water goes to transpiration, 2) achieving high level of production per unit of transpiration, and 3) achieving a balance between seasonal supply and use of water. Though significant genetic improvement of TE is unlikely (Tanner and Sinclair, 1983), improving crop management practices can lead to an increased TE (Ritchie, 1983).

The reciprocal of TE is the transpiration ratio (TR), which is the ratio of the weight of water transpired by a plant during its growing season to the weight of dry matter produced, usually exclusive of roots (Glickman, 2000). Stewart and Peterson (2015) described grain yield as a function of TR and other attributes, and suggested the following equation.

$GY = [ET \times (T/ET) \times (1/TR) \times HI]$ …... (1)

where GY is the dry grain yield (kg ha^{-1}), ET is evapotranspiration (kg ha^{-1}), T/ET is the fraction of evapotranspiration transpired by the crops, TR is the transpiration ratio (number of kilograms water transpired to produce 1 kg of aboveground dry biomass), and HI is harvest index (kg dry grain per kg aboveground dry biomass).

Stewart and Peterson (2015) mentioned that this equation applies to all situations, where grain crops are produced, but the ranges of values for each of the components were found considerably greater and more variable in dryland farming areas.

2.10 Water Use Efficiency

The term water use efficiency (WUE) has been used to describe harvestable products per unit of water used in ET called grain water use efficiency (WUEg) (Evans and Wardlaw, 1976; Stewart and Peterson, 2015). WUE is also expressed as units of total aboveground dry matter produced per unit of water consumed in ET called biomass water use efficiency (WUEb) (Jensen et al., 1981; Begg and Turner, 1976). TE is often used as a measure of WUE (Eamus, 1991).

Transpiration can be increased by reducing evaporation, runoff, and drainage from the crop root zone (Gregory et al., 1997). However, increasing WUE is a key challenge facing researchers and scientists (Zea-Cabrera et al., 2006). Passioura (1996) described grain yield as a partial function of WUE and developed the following equation.

$Y = WUE \times WU \times HI$ ……………………………………………. (2)

Or,

$Y = (B/WU) \times WU \times HI$ …………………….……………………… (3)

This turns to the basic equation as given below (Donald and Hamblin, 1976).

$Y = B \times HI$……….………………………………………...... (4)

where Y is grain yield (g DM m^{-2}), WUE is water use efficiency (g DM/g H_2O), WU is water use (g H_2O m^{-2}), HI is harvest index (g Y/ g B), DM is dry matter (g), ET is evapotranspiration (g H_2O m^{-2}), and B is aboveground biomass (g DM).

Sparse or erratic rainfall distribution in space and time coupled with water loss through runoff, deep drainage (below the root zone), and evaporation from the soil surface are some of the factors that account for low WUE (Mando, 1997). WUE can vary depending on the definition of WUE used, type of crop, a portion of the crop harvested, and the weather conditions. However, where water is limited, the greater the proportion of water that passes through the plant the greater will be the dry matter production; and the greater the WUE, the greater the dry matter production (Turner and Burch, 1983).

The term drought resistant and WUE are sometimes used synonymously, although as pointed out by Hsiao and Acevedo (1974), they are frequently unrelated. Drought resistance is the ability of plants to survive and yield satisfactorily under conditions of drought, whereas WUE is simply the efficiency with which water is used to produce dry matter (Turner and Burch, 1983).

The major environmental factor influencing the WUE of a crop is atmospheric humidity. A lowering of the VPD of the atmosphere around a leaf will proportionally increase the transpiration rate of the leaf. However, photosynthesis will not be affected unless the stomata close as a result of the direct effect of humidity on the stomata or an indirect effect through a lowering of the leaf water potential. Thus, if some compensatory closure of stomata does not occur, a decrease in humidity will decrease the WUE of the plant. Other environmental factors that influence WUE are air temperature, irradiance, and soil water availability. The level of CO_2 in the atmosphere also influences the efficiency of water use by plants, where WUE increases with the increase in CO_2 concentration (Turner and Burch, 1983). Law et al. (2002) found a strong effect of VPD on WUE of forest trees, grasslands, and field crops.

2.11 Mulching

Mulching is considered as one of the crucial cultural practices for increasing WUE (Khurshid et al., 2006). It is used in manipulating crop growing environment to increase yield and improve product quality by conserving soil moisture, ameliorating soil temperature, reducing soil erosion, suppressing weeds, improving soil structure, and enhancing organic matter content (Li et al., 2004; Awodoyin and Ogunyemi, 2005; Chakraborty et al., 2008).

Evaporation from bare soil surface results in a substantial loss of moisture and has a direct impact on crop yield in rainfed agriculture of arid and semi-arid regions (Mellouli et al., 2000). Mulching reduces evaporation from the soil surface by altering water distribution between evaporation and plant transpiration (Raeini-Sarjaz and Barthakur, 1997, Pabin et al., 2003; Hartkamp et al., 2004), and maintains soil under stable temperature (Lal, 1974; Ji and Unger, 2001; Kar and Kumar, 2007). It helps to increase soil water retention and modify the microclimate (Albright et al., 1989; Feng, 1999). Residue on the soil surface reduces evaporation of soil water in periods of drought or light rains (Lal, 1974) and provides the best opportunity for increasing crop productivity (Carter, 1998). Mulch also prevents rain from hitting the soil directly and reduces the impact of the water drops.

Unger (1978) studied the effect of straw mulch on soil water storage over four years in Bushland, Texas and found that the average precipitation storage in a Pullman clay loam soil covered with 12.0 Mg ha^{-1} (5.3 ton ac^{-1}) of wheat residue was almost twice (21.4 vs. 12.0 cm [8.4 vs. 4.7 in]) than without residue. Precipitation storage in the central and Northern Great Plains increased from 16% with no mulch to 37% with 6.72 Mg ha^{-1} (3.00 ton ac^{-1}) of mulch (Greb et al., 1970). A study conducted by Zhang et al. (2005) in North China Plain used combine harvesting for winter wheat that left straw mulch on the soil surface and grew corn. They found that the mulch reduced evaporative loss by 40.0 to 50.0 mm year^{-1} (1.6 to 2.0 in year^{-1}) measured by microlysimeters, and average WUE was improved 8 to 10% for the 12 seasons. Langdale et al. (1992) conducted a 5-year study in Georgia and reported that crop residues on the soil surface increased soil carbon and potential N mineralization in clover and sorghum fields.

According to Jordan et al. (2010), long-term mulching improved both chemical and physical properties of soil in semiarid regions of Spain. A study conducted by Lal (1976) in a semiarid region of Nigeria found that 4.0-6.0 Mg ha^{-1} (1.8-2.7 ton ac^{-1}) of straw mulch improved soil physical properties. Santos et al. (2010) grew beans in a semiarid climate of Northeast Brazil and noted the significant influence of straw mulch in improving soil moisture content both in dry and rainy seasons. Uwah and Iwo (2011) conducted a two-year corn field experiment on the acidic coastal plain soils of south-eastern Nigeria with five mulch rates of 0.0, 2.0, 4.0, 6.0, and 8.0 Mg ha^{-1} (0.0, 0.9, 1.8, 2.7, and 3.5 ton ac^{-1}). They found that soil moisture reserves were highest at 8.0 Mg ha^{-1} (3.5 ton ac^{-1}) mulch rate, followed by 6.0 Mg ha^{-1} (2.7 ton ac^{-1}). The unmulched plots had the lowest soil moisture reserves and produced less than half corn yield that of at 6.0 or 8.0 Mg ha^{-1} (2.7 or 3.5 ton ac^{-1}) rates.

Mulch increased grain (17%) and biomass (19%) yields and WUE (14%) compared with bare soil treatment in Bushland, Texas when it effectively suppressed evaporation of soil moisture and made more of the soil water available for transpiration (Tolk et al., 1999). Unger (1978) in the same location obtained 3.99 Mg ha^{-1} (1.78 ton ac^{-1}) of sorghum yield with 12.0 Mg ha^{-1} (5.3 ton ac^{-1}) mulch treatment compared with 1.78 Mg ha^{-1} (0.79 ton ac^{-1}) for bare field treatment. In semiarid Nigeria, soil temperature differences of as much as 8ºC (14.4ºF) were observed between mulched and unmulched plots at 5 cm (2 in) depth; and when mulch was applied uniformly, the grain yield increased from 22-52% (Lal, 1974). In contrast, Wicks et al. (1994) applied 0, 1.7, 3.4, 5.1, and 6.8 Mg ha^{-1} (0, 0.7, 1.5, 2.3 and 3.0 ton ac^{-1}) of wheat straw mulch and reported reductions in corn yield at the higher mulch levels due to the lack of sufficient growing degree-days (GDD) to compensate for lower soil temperatures in cool and rainy weather conditions of west-central and western Nebraska.

Mulching combined with reduced tillage is effective in reducing surface runoff, improving soil structure, conserving soil moisture, and enhancing organic matter content (Liebig et al., 2004; Giller et al., 2009). When the plant attains a certain height, its canopy can also shade the soil surface, thus substituting for the beneficial effects of residue during the latter part of the growing season (Adams et al., 1976).

CHAPTER III

MATERIALS AND METHODS

STUDY 1: Improving Microclimate Through Manipulating Plant Geometry in Grain Sorghum

3.1.1 Design of Experiment

A-two year grain sorghum study was conducted in the greenhouse of West Texas A&M University, Canyon, Texas in the summer 2013 and 2014. Sorghum (cultivar: DK-S36-06) was grown in two geometries (clump and ESP), two water levels (high and low) and three soil surface types (lid covered, straw-mulched, and bare surface). For both years, the greenhouse temperatures were maintained between 20ºC (68ºF) (night minimum) and 32ºC (90ºF) (day maximum), and the RH for the growing period ranged from 28 to 95%. No supplemental light source was provided.

Thirty-six wooden boxes having a volume of 68 L (100×24.3×28 cm) (Figure 3) and filled with 46.3 kg of Calcined clay were used to grow sorghum. This material is porous, has a low bulk density (0.68 g cm^{-3} after packing), retains a large quantity of plant available water, is chemically inert and maintains good aeration and drainage properties needed for plant growth (Ingram et al. 1993). All boxes were brought to 42% volumetric water content by adding 28.6 L of filtered water. Before adding water, 75 g of “Miracle-Gro water soluble all-purpose plant food” was mixed uniformly in each box. This fertilizer provided 18.0-2.6-10.0 g box^{-1} of N-P-K, respectively, and some amounts of boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn). Potential water leakage was prevented by lining each box with a plastic sheet. Boxes were randomized in a nested split plot design with three replications.

Sorghum seeds were planted on 15 May 2013 and 23 May 2014 and before planting, all the boxes were weighed using a common balance. In clump geometry, six plants were grown in two clumps (three plants in each clump) per box, which were 50 cm (20 in) apart and 25 cm (10 in) away from each end of the box. In ESP geometry, six plants were individually spaced 16.6 cm (6.5 in) apart in a row, leaving 8.3 cm (3.4 in) at either end of the boxes (Figure 3). Five to six seeds in clump and three to four seeds in ESP geometry were planted. When the seedlings reached 10-12 cm (4-5 in), they were thinned to three plants in each clump and individual plants in ESP.

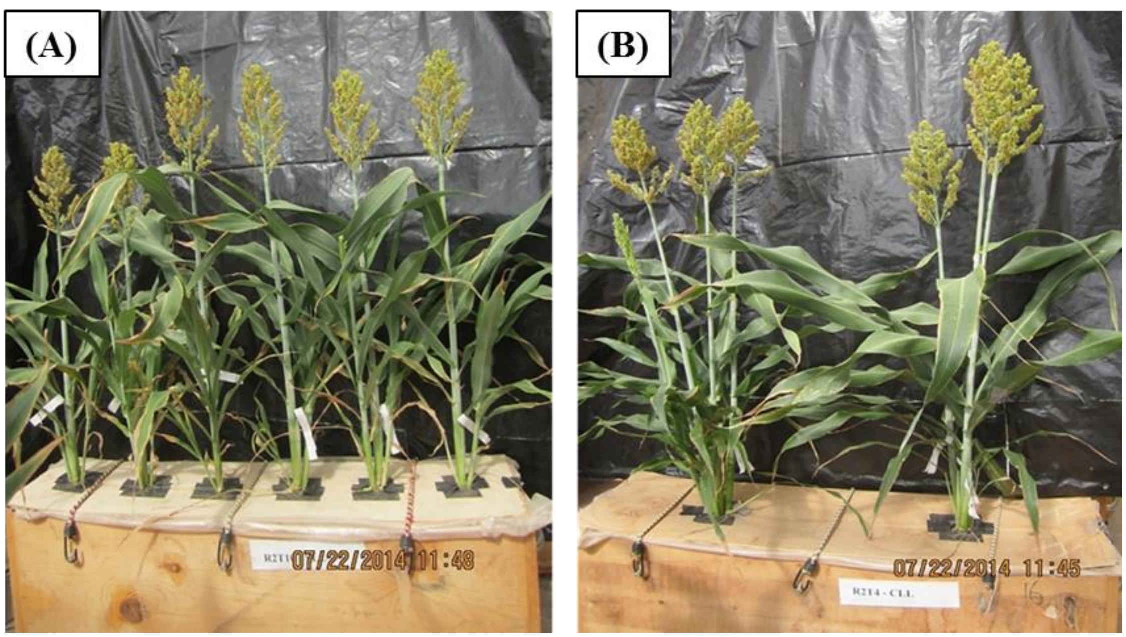

Figure 3. Evenly spaced planting (ESP) geometry (A) and clump geometry (B) in the greenhouse.

In 2013, water was added to the boxes based on visual water stress observed in plants at low water treatments. Before adding water, experimental boxes were weighed to monitor the amount of water used and determine how much should be added. At each watering, plants at low water treatment were provided with 50% less water than plants growing at the high water treatment. For all treatments, water was added on the same day. This protocol caused plants at some low water treatment boxes (especially with bare soil surface) to become severely stressed before plants at high water treatments (especially with lid covered surface) were in need of added water. Because of this gap in water requirement, small amounts of water were added every 4-5 days to make sure that neither the stressed plants at low water treatments died nor the high water treatments exceeded the initial volumetric water content of 42%. Hence, water management became quite problematic, so a different watering protocol was used in 2014. In 2014, volumetric water contents between 35-42% and 28-35% were maintained for high and low water treatments, respectively. To monitor the water use, every box was provided with a digital balance. Using this protocol, overall amounts of added water were higher than for the previous method, and plants at low water treatment received 26% less water than plants at high water treatment. Total amounts of 46.4 L at high and 23.2 L at low water treatments were added in 2013 and in 2014, 61 L and 45 L were added for high and low water treatments, respectively.

For lid surface treatment, boxes were covered with wooden lids with holes for growing plants. The holes made for plants had an area of 7.9 cm^2 for ESPs and of 20.3 cm^2 for clumps. In order to prevent evaporation from the holes, they were covered with plastic tape, leaving a small portion sufficient for emerging seedlings. The tape was readjusted as the plants grew. All water lost from these boxes was assumed to be transpiration. The mulched treatment was covered with wheat straw of 4 Mg ha^{-1} (1.8 ton ac^{-1}) (Shaheen et al., 2010).

3.1.2 Measurements

Vapor Pressure Deficit

Air temperature and relative humidity (RH) within the plant canopy were measured using the LASCAR EL-USB-2+ sensors at different growth stages, but the emphasis was given for the booting through grain formation period (50-70 DAP), which is considered most critical growth stages for water stress in grain sorghum (Craufurd et al., 1993). These sensors measure and store up to 16,382 RH (0 to 100%) and 16,382 temperature (-35 to +80°C [-31 to 176ºF]) readings (LASCAR, 2008). Depending on the plant height at different treatments, sensors were kept 45.0-60.0 cm (1.5-2.0 ft) above the soil surface (Figure 4).

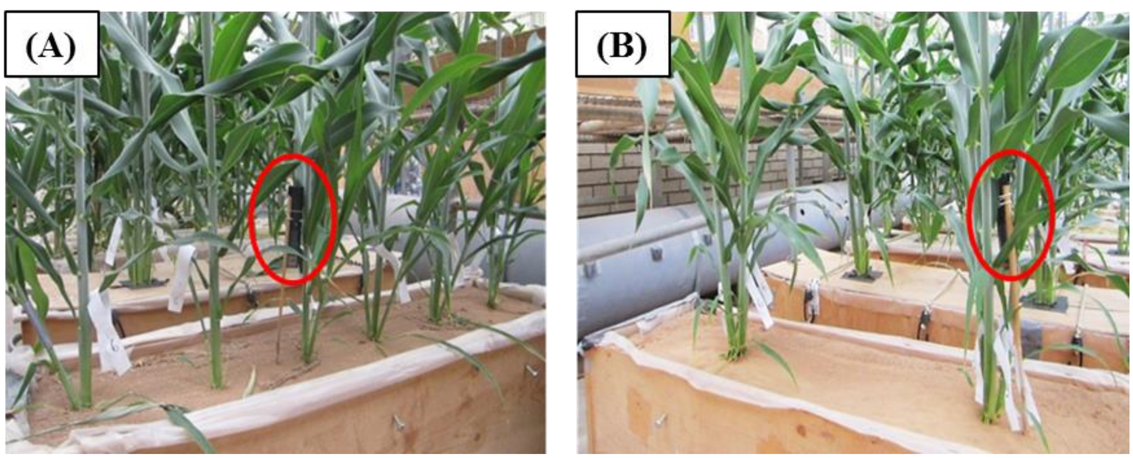

Figure 4. Measurement of temperature and humidity using LASCAR EL-USB-2^{+} sensors for evenly spaced planting (ESP) geometry (A) and clump geometry (B) in the greenhouse.

The measurements were recorded from three replications, every five minutes continuously for three days in 2013 and five days in 2014. VPD was calculated using the following equations described by CronkLab (2015):

$SVP = 610.7 \times 10^{7.5T/(237.3+T)}$ …………………………………….. (5)

and $VPD = [(100 - RH)/100] \times SVP$ ………………….…………… (6)

where SVP is saturated vapor pressure (P), T is temperature (ºC), VPD is vapor pressure deficit (kPa), and RH is relative humidity (%).

Tiller Number and Leaf Area

All the plants were included in counting tiller number at flag leaf stage, and then leaf area per plant (including tillers) was measured using:

$LA = W \times L \times 0.75$ …………………………………..………… (7)

where LA is the leaf area (cm^2), W is the maximum width (cm) of the leaf, L is the leaf length (cm) from leaf collar to the end of the leaf tip, and 0.75 is a correction factor (*k*) for sorghum (Sticker et al., 1961; Mass et al., 1987).

Cumulative Water Use

The sorghum plants were harvested on Sept. 08 (118 days after planting, DAP) in 2013 and on Sept. 16 (116 DAP) in 2014. Before harvesting, all the boxes were weighed on the common balance in order to calculate the ET as:

$V = (w_i + v_t) - w_f$ ….…………………………………….………..…. (8)

where V is the cumulative volume (L) of water used in ET, w_i is the initial weight (kg) of a box at seeding, v_t is the total volume (L) of water added during the crop growing period, and w_f is the final weight (kg) of a box before crop harvest. Since water has density of 1 g cm^{-3} (or, 1 g ml^{-1}), weight of water is equivalent to its volume.

Transpiration Efficiency and Water Use Efficiency

Samples were dried in the oven at 70ºC (158ºF) until a constant weight was recorded. After drying, they were weighed to obtain the aboveground biomass and threshed to measure grain yields. The biomass transpiration efficiency (TEb) and grain transpiration efficiency (TEg) for the lid surface treatment were calculated by dividing the weight of total aboveground dry biomass and grain yield, respectively, by the total amount of transpiration. Similarly, biomass water use efficiency (WUEb) and grain water use efficiency (WUEg) were calculated by dividing aboveground dry biomass and grain yield, respectively, by total amount of water used in ET.

3.1.3 Statistical Analysis

Data were analyzed via two-way analysis of variance (ANOVA) using PROC MIXED in SAS 9.3 (SAS Institute, Inc. 2009). Year, planting geometry, water level and surface type were considered as fixed effects. Replication was a random effect. The mean separation test was done using least significance difference (LSD), and differences were considered significant at $P < 0.05$. ANOVA was not used for VPD data, which was significantly different between clumps and ESPs for daytime (8:00 to 20:00 h CST), but while analyzing 24 h data, the test was not different, because VPDs for both geometries were same from late evening to early morning (20:00 to 8:00 h CST). The PROC REG in SAS 9.3 was used to develop regression coefficients between aboveground biomass or grain yield and water transpired from the plants in lid surface treatment.

STUDY 2: Growing Corn in Clumps: A Strategy to Improve Microclimate, Water Use Efficiency, Grain Yield, and Harvest Index

3.2.1 Design of Experiment

Gruver field study (GFS) was conducted in summer 2014 on the Barkley Tomlinson Farm, located near Gruver, Texas (36º15′46″N, 101º24′19″W; elevation 977 m [3,205 ft] above mean sea level). The field has a soil type of Sherm clay loam (fine, mixed, mesic Torrertic Palevstrooll) developed in a relatively cool, subhumid to semiarid climate from medium- to fine-textured sediments largely or entirely of eolian origin. Sherm soil samples from nine sites had mean sand, silt, and clay contents of 219, 439, and 342 g kg^{-1}, respectively at 0 to 15 cm (0 to 6 in) depth (Unger and Pringle, 1986).

Irrigation was carried out using a center pivot irrigation system. There were three irrigation levels, namely high irrigation treatment (HIT), medium irrigation treatment (MIT) and low irrigation treatment (LIT). For HIT, the sprinkler system operated continuously through the irrigated period and for MIT, sprinkler nozzles were turned off every other irrigation cycle. For LIT, water was applied only three times. The first irrigation was applied to soften the crusted soil and ensure emergence and early growth. The second and third irrigations occurred to relieve severe moisture stress. The sprinkler took approximately 72 h to make a complete turn delivering 25 mm (1 in) of water throughout the field. Nozzles were calibrated to supply an equal amount of water for the same water treatments. Four rain gauges were placed in the field to measure the accuracy of irrigation and to measure the amount of rainfall during the study period. Total amounts of 46, 326, and 664 mm (1.8, 13, and 26 in) of irritation water were applied to LIT, MIT, and HIT, respectively, throughout the crop period (Table 1).

Table 1. Total precipitation and irrigation at Gruver, Texas and precipitation at Bushland, Texas from June-October (crop growing period) in 2014 and 2015, respectively.

Study site		June	July	Aug.	Sept.	Oct.	Total	P + I
Gruver (June 05- Oct. 19, 2014)								
Precipitation (P) (mm)†		99	103	53	25	0	280	-
Irrigation (I) (mm)	LIT	13	25	8	0	0	46	326
	MIT	56	150	120	0	0	326	606
	HIT	81	293	262	28	0	664	944
Bushland (June 24-Oct. 02, 2015)								
Precipitation (P) (mm)		0	73	114	10	23	220	-

Note: LIT = low irrigation treatment, MIT = medium irrigation treatment, HIT = high irrigation treatment. †25.4 mm = 1 in.

Source: Measured in the study field (Gruver) and USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas (Bushland).

Upon harvest of the previous crop (silage wheat), strip till was done to prepare the land during the first week in June 2014 using a 12-row no-till strip tiller. This machine placed liquid fertilizer of N-P-K of 28-49-23 kg ha^{-1} (25-44-21 lb ac^{-1}), respectively to a depth of 18 cm (7 in). For HIT and MIT, additional fertilizer providing N-P-K of 44-0-0 kg ha^{-1} (39-0-0 lb ac^{-1}), respectively was also applied through the water delivery system.

The experimental design was split-plot with four replications of plot size 37.2 m^2 (400 ft^2). The irrigation levels (HIT, MIT, and LIT) were considered whole-plot factors and planting geometries (clump and ESP) were sub-plot factors. The row spacing was maintained 76 cm (30 in) for all the treatments, but the plant to plant distance varied between the planting geometries and among the irrigation levels. For LIT, MIT, and HIT, the planting population was 40,000, 60,000 and 80,000 plants ha^{-1} (16,000, 24,000, and 32,000 plants ac^{-1}), respectively. The ESP and clump geometries in LIT, MIT, and HIT had the plant to plant spacing of 33 and 99 cm (13 and 39 in), 22 and 66 cm (9 and 27 in), and 16 and 48 cm (6 and 18 in), respectively (Figure 5).

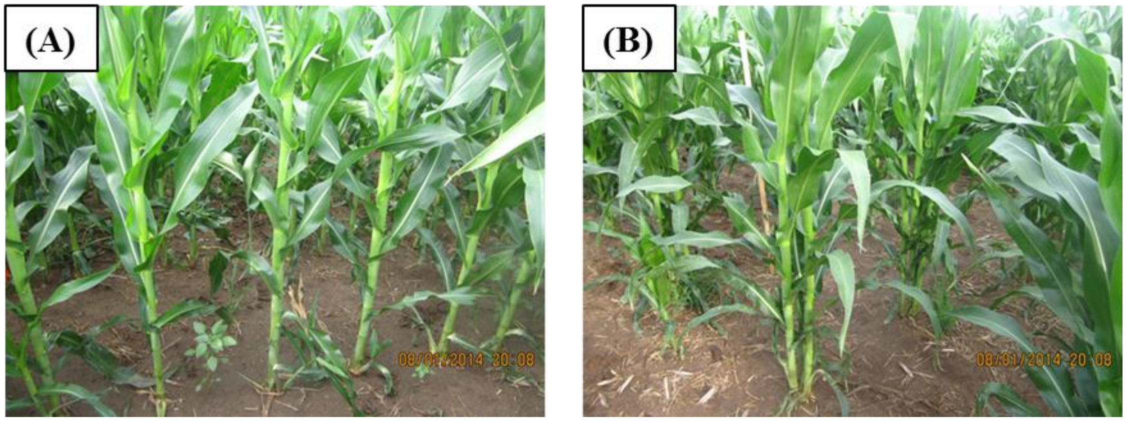

Figure 5. Evenly spaced planting (ESP) geometry (A) and clump geometry (B) under medium irritation treatment (MIT) in Gruver field study, 2014

Corn seeds (hybrid: Pioneer P1151AM) were planted on June 05, 2014, using a hand planter designed to plant the number of seeds as required. Four to five seeds in clump geometry and two to three seeds in ESP geometry were planted. When the seedlings reached about 15 cm (6 in), they were thinned to three plants for each clump and individual plants for ESP.

Bushland field study (BFS) was conducted at the USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas (35º11′31″N, 102º03′53″ W; elevation 1,180 m [3,871 ft] above mean sea level). The field has a soil type of Pullman clay loam (fine, mixed, super active, thermic Torrertic Paleustoll) containing 170, 530, and 300 g kg^{-1} of sand, silt, and clay, respectively at 0 to 15 cm (0 to 6 in) depth (Unger, 1999). The average annual precipitation at Bushland is 470 mm (19 in) which is considerably lower than the average annual potential evapotranspiration of 1,880 mm (71 in) (Stewart, 1988).

A randomized complete block design (RCBD) was used to compare clump and ESP geometries for field corn planted in four replications under dryland condition. Each plot (27.8 m^2 [300.0 ft^2] area) had six rows of crops 67 cm (30 in) apart and were oriented in a North-South direction. The targeted plant population for both geometries was 35,000 plants ha^{-1} (14,000 plants ac^{-1}). In clump geometry, each three plants were clustered 114 cm (45 in) apart and in ESP geometry, single plants were planted 38 cm (15 in) apart in the rows. Since corn was grown in a fallowed area and plant nutrients generally are not limiting after a fallow period at Bushland (Bandaru et al., 2006), fertilizer was not applied. Corn seeds (hybrid: N42Z-3111A) were planted on 24 June, 2015, using the same methods as mentioned in the GFS.

3.2.2 Measurements

Thermal Imaging

For both studies, two thermal images were taken from each plot using a thermal infrared camera (ThermaCAM S45 HS, FLIR System, Sweden) at the hottest part of day (14:00 - 15:00 h CST). Images were taken at the silking and grain filling stages, which have been shown to the most sensitive growth stages to water stress in corn (Doorenbos and Kassam, 1979; Musick and Dusek, 1980; KSU, 2007). Following the thermal imaging, pictures from each plot were taken using a normal digital camera (Cannon PowerShot ELPH 130 IS). All images were captured at a distance of about 1.5 m (5 ft) from the top of the closest canopy to enclose leaves in the upper part of the canopy. Images were processed using IR Crop Stress Image Processor Software to filter out background soil and to obtain mean canopy temperature (CT). A rectangular area within each image covering middle two rows was selected for the measurement of CT based on several leaves having about 30,000 pixels (Figure 6). The temperature averaging over several leaves reduces the impact of variation in leaf temperature due to the different leaf angle facing to the sun (Grant et al., 2006).

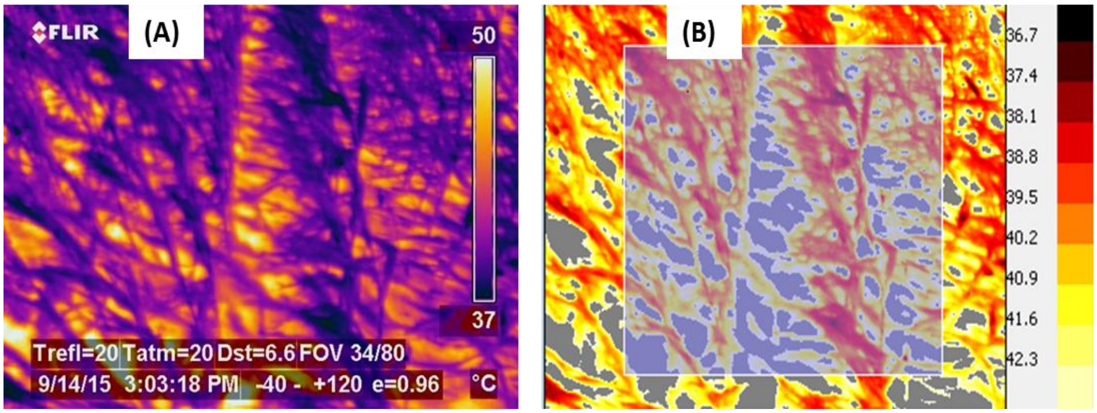

Figure 6. Example of a picture taken by the thermal camera (A) and the same picture processed using IR Crop Stress Image Processor Software (B). Grey patches in picture B are the soil surfaces filtered out by the software for the temperature range of 35-43ºC (95-109ºF).

Vapor Pressure Deficit

Air temperature and RH within the plant canopy were measured using the LASCAR EL-USB-2$^+$ sensors at different growth stages, but as in the case of thermal imaging, the emphasis was given to the reproductive (tasseling/silking) and grain filling states, where sensors were placed at about 1.2 m (4.0 ft) height. The measurements were recorded from all plots every five minutes continuously for five days. VPD was calculated using the following equations described by CronkLab (2015).

SVP = $[610.7 \times 10^{7.5T/(237.3+T)}]$ …………………………………….. (9)

VPD = $[(100 - RH)/100] \times SVP$ ………...………………………… (10)

where SVP is saturated vapor pressure (P), T is temperature (ºC), VPD is vapor pressure deficit (kPa), and RH is relative humidity (%).

Tiller Number and Leaf Area Index

Tillers per plant were counted at flag leaf stage, taking 18 plants (6 clumps) as a sample from the middle two rows. The LAI-2200 plant canopy analyzer was used to measure the LAI at flag leaf stage. The instrument uses measurements from above and below the canopy to determine the interception of light by the canopy at five zenith angles. To avoid the effect of direct sunlight, measurements were taken early in the morning using 30º view cap.

Biomass, Grain Yield, and Harvest Index

Corn samples in GFS and BFS were harvested, respectively on Oct. 19, 2014, (137 DAP) and Oct. 02, 2015, (101 DAP). For GFS, corn was harvested from the middle two rows having an area of 7.5, 6.0, and 4.6 m^2 (80.7, 64.6, and 49.5 ft^2), respectively for LIT, MIT, and HIT. Six plants (two clumps) from each plot were harvested for HI calculation (dry weight of kernel divided by the dry weight of aboveground biomass) and were kept separately, while a full sample was used for determining grain yield. Corn in BFS was harvested from the middle four rows (13.7 m^2 [148 ft^2] area) including 12 plants (4 clumps) from each row. The middle two rows were harvested for HI calculation, while adjoining two rows were added on grain yield.

Samples were dried in the oven at 70ºC (158ºF) for a week and then weighed using a digital balance to obtain aboveground biomass. Ears were subsequently threshed to determing grain mass. Moisture content in kernels was measured using a mini GAC-plus moisture tester, then subtracted to adjust at 0% in order to calculate the HI. Grain yield was reported at 15.5% moisture (wet basis). For both studies, total grain yield and HI were used to calculate the aboveground biomass per plot.

Water Use Efficiency

For GFS, soil water contents at planting and harvesting were not available. So, WUEg was calculated dividing the dry grain yield per hectare by total water added through irrigation and precipitation (mm) during the crop period. For BFS, gravimetric soil water contents were determined by taking soil cores at 0-15, 15-30, 30-60, 60-90, and 90-120 cm (0-6, 6-12, 12-24, 24-36, 36-48, and 48-60 in) deep at planting and after harvesting. These values were converted to volumetric water content using the bulk density for different soil profiles of Pullman clay loam reported by Unger and Pringle (1981). Evapotranspiration was determined by using soil water balance method assuming no runoff and no deep percolation. WUEg was computed on a dry grain basis (0 g moisture kg^{-1} grain).

3.2.3 Statistical Analysis

Statistical analysis was done using SAS (SAS Institute, Inc., 2009). For GFS, analysis of variance (ANOVA) was conducted through PROC MIXED to evaluate the effect of main factor and interaction. Replication was considered as the random effect, while planting geometry and irrigation were considered as fixed effects. For BFS, an independent t-test was performed to compare the differences between clumps and ESPs. Mean values for GFS were compared with the least significance difference (LSD) at the 5% level.

STUDY 3: Grain Sorghum Transpiration Efficiency at Different Growth Stages As Affected By Growing Period Vapor Pressure Deficit

3.3.1 Design of Experiment

Two sequential greenhouse (GH1 and GH2) and growth chamber (GC1 and GC2) studies were conducted in Summer 2015 through Spring 2016 at West Texas A&M University, Canyon, Texas. For all studies, grain sorghum (cultivar: DK-S36-06) was grown in clump geometry (3 plants clustered). The GH and GC temperatures were maintained between 20ºC (68ºF) (night minimum) and 32ºC (90ºF) (day maximum), but there were no facilities to regulate RH.

Sixteen wooden boxes having a volume of 68 L (100×24.3×28 cm) for each GH study and the same number of plastic boxes having a volume of 28 L (46×30.5×20 cm) for each GC study were used to grow sorghum plants. Wooden and plastic boxes were filled with 46.3 kg and 19 kg of calcined clay, respectively. All boxes were brought to 42% volumetric water content by adding 28.5 L (wooden boxes) and 11 L (plastic boxes) of filtered water. Potential water leakage from wooden boxes was prevented by lining all boxes with a plastic sheet. Before adding water, 70 g of "Miracle-Gro water soluble all-purpose plant food" was mixed uniformly with the calcined clay in each wooden box. This fertilizer provided 18.0-2.6-10.0 g box^{-1} of N-P-K, respectively. For the plastic boxes, 35 g of the same fertilizer was used which provided 9.0-1.3-5.0 g box^{-1} of N-P-K, respectively. This fertilizer also provided some amounts of boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn). Based on the total amount of biomass produced in the GH1 and GC1 studies, plants were able to utilize less than half of the N applied in each box, so in GH2 and GC2 studies, same fertilizer was added at 30 and 15 g box^{-1}, respectively.

The experimental design was randomized compete block design (RCBD) with four replications. Sorghum seeds were planted on July 17, 2015 for the first (GH1 and GC1) studies and on Nov. 06, 2015 for the second (GH2 and GC2) studies. Before planting, all the boxes were weighed using a common balance. For the GH studies, in each box, six plants were grown in two clumps (three plants per clump), which were 50 cm (20 in) apart and 25 cm (10 in) away from each end of the box. For GC studies, three plants were grown in a clump at the center of each box. Volumetric water content in each box was maintained between 35-42% throughout the crop period, ensuring that sorghum plants were never water stressed. Boxes were covered with lids having holes for growing plants. The holes made for each clump had an area of 20.3 cm^2. In order to prevent evaporation, the holes were covered with plastic tape, leaving only a small portion sufficient for emerging seedlings. The tape was readjusted as the plants grew. Boxes were sealed to the lids using tape so all water lost from the boxes was assumed to be transpiration.

Boxes were weighed every 4-5 days to monitor the amount of water used by plants and the amount to be added. Plants were harvested at six leaf stage (S1), flag leaf stage (S2), grain filling stage (S3), and grain maturity stage (S4) (Figure 7). Though there was a small variation among the studies, on average, plants were harvested at 35 DAP (S1), 50 DAP (S2), 75 DAP (S3) and 105 DAP (S4) based on the harvesting plan prepared at seeding. Plants grown in four boxes (one box from each replication) were harvested at each growth stage totaling 24 plants in each GH study and 12 plants in each

GC study. After harvesting, plant samples were separated into shoot and root systems. Roots were washed carefully insuring that no roots were lost, and then placed on blotting paper to absorb excess water. Samples were oven dried at 70ºC (158ºF) until the constant weight was recorded. Finally, dry weights of roots, shoots, and their total were measured.

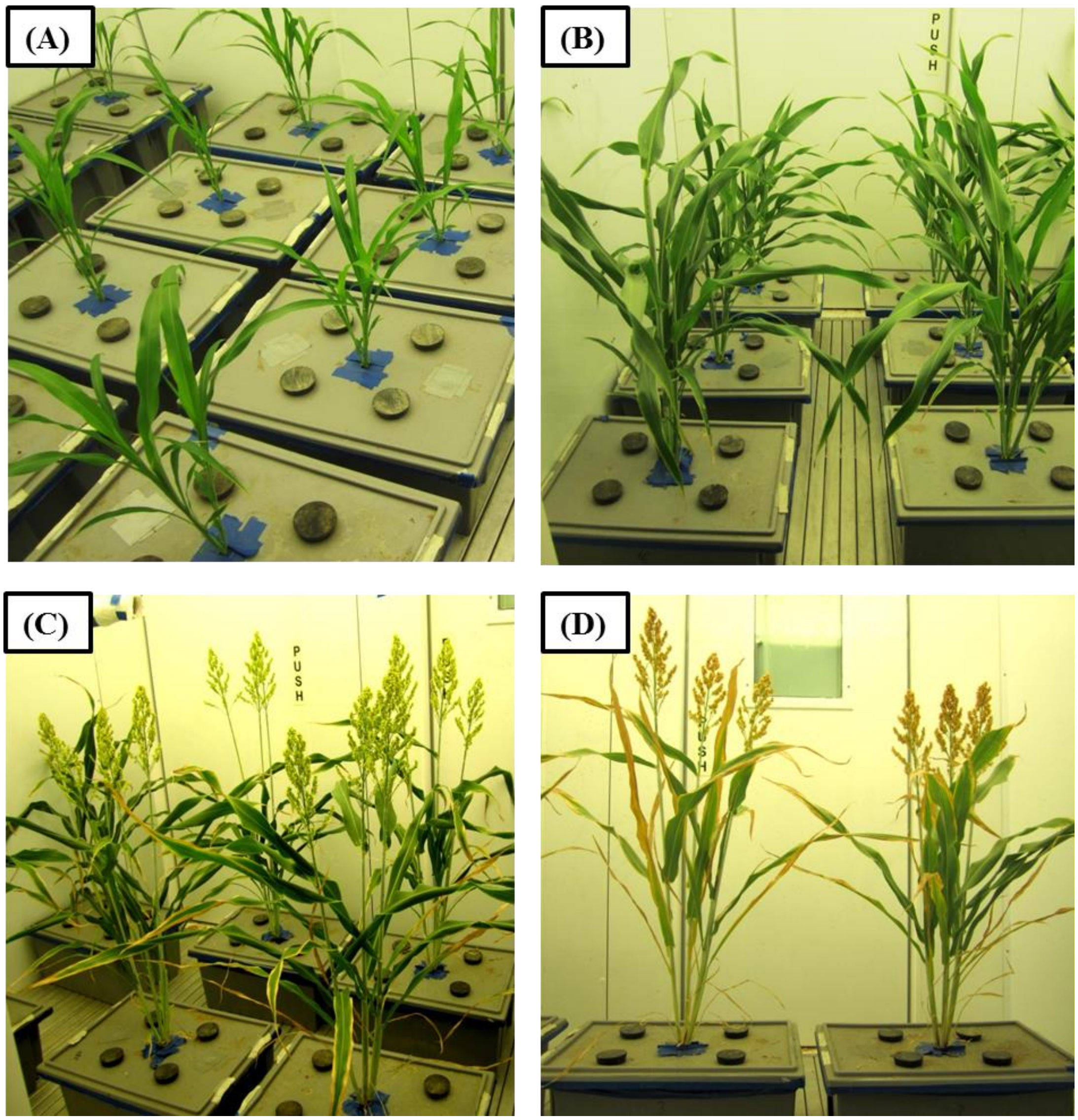

Figure 7. Sorghum plants at different growth stages in the growth chamber, six-leaf stage (A), flag leaf stage (B), grain filling stage (C), and grain maturity stage (D).

3.3.2 Measurements

Temperature and Relative Humidity

The air temperature and relative humidity (RH) in GH and GC were measured every 30 min. using two sets of LASCAR EL-USB-2+ sensors starting seedling emergence through final harvest at grain maturity. Sensors were placed above the crop canopy height.

Cumulative Water Use

Before each harvest, boxes were weighed on a common balance in order to calculate the cumulative water used in transpiration as:

$V = (w_i + v_t) - w_f$ .... (11)

where V is the cumulative volume (L) of water lost by transpiration, w_i is the initial weight of a box at seeding (kg), v_t is the total volume of water added during the crop growing period (L), and w_f is the final weight of a box before crop harvest (kg). Since water has density of 1 g cm^{-3} (or, 1 g ml^{-1}), weight of water is equivalent to its volume.

Shoot: Root Ratio

The shoot to root (S:R) ratio was calculated on a dry weight basis by dividing the total shoot mass by the root mass obtained from each box.

Transpiration Efficiency

The TE values were calculated by dividing the aboveground dry matter (shoot) and total dry matter (shoot + root) by the total volume of water transpired by plants during the growing period and called shoot transpiration efficiency (TE_{shoot}) and total transpiration efficiency (TE_{total}), respectively. Since evaporation was prevented from each box, water used as transpiration (T) was equivalent to water used in evapotranspiration (ET) (i.e. T/ET = 1).

3.3.3 Statistical Analysis

Data were analyzed using PROC MIXED in SAS 9.3 (SAS Institute, Inc., 2009). Since environmental conditions varied between two GH or GC studies, data were analyzed via two-way analysis of variance (ANOVA) considering environment as an interacting factor with plant growth stage. Environment and growth stage were considered as fixed effects and replication was random effect. The mean separation test was done using least significance difference (LSD) and differences were considered significant at $P < 0.05$. The PROC REG in SAS 9.3 was used to develop a regression model between dry shoot and cumulative water used in transpiration. A regression model was also developed between TE_{shoot} and crop growing period mean VPD.

STUDY 4: Transpiration Efficiency of Old and Modern Wheat Cultivars During Vegetative Growth

3.4.1 Design of Experiment

A study was conducted in the greenhouse of West Texas A&M University, Canyon, Texas in Winter 2014. Six wheat cultivars released in 1964 (Triumph 64), 1966 (Scout 66), 1971 (TAM W 101), 1979 (TAM 105), 2003 (TAM 111), and 2005 (TAM 112) were tested against two water levels (high and low). The experimental design was a randomized complete block design (RCBD) with four replications. The greenhouse temperatures for the crop growing period were maintained between 20°C and 32°C (68°F and 90°F). Relative humidity for the same period ranged from 28 to 100%.

Wheat was grown in 48 plastic boxes having a volume of 41.8 L (44×38×25 cm) and filled with 28.5 kg of Calcined clay. Boxes were covered with plastic lids with holes (area = 7.9 cm^2) for growing plants. Evaporation from the holes was minimized using a plastic tape, leaving a small hole sufficient for the emerging seedlings. The tape was adjusted as the plants grew.

All the boxes were brought to 42% volumetric water content by adding 17.6 L of filtered water and weighed using a common balance. Before adding water, 40 g of "Miracle-Gro water soluble all-purpose plant food" was mixed uniformly in each box. This fertilizer provided N-P-K of 12.2-1.8-6.6 g box^{-1}, respectively, and some amounts of boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn). Wheat seeds (six cultivars) were planted on Jan. 26, 2014. Forty plants, divided into four bunches, were grown in each box.

Volumetric water contents of 35-42% and 28-35% were maintained for high and low water treatments, respectively, throughout the crop growing period. Water use from each box was monitored by weighing all the boxes every 4-5 days using a common balance. For all high water treatments or low water treatments, water was added on the same day; however, with each watering, each box received different amounts based on the amount of water used by plants. Wheat plants were harvested on Mar. 28, 2014 (62 DAP) at the vegetative growth stage. Plant samples were dried in the oven at 70°C (158°F) until the constant weight was recorded.

3.4.2 Measurements

Leaf Chlorophyll Content

The leaf chlorophyll content (LCC) was measured using a handheld chlorophyll meter (Minolta SPAD-502) at 40 DAP (Figure 8A). This equipment measures the chlorophyll content via light transmittance (absorbance of red light at 650 nm and infrared light at 940 nm) and compensates for differing leaf thicknesses. Measurements were taken during the morning hours from three fully developed upper leaves of plants in each box. During sampling, accuracy of the reading was checked by taking multiple readings from the same leaf. The instrument was calibrated regularly to ensure the accuracy of the reading.

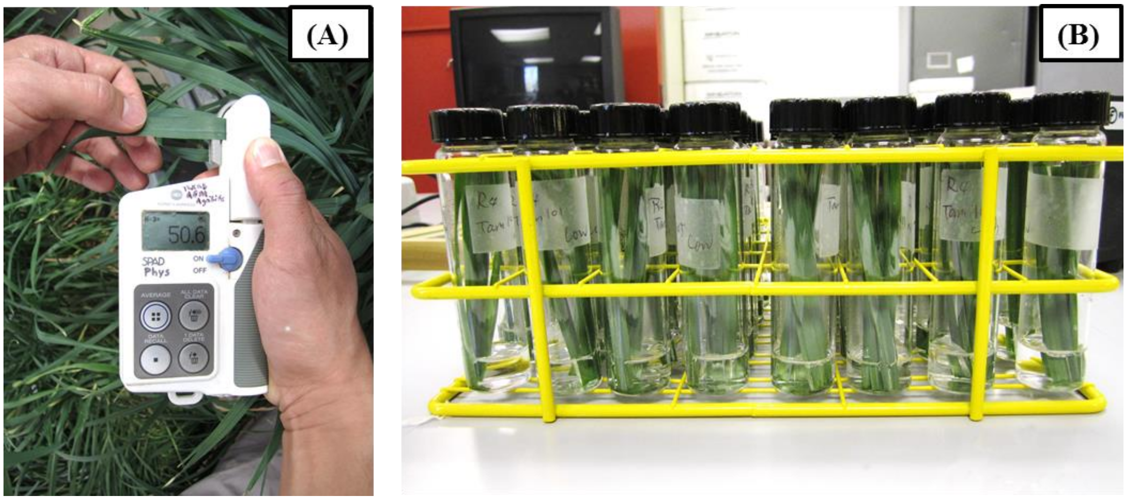

Figure 8. Leaf chlorophyll measurement using chlorophyll meter (Minolta SPAD-502) (A) and leaf samples kept in tubes with water to achieve leaf turgidity during leaf relative water content measurement (B).

Leaf Relative Water Content

Leaf relative water content (LRWC) provides a measurement of the “water deficit” of the leaf, and may indicate a degree of stress expressed under drought and heat stress (Pask et al., 2012). LRWC in plants decreases as water stress increases. So, under non-stress conditions, LRWC of the plant would be near 100% with water potential values approaching zero. LWRC was measured at 25 and 35 DAPs (Figure 8B). Six fully expanded upper leaves from randomly chosen plants were selected from each box. Top and bottom of the leaves were cut together to leave a 5 cm (2 in) midsection. They were immediately placed into the pre-weighed glass tubes (tubeW), reweighed (tubeW+freshW), and sealed with lids. One centimeter of distilled water was added to each tube and kept in a refrigerator at 4°C (39°F) for 24 h (overnight) to achieve turgidity of the leaves. After 24 h, leaf samples were taken out of the tube, and quickly and carefully made dry using a paper towel. All the samples were weighed (TW; turgid weight). Leaf samples were then placed in a labeled envelope and dried at 70°C (158°F) for 24 h. After 24 h, samples were re-weighed (DW; dry weigh), and LRWC was calculated as:

Fresh weight = tubeW+FW – tubeW …………………………………… (12)

LRWC (%) = ((FW-DW) / (TW-DW)) × 100 ………………………….. (13)

where FW is fresh weight, TW is turgid weight, and DW is dry weight.

Cumulative Water Use

Before harvesting, all the boxes were weighed on a common balance in order to calculate the cumulative water use as:

$V = (w_i + v_t) - w_f$ …………………………………………………….…… (14)

where V is the cumulative volume (L) of water used in transpiration, w_i is the initial weight of a box at seeding (kg), v_t is the total volume of water added during the crop growing period (L), and w_f is the final weight of a box before crop harvest (kg). Since water has density of 1 g cm^{-3} (or, 1 g ml^{-1}), weight of water is equivalent to its volume.

Transpiration Efficiency

Since the study had an objective of comparing TE among the wheat cultivars, the experimental boxes were covered with plastic lids from seeding through harvesting to make sure that all water lost from the boxes is to be transpiration. However, the linear regression line did not pass through the origin indicating that boxes lost some water in the form of evaporation. Hence, the measured water loss could not be fully attributed to transpiration, and aboveground biomass produced per unit of water used is reported as biomass water use efficiency (WUEb).

3.4.3 Statistical Analysis

Data were analyzed via two-way analysis of variance (ANOVA) using PROC MIXED in SAS 9.3 (SAS Institute, Inc., 2009). Cultivars and water levels were considered as fixed and replications as random factors. Differences were considered significant and mean separation was done at $P < 0.05$. The PROC REG was used to develop a regression model between aboveground biomass and water transpired by plants in each box.

CHAPTER IV

RESULTS AND DISCUSSION

STUDY 1: Improving Microclimate Through Manipulating Plant Geometry in Grain Sorghum

4.1.1 2013 and 2014 Studies

Leaf area, aboveground biomass, and grain yield were significantly ($P < 0.05$) higher in 2014 than in 2013 (Tables 2 and 3). The difference increased from high water to low water, and lid to straw mulch to bare surface treatments (Table 4). It was mainly because watering was done adopting different methods in 2013 and 2014. Compared to 2014, total water added in 2013 was lower by 14.6 L (23.9%) at high water and 21.8 L (48.4%) for low water treatments. Small amounts of water added each time likely increased the evaporative loss in 2013 from straw mulch and bare surface treatments, hence, WUEs were significantly ($P < 0.05$) lower than in 2014. However, HI remained similar for both years (Tables 2 and 3).

Table 2. P-values of sorghum leaf area, tiller number, aboveground biomass (AGB), grain yield, harvest index (HI), biomass water use efficiency (WUEb), and grain water use efficiency (WUEg) as affected by year, geometry, water, and soil surface as determined by analysis of variance (ANOVA).

Effect	Leaf area	Tillers	AGB	Grain yield	HI	WUEb	WUEg
Year (Y)	<0.0001	-§	<0.0001	<0.0001	0.1602	<0.0001	<.0001
Geometry (G)	<0.0001	<0.0001	0.0045	0.2435	0.001	0.0273	0.4073
Water (W)	0.0011	0.6807	<0.0001	<0.0001	0.0016	0.0003	<0.0001
Surface (S)	<0.0001	0.0021	<0.0001	<0.0001	0.7844	<0.0001	<0.0001
Y×G	<.0001	-	0.1029	0.4912	0.2235	0.4108	0.7790
Y×W	0.0011	-	0.0013	0.0034	0.0505	0.0362	0.6005
Y×S	<.0001	-	0.3332	0.1824	0.0439	<.0001	0.7958
G×W	0.4571	0.5948	0.4096	0.9710	0.6828	0.7752	0.8363
G×S	0.3107	0.2099	0.9924	0.3877	0.8688	0.9670	0.7958
W×S	0.5305	0.4412	0.0134	0.0013	0.8997	0.0023	0.0153
Y×G×W	0.4571	-	0.9831	0.7854	0.9042	0.9191	0.9789
Y×G×S	0.3107	-	0.8562	0.7128	0.9638	0.7556	0.9465
Y×W×S	0.5305	-	0.0277	0.0005	0.1510	0.0023	<.0001
G×W×S	0.3370	0.6068	0.9968	0.6115	0.5431	0.9752	0.8007
Y×G×W×S	0.3370	-	0.6996	0.9467	0.5998	0.7910	0.8667

§Tiller data was not obtained for 2013.

Table 3. Mean leaf area, tiller number, aboveground biomass (AGB), grain yield, harvest index (HI), biomass water use efficiency (WUEb), and grain water use efficiency (WUEg) of sorghum grown in 2013 and 2014 at two planting geometries, two water levels, and three soil surface types.

Effect	Leaf area (cm^2)	Tillers ($plant^{-1}$)	AGB‡ ($g\ box^{-1}$)	Grain yield‡ ($g\ box^{-1}$)	Harvest index¶	WUEb ($kg\ m^{-3}$)	WUEg ($kg\ m^{-3}$)
Year							
2013	778.9 b†	-	160.8 b	72.4 b	0.44 a	3.34 b	1.48 b
2014	1430.8 a	-	273.4 a	125.1 a	0.46 a	3.99 a	1.83 a
Geometry							
Clump	988.0 b	0.4 b	210.4 b	100.3 a	0.48 a	3.57 b	1.67 a
ESP	1221.8 a	1.2 a	223.8 a	97.2 a	0.43 b	3.77 a	1.64 a
Water							
High	1248.4 a	0.9 a	261.8 a	122.4 a	0.47 a	3.87 a	1.89 a
Low	961.4 b	0.8 a	172.5 b	75.1 b	0.44 b	3.47 b	1.42 b
Surface							
Lid	1532.3 a	1.0 a	301.6 a	136.5 a	0.45 a	5.33 a	2.36 a
Straw	1127.4 b	1.1 a	218.0 b	98.1 b	0.45 a	3.60 b	1.64 b
Bare	654.9 c	0.4 b	131.8 c	61.7 c	0.46 a	2.08 c	0.97 c

†Within each effect and each column, means with different letters were significantly different at $P < 0.05$.

‡Aboveground biomass and grain yield are expressed as oven-dried.

¶Harvest index is based on dry weight of grain divided by dry weight of aboveground biomass.

4.1.2 Vapor Pressure Deficit

For both years, plants grown in clump geometry consistently has lower VPD within the canopy as compared to those in ESP geometry, though the VPD values and differences varied with time of day (Figures 9 and 10). VPDs for clumps and ESPs did not differ during the night hours, but as the day progressed, different VPDs were observed. In most cases, the maximum VPD was found about 11:00 h CST, though it was not the hottest part of the day. This was because as the temperature rose, the greenhouse shade closed and cooling fan started to circulate cool and moist air which decreased temperature and increased humidity. This process occurred continuously throughout the day, resulting in the fluctuation of temperature and humidity, hence the VPD. For 2013, VPD for different treatments is reported at different growth stages (i.e. booting, flowering, and grain formation), and for 2014, it is presented only for booting stage.

In 2013, with bare surface, at low water, clump showed the mean VPD of 2.19 (±0.05 se) kPa and ESP showed 2.33 (±0.06 se) kPa, and at high water, clump had the mean VPD of 2.14 (±0.5 se) kPa which was lower than 2.36 (±0.05 se) kPa in ESP (50-52 DAP; Figures 9A, 9B). With straw mulch surface, at low water, clump and ESP had mean VPDs of 1.95 (±0.05 se) kPa and 2.05 (±0.06 se) kPa, respectively, and with high water, clump had the mean VPD of 1.94 (±0.04 se) kPa and ESP had 2.16 (±0.06 se) kPa (61-63 DAP; Figures 9C, 9D). With lid surface, at low water, clump had mean VPD of 1.72 (±0.04 se) kPa and ESP had 1.83 (±0.05 se) kPa, and at high water, clump had the mean VPD of 1.77 (±0.04 se) kPa and ESP had 1.90 (±0.05 se) kPa (65-67 DAP; Figures 9E, 9F).At 49-53 DAP in 2014, with bare surface, at low water, clump and ESP had the mean VPD of 1.72 (±0.04 se) kPa and 1.85 (±0.05 se) kPa, respectively, and at high water, clump had the mean VPD of 1.71 (±0.04 se) kPa and ESP had 1.94 (±0.05 se) kPa (Figures 10A, 10B). With straw mulch surface, at low water, clump showed the mean VPD of 1.74 (±0.04 se) kPa and ESP showed 1.87 (±0.05 se) kPa, and at high water, clump had the mean VPD of 1.72 (±0.04 se) kPa, which was lower than 1.87 (±0.05 se) kPa in ESP (Figures 10C, 10D). With lid surface, at low water, clump had the mean VPD of 1.56 (±0.04 se) kPa and ESP had 1.78 (±0.05 se) kPa, and at high water, clump had the mean VPD of 1.73 (±0.04 se) kPa and ESP had 1.94 (±0.05 se) kPa (Figures 10E, 10F).

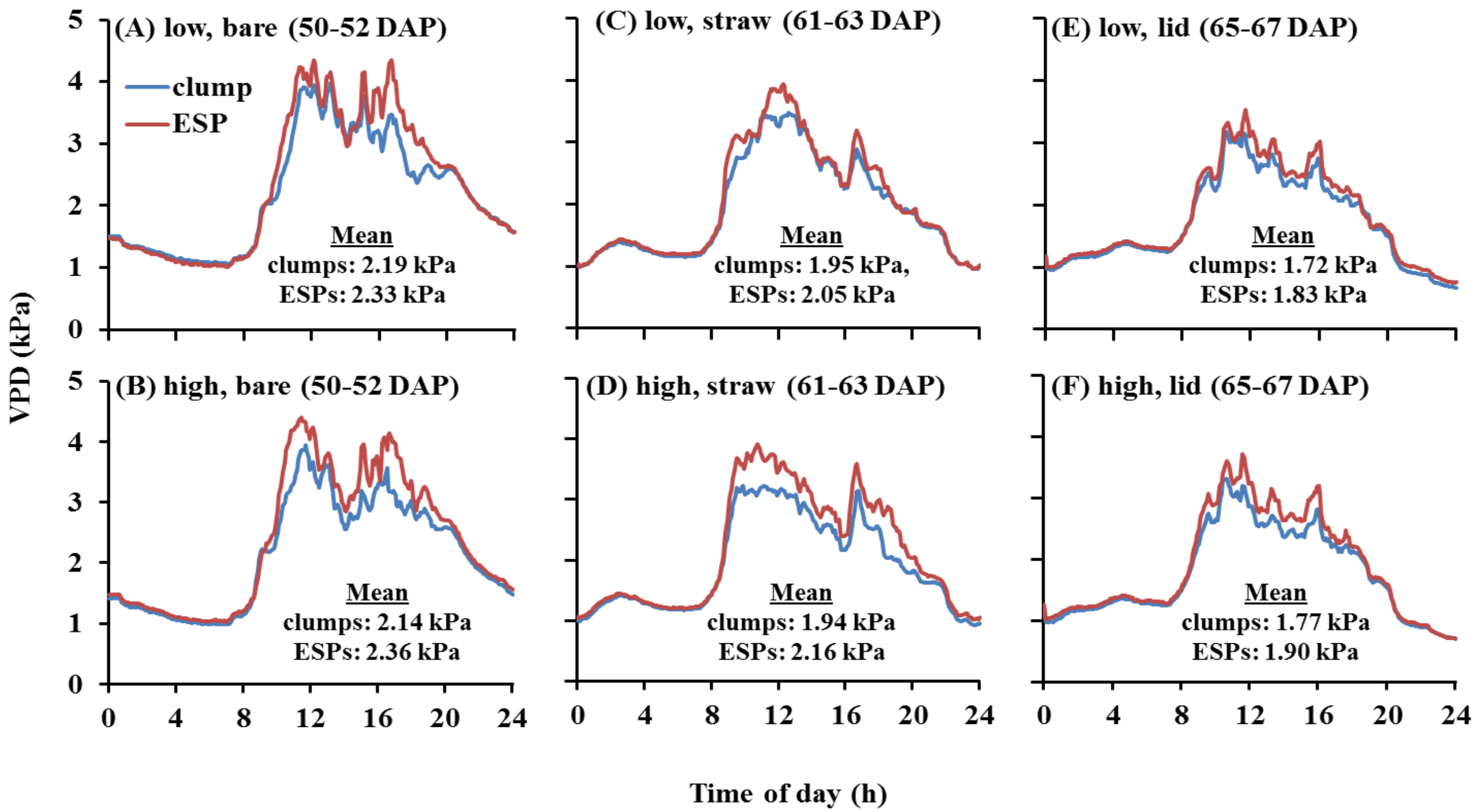

Figure 9. Average 3-day vapor pressure deficit (VPD) within the plant canopy recorded every five minutes for different treatments in 2013 at 50-52, 61-63, and 65-67 DAP corresponding to booting, flowering, and grain formation growth stages, respectively. Measurements taken during the same DAPs and within each year can be compared. DAP = days after planting, ESPs = evenly spaced plantings.

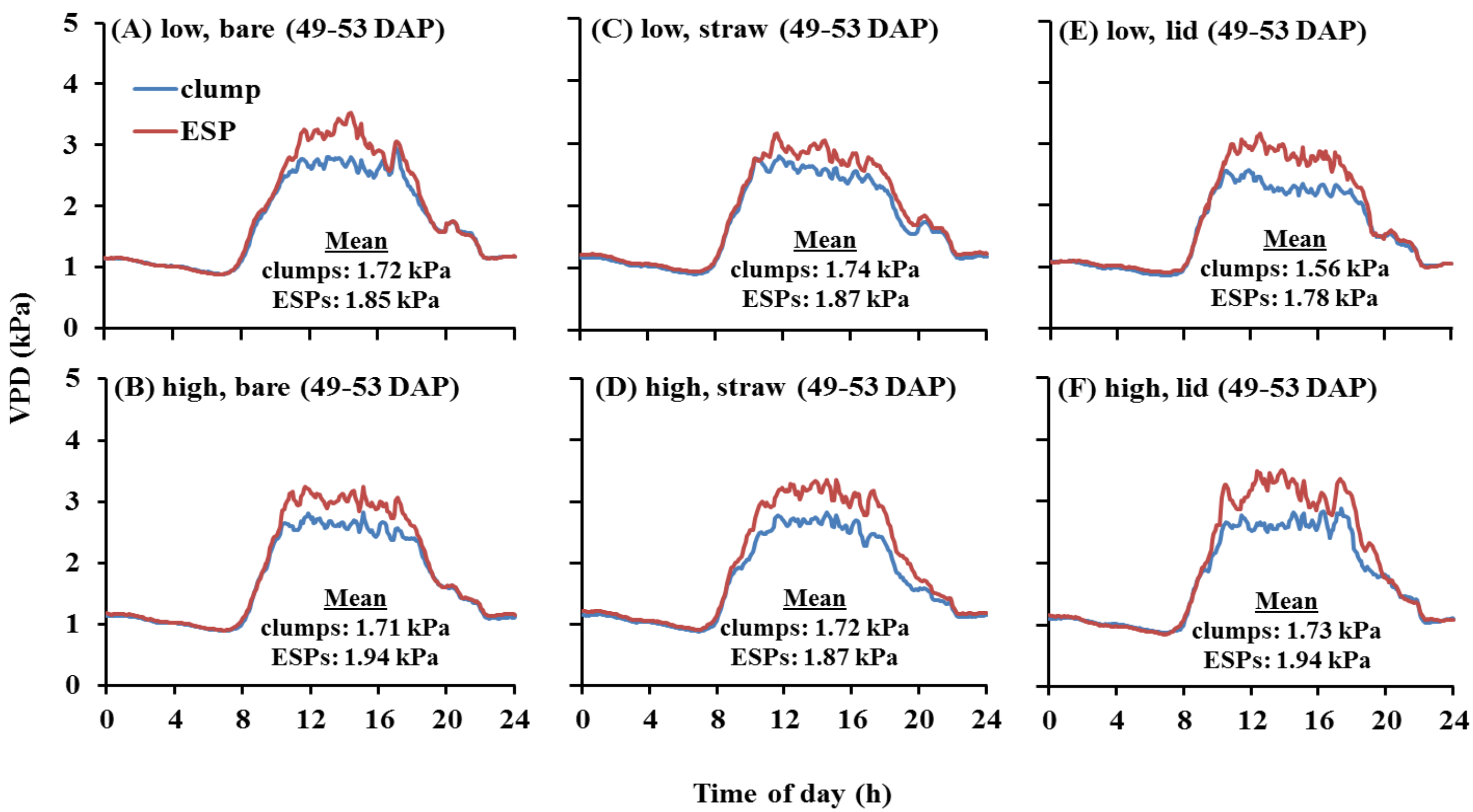

Figure 10. Average 5-day vapor pressure deficit (VPD) within the plant canopy recorded every five minutes for different treatments in 2014 at 45-53 DAP corresponding to booting growth stage. DAP = days after planting, ESPs = evenly spaced plantings.

Canopy temperature (CT) is one of the many physiological attributes that is related to both plant water status and metabolic processes such as photosynthesis, respiration and transpiration (Pradhan et al., 2014). Increase in canopy or leaf temperatures during the day is a function of increasing water stress (Stevenson and Shaw, 1971; Jackson et al. 1977; Mahan et al., 2012). At water stressed environments, the stomata close and increase the leaf temperatures (Aston and Van Bavel, 1972; Jackson et al., 1977). Since closing stomata disrupts photosynthesis, under water-limiting conditions, plants having less leaf area with opened stomata are better than plants having more leaf area with closed stomata on some or all of the leaves (Glenn et al., 2008; Rajan et al., 2010). In this study, clumps helped to reduce the leaf area per plant significantly ($P < 0.05$) (1221.8 vs. 988.0 cm^2 for ESPs) and kept the stomata opened, which reduced the temperature and increased the humidity within the plant canopy. Visual water stress symptoms were more apparent for the plants in ESPs compared to the plants in clumps because increased leaf area also increased transpiration and decreased soil water faster, which was also reported by Rajan et al. (2010). Further, plants in ESPs might lose more water through transpiration, which triggered stomata to be closed and increased VPD within the crop canopy. Lin (2007) suggested that shade improves the microclimate by keeping plants cooler during the day and warmer at night. In the present study too, as hypothesized, plants in clump geometry benefited from mutual shading, which helped to reduce the VPD within crop canopy.

4.1.3 Tiller Number

Tiller data were not obtained for 2013 because few were formed, while in 2014, ESPs produced significantly ($P < 0.05$) more tillers (1.2 tillers $plant^{-1}$) compared to the clumps (0.4 tillers plant^{-1}) (Tables 2 and 3). Out of the productive tillers (which produced harvestable grains), per tiller grain yield was greater for clumps (3.2 g tiller^{-1}) than those for ESPs (2.1 g tiller^{-1}). The mean tiller number was not different (P > 0.05) between high (0.9 tillers plant^{-1}) and low (0.8 tillers plant^{-1}) water treatments because both were started with 42% volumetric water content and most of the tillering occurred at the early vegetative growth stage when soil-water was not a limiting factor. Since low water treatment was provided with 26% less water than high water treatment, the percentage of tillers that produced harvestable grains was significantly higher at high water, 66.7% of total tillers compared to 28.7% at low water treatment. For surface types, plants with lid (1.0 tiller pant^{-1}) and straw (1.1 tillers plant^{-1}) surface had a similar number of tillers, while plants with bare surface had significantly (P < 0.05) fewer (0.4 tillers plant^{-1}) (Table 3).

Tillers are formed because of the activity of the axillary meristem in the axils of the leaves adjacent to the main stem (Gerik and Neely, 1987; Bennett and Leyser, 2006). Lafarage and Hammer (2002) observed that tiller emergence was driven by tiller site formation at the base of every leaf, and by the number of buds that develop into tillers. Where water and nitrogen are not limiting factors, tiller production is affected by plant carbon balance and in particular the availability of assimilates (Mitchell, 1953; Ong and Marshall, 1979). A low light interception, a short photoperiod, or high planting density reduces the assimilate supply (Gerik and Neely, 1987; Gautier et al., 1999). Less available growing space decreases tillering in a dense canopy (Liddle et al., 1982; Casal et al., 1986). This was likely to be a reason for having lesser number of tillers in clumps compared to ESPS in the present study. Tiller emergence is also related to assimilate supply and light quality (Lafarage et al., 2002). For instance, the production of tillers or branches reduced as the red light to far-red light ratio (R:FR) is decreased (Casal et al., 1985; Davis and Simmons, 1994; Gautier et al., 1999; Krishnareddy et al., 2009; Finlayson et al., 2010). Because three plants were grown together in each clump, they might allow lower R: FR light ratio reaching at the base of the plants resulting less tiller formation.

4.1.4 Aboveground Biomass

Aboveground biomass was significantly ($P < 0.05$) affected by all main effects and year × water, water × surface, and year × water × surface interaction (Table 2). The mean aboveground biomass amounts for clumps and ESPs were 210.4 g box^{-1} and 223.8 g box^{-1}, respectively, indicating that ESPs produced 13.4 g box^{-1} (6.4%) more biomass compared to clumps. The soil surface showed different biomass production in response to water levels and years. In both years and water levels, plants growing with lid surface had significantly higher biomass than plants with straw mulch and bare surface. A significant difference was also found between straw mulch and bare surface treatments. Compared to straw mulch, plants with bare surface had significantly lower biomass by 112 g box^{-1} (50%) and 53.4 g box^{-1} (58.3%) in 2013, and 90.4 g box^{-1} (29%) and 89.1 g box^{-1} (36.8%) in 2014 at high and low water, respectively (Table 4).

Table 4. Mean aboveground biomass (AGB), grain yield, biomass water use efficiency (WUEb), and grain water use efficiency (WUEg) of sorghum grown in 2013 and 2014 at two water levels and three surface types.

Year	Water level	Soil surface	AGB¶ (g box^{-1})	Grain yield¶ (g box^{-1})	WUEb (kg m^{-3})	WUEg (kg m^{-3})
2013	High	Lid	303.4 a†	135.8 a	5.26 a	2.35 a
		Straw	224.1 b	112.0 b	3.76 b	1.88 b
		Bare	112.1 c	52.5 c	1.90 c	0.89 c
		Mean	**213.2 B‡**	**100.1 B**	**3.64 AB**	**1.71 AB**
	Low	Lid	195.7 a	80.8 a	5.55 a	2.30 a
		Straw	91.5 b	38.3 b	2.56 b	1.07 b
		Bare	38.1 c	15.2 c	1.05 c	0.42 c
		Mean	**108.4 C**	**44.8 C**	**3.05 B**	**1.26 B**
2014	High	Lid	398.2 a	194.9 a	5.35 a	3.06 a
		Straw	311.7 b	134.9 b	4.09 b	1.82 b
		Bare	221.3 c	104.5 c	2.86c	1.37 c
		Mean	**310.4 A**	**144.8 A**	**4.10 A**	**2.08 A**
	Low	Lid	309.0 a	134.6 a	5.17 a	1.74 a
		Straw	244.7 b	107.1 b	3.98 b	1.79 a
		Bare	155.6 c	74.5 c	2.50 c	1.21 b
		Mean	**236.4 B**	**105.4 B**	**3.88 AB**	**1.58 B**

†Within each water level in each column for each year, means with the different lowercase letter were significantly different at $P < 0.05$.

‡In each column, means with the different uppercase letters were significantly different at $P < 0.05$.

¶Aboveground biomass and grain yield are expressed as oven-dried.

Bandaru et al. (2006) grew grain sorghum in Bushland, Texas and reported that aboveground biomass at harvest was significantly lower for the clumps compared to

ESPs which was verified by this study. In the same location, however, Kapanigowda et al. (2010b) found a significantly higher aboveground biomass in clumps compared with ESPs at harvest in maize. Since aboveground biomass is the major function of water transpired by plants, plants growing at high water were able to transpire more water and produced higher amounts of biomass than plants at low water. Evaporation was restricted in lid covered boxes and all the water lost was assumed to be transpiration. Thus, lid treatment plants produced higher amounts of biomass than other treatments. Straw mulch significantly increased the aboveground biomass due to improved WUE compared to bare surface (Table 3). Lal (1976) and Jordan et al. (2010) suggest that straw mulch increases crop yield by improving soil physical and chemical properties.

4.1.5 Grain Yield

The grain yield was significantly ($P < 0.05$) affected by the year × water × surface, year × water, and water × surface interaction and all main effects except geometry ($P > 0.05$; Table 2). For both years and water treatments, plants growing with lid surface produced higher grain yields followed by plants with straw mulch and bare surface. A significant difference was also found between straw mulch and bare surface treatments. Compared to straw mulch, the mean grain yield for plants with bare surface was lower by 59.5 g box^{-1} (53.1%) and 23.1 g box^{-1} (60.3%) in 2013, and 30.4 g box^{-1} (22.5%) and 32.6 g box^{-1} (30.4%) in 2014 at high and low water treatment, respectively (Table 4). Although there was no significant difference between clumps and ESPs, the mean values of grain yields in most of the treatments were consistently higher in clumps compared to ESPs both in 2013 and 2014 (Figure 11).

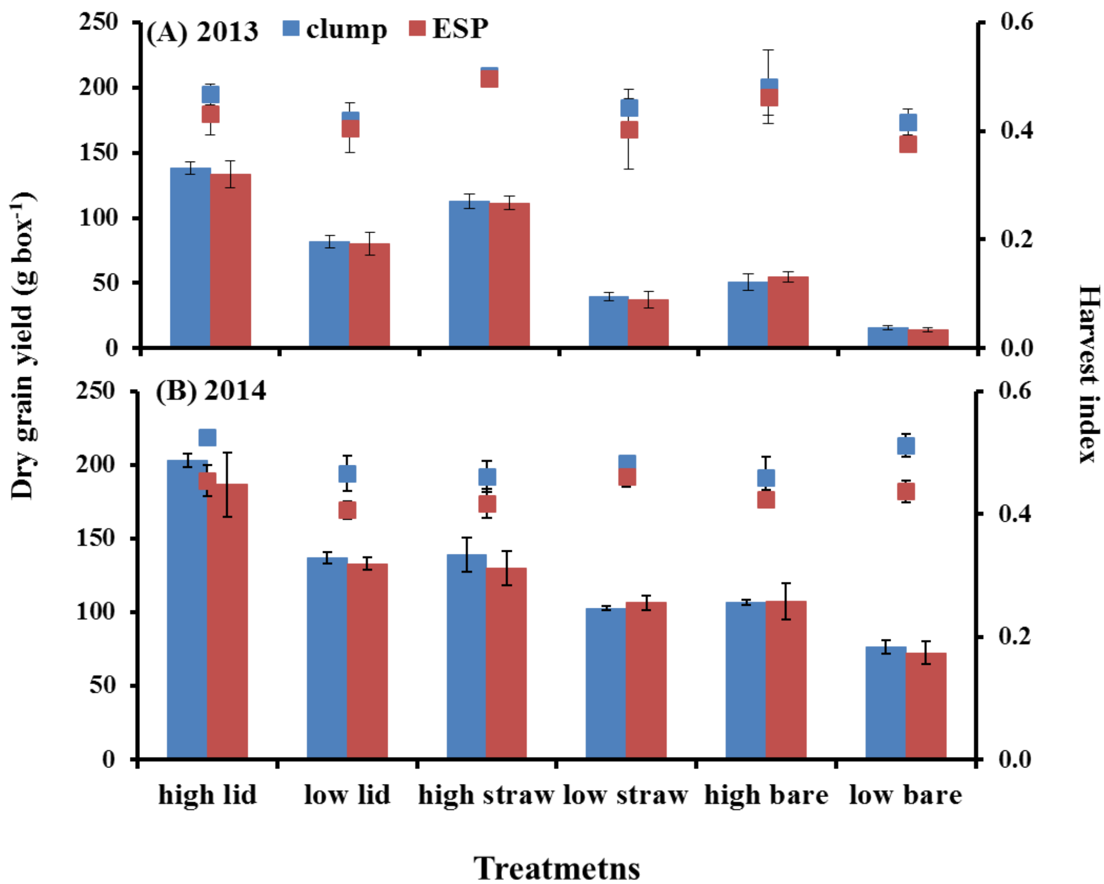

Figure 11. Dry grain yield (left axis with bars) and harvest index (right axis with squares) of sorghum in 2013 (A) and 2014 (B) for each treatment. ESP = evenly spaced planting.

Unger (1978) produced 3.99 Mg ha^{-1} (1.78 ton ac^{-1}) of sorghum grain yield with 12.0 Mg ha^{-1} (5.4 ton ac^{-1}) mulch treatment compared with 1.78 Mg ha^{-1} (0.79 ton ac^{-1}) for bare surface treatment. Mulch increased biomass as well as grain yields only when it effectively suppressed evaporation of soil moisture and made most of the soil water available for transpiration (Tolk, 1999). Increased grain yield in clumps compared to ESPs was reported by Bandaru et al. (2006) in sorghum and Kapanigowda et al. (2010b) in maize.

4.1.6 Harvest Index

The harvest index was significantly ($P < 0.05$) affected by the main effects of planting geometry and water (Table 2). Clumps had higher HI, 0.48 compared to ESPs, 0.43. Similarly, plants growing at high water had the HI of 0.47, which was higher than the HI of 0.44 for plants at low water treatment (Table 3). As a whole, in both years, clump performed better at low water than at high water treatment (Figure 11).

The maximum HI of 0.55 reflects the genetic potential of most current sorghum hybrids (Hammer and Muchow, 1994). When produced under little or no water stress, the HI for grain sorghum has a genetic potential of about 0.53 (Prihar and Stewart, 1990). Prihar and Stewart suggested that the HI for grain sorghum decreased sharply with increasing water stress. However, Garrity et al. (1983) found no change in sorghum HI for a range of water deficits. In this study, HI decreased from 0.47 at high to 0.44 at low water treatment, but remained similar among the surface types. Though plants growing with bare surface produced significantly fewer grains, because of their poor vegetative growth as well as less number of tillers, the HI was competitive with other treatments. Kapanigowda et al. (2010a, 2010b) and Mohammed et al. (2012) reported increased HI in clumps compared to ESPs when crops were grown under dryland conditions.

4.1.7 Transpiration Efficiency

Neither TEb nor TEg was significantly ($P > 0.05$) affected by the main effects (year, geometry, and water) or their interaction effect; hence, a common regression line is used to represent both clumps and ESPs for each of TEb and TEg. On average, plants produced 5.33 kg and 2.38 kg of dry biomass and grain yield, respectively for each cubic meter of water transpired (Figure 12).

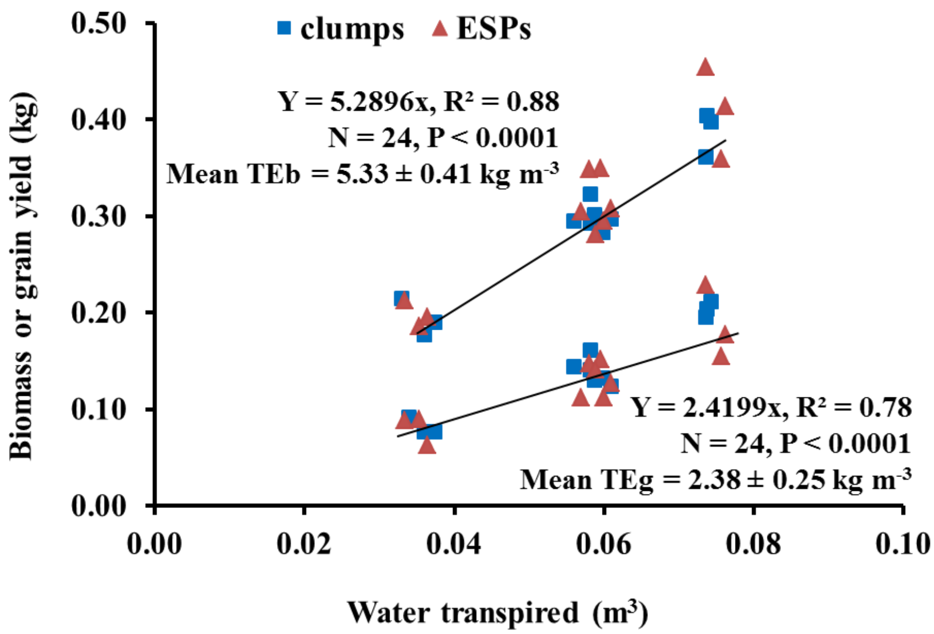

Figure 12. Linear regression between water transpired, and aboveground biomass (upper line) or grain yield (lower line) for plants grown with lid covered surface treatments in 2013 and 2014. TEb = biomass transpiration efficiency, TEg = grain transpiration efficiency, ESP = evenly spaced planting.

Previous studies have shown a linear relationship between crop dry biomass and total water transpired by crops during the growing season (Tanner and Sinclair, 1983; Ben-Gal and Shani, 2002; Haefele et al., 2009; Mantovani et al., 2014). In this study too, as shown in Figure 12, aboveground biomass ($R^2 = 0.88$, $P < 0.0001$) and grain yield ($R^2 = 0.78$, $P < 0.0001$) increased linearly with cumulative water transpired. Xin et al. (2009) studied 25 sorghum lines and reported the mean TEb of 5.72 kg m^{-3}, and mentioned that TEb was greatly influenced by VPD. Similar to this, sorghum in the present study produced 1 g of biomass for each 188 g of water transpired (i.e. 5.33 kg m^{-3}) in the mean VPD ranging from 1.56 to 2.36 kPa, which was also close to the findings of Sinclair and Weiss (2010). They reported that C_4 crops grown in an “average” transpiration environment of 2 kPa VPD will produce 1 g of biomass for every 220 g of water transpired, but for an arid region with a transpiration environment of 2.5 kPa VPD, crops use about 280 g for each g biomass and 160 g when growing in a humid transpiration environment of 1.5 kPa VPD. Because of the expected lesser VPDs within clumps, it was hypothesized that the TEb for clumps would be higher than for ESPs, but the TEb values for clumps and ESPs were similar. It might be because the transpiration was measured only from the lid surface treatments, where plants were not water stressed. Despite the similar TEb, ESPs produced more biomass indicating that they transpired more water than clumps, mainly due to the higher tiller number (leaf area) per plant.

4.1.8 Water Use Efficiency

WUEb and WUEg were significantly ($P < 0.05$) affected by year × surface, water × surface, and year × water × surface interaction and all the main effects except geometry ($P > 0.05$) for WUEg (Table 2). WUEb was significantly higher for ESPs (3.77 kg m^{-3}) than for clumps (3.57 kg m^{-3}), but WUEg was relatively higher for clumps (1.67 kg m^{-3}) than for ESPs (1.64 kg m^{-3}), and it was reflected as higher HI for clumps than for ESPs. High water treatment significantly ($P < 0.05$) increased both WUEb and WUEg compared to low water treatment (Table 2). Lid surface treatment had the mean WUEb of 5.33 kg m^{-3} and WUEg of 2.36 kg m^{-3}. For straw mulch and bare surface treatments, the mean WUEb values were 3.60 kg m^{-3} and 2.08 kg m^{-3} and WUEg values were 1.64 kg m^{-3} and 0.97 kg m^{-3}, respectively (Table 3), suggesting a 42.2% reduction in WUEb and a 40.7% reduction in WUEg when soil surface was changed from straw mulch to bare.

In both years and both water levels, compared to bare surface, straw mulch significantly increased WUEb and WUEg by reducing evaporative loss, which was also suggested by Pabin et al. (2003), Khurshid et al. (2006), and Shaheen et al. (2010). Zhang et al. (1998) found 44% and 29% improvement in WUEb and WUEg while using straw mulch in winter wheat under rainfed conditions. These values are comparable with 42.2% and 40.7% reduction in WUEb and WUEg, respectively while changing soil surface from straw mulch to bare in the present study. Mulching is an efficient way to reduce evaporation and improve WUE because mulches help to modify the microclimate and crop growing conditions (Albright et al., 1989; Pabin et al., 2003; Hartkamp et al., 2004; Huang et al., 2005).

4.1.9 Conclusions

The results of this study suggest that plants providing shade for each other is the primary mechanism for improving microclimate when crops are grown in hot and water deficit environments. As hypothesized, sorghum plants in clumps created mutual shading and exposed less leaf area per plant to the greenhouse environment. Consequently, they consistently showed lower VPD than ESPs in both years under different water levels and soil surface types. This suggested that clumps improved microclimate within crop canopy. Since the number of tillers and vegetative growth were significantly reduced in clumps compared to ESPs, clumps were able to partition more of the biomass to grain increasing the HI. Compared to high water, low water treatment significantly reduced the sorghum leaf area, aboveground biomass, grain yield, HI, and WUE. This indicates that water stress (drought) is the most important factor affecting crop yields. Similarly, compared to the bare soil surface, mulched treatment produced significantly higher grain yields with higher WUE. Hence, mulching conserved the soil water and made it available to the plants. Compared to conventional ESP geometry, clumps improved microclimate, reduced vegetative mass, produced relatively higher grain yields, and significantly increased the HI. These are some of the important attributes to be considered while plants are grown under semi-arid environments. The importance of microclimate in determining crop performance is well established (Ong et al., 2007), and current results suggest that growing plants in clumps is a way to improve microclimate. Hence, clump geometry appears to be a potential alternative for large-scale implementation, which requires no additional input cost.

STUDY 2: Growing Corn in Clumps: A Strategy to Improve Microclimate, Water Use Efficiency, Grain Yield, and Harvest Index

4.2.1 Weather Conditions

The rainfall conditions of Gruver and Bushland during the crop growth period (June to Oct.) in 2014 and 2015 are presented in Table 1 (page 42). Measured in the study field, Gruver site received cumulative precipitation of 280 mm (11 in) for the crop period. According to the U.S. Climate Data (http://www.usclimatedata.com), for the same period, the weekly average maximum air temperature ranged from 23.6-37.3°C (74.4-99.2°F). The Bushland site received a total precipitation of 220 mm (9 in) during the crop period. The weekly average maximum air temperature for the same period ranged from 31.2-39.1°C (88.1-102.4°F) (USDA-ARS Conservation and Production Research Laboratory, Bushland, Texas).

4.2.2 Canopy Temperature

For GFS, plant CT was significantly ($p < 0.05$) influenced by the main effect of geometry and irrigation (Table 5). Measured at 75 and 88 DAPs, ESPs showed 0.7ºC (1.3ºF) and 0.8ºC (1.4ºF) warmer temperature than those for ESPs, respectively. At 75 DAP, plants growing with LIT (40.4ºC [104.7ºF] average CT) were 8.2ºC (14.8ºF) warmer than plants with MIT and 8.0ºC (14.4ºF) than HIT. At 88 DAP, plants with LIT (34.3ºC [93.7ºF] average CT) were 4.9ºC (8.8ºF) warmer than MIT and 5.6ºC (10.1ºF) than HIT. Plants of MIT and HIT treatments had similar temperatures at 75 DAP, but they were significantly ($P < 0.05$) different at 88 DAP with 0.7ºC (1.3ºF) higher temperature for MIT (Table 6). For BFS, the effect of planting geometry on CT was significant at $P = 0.0636$ at 75 DAP and at $p = 0.1086$ at 83 DAP. On average, plants in

ESPs were 1.1ºC (2.0ºF) and 0.7ºC (1.3ºF) warmer than clumped plants at 75 and 83 DAP, respectively (Table 6). Different CTs and their effects in plants are illustrated in Figure 6. The mean temperature for the clumps was 36.7ºC (98.1ºF), while it was 38.6ºC (101.5ºC) for ESPs. As a result, visual water stress symptoms were more apparent for the plants in ESPs compared to the plants in clumps, which was clearly detected by the thermal camera as well (Figure 13).

Table 5. P-values of corn canopy temperature, tiller number, leaf area index (LAI), aboveground biomass (AGB), grain yield (GY), harvest index (HI), and water use efficiency (WUE) as affected by planting geometry and irrigation regime for Gruver field study (GFS), 2014 and t-test (P > T) for Bushland field study (BFS), 2015 as determined by analysis of variance (ANOVA).

	Canopy temperature								
Effect	75 DAP	83 DAP	88 DAP	Tillers	LAI	AGB	GY	HI	WUEg
GFS									
Geometry (G)	0.0095	-	<.0001	0.0030	0.0212	0.6538	0.0695	0.0465	0.2706
Irrigation (I)	<.0001	-	<.0001	0.0032	<.0001	<.0001	<.0001	<.0001	<.0001
G × I	0.4502	-	0.5963	0.0043	0.3467	0.1132	0.1301	0.0061	0.2582
BFS									
Geometry	0.0636	0.1086	-	0.1243	0.1468	0.2207	0.8577	0.0950	0.8490

Table 6. Means of canopy temperatures for the hottest part of day (14:00 – 15:00 h CST) as affected by irrigation and planting geometry in Gruver field study (GFS), 2014 and planting geometry in Bushland field study (BFS), 2015.

		Canopy temperature (ºC)	
Geometry	Irrigation	75 DAP	88 DAP
GFS			
Clump		34.6 b†	30.4 b
ESP		35.3 a	31.2 a
	HIT	32.4 b	28.7 c
	MIT	32.2 b	29.4 b
	LIT	40.4 a	34.3 a
BFS		75 DAP	83 DAP
Clump		37.6 a	40.7 a
ESP		38.7 a	41.4 a

Note: LIT = low irrigation treatment, MIT = medium irrigation treatment, HIT = high irrigation treatment, DAP = days after planting.

†For each study and column, means with different letters within geometry and irrigation represent significant differences at $P < 0.05$.

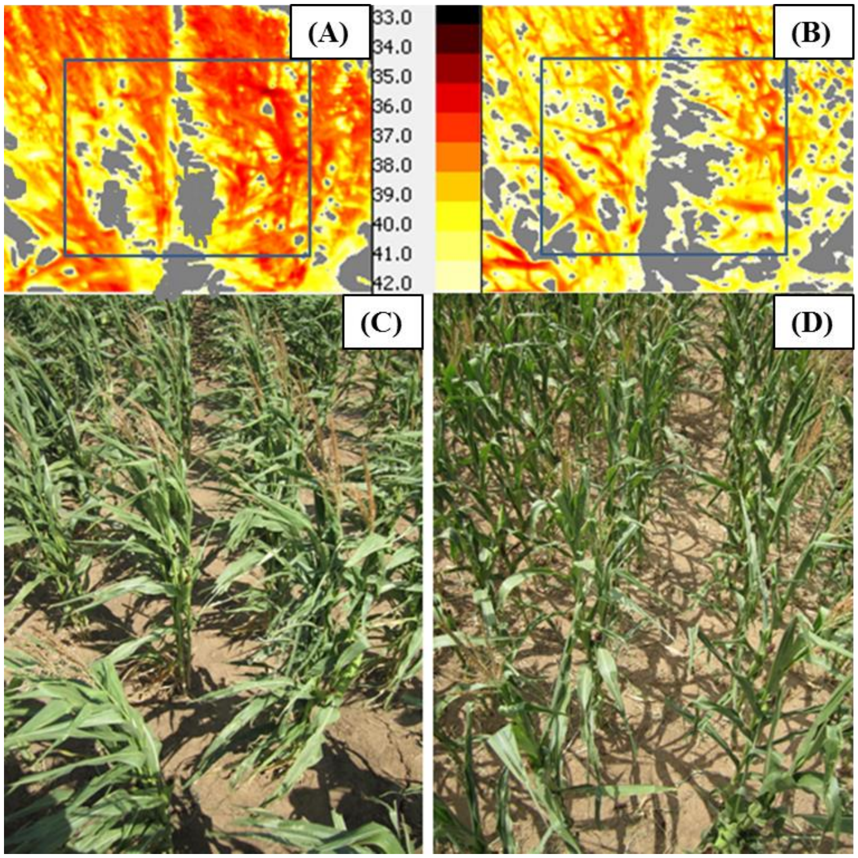

Figure 13. Example of images taken by a thermal camera (A and B) and by a digital camera (C and D) for clumps (A and C) and evenly spaced plantings (B and D), for the same plots at the same time (one after another) during the hottest part of day. The vertical color bar between two thermal images represents the canopy temperature, which changes from dark red to light yellow color as the temperature increases. The visual water stress symptoms were higher for ESPs (D) than for clumps (C).

The use of CT to detect water stress in plants was based on the assumption that transpired water when evaporates, cools the leaves. Under high solar radiation and drought condition, stomatal resistance increases because of an increase in air temperature and a decrease in soil moisture availability, which consequently increases CT (Roberts et al., 2000; Urban et al., 2007). Hence, an increase in canopy or leaf temperature during the day is a function of increasing water stress (Stevenson and Shaw, 1971; Jackson et al., 1977; Mahan et al., 2012). In this study, compared to the clumps, ESPs might have had more exposed leaf area per plant to the environment, which resulted in a higher amount of water loss through stomata opening, thereby depleting the soil moisture faster. Consequently, a lower amount of soil water might be available for plants in ESPs keeping their stomata closed during the hottest part of day. Sandhu and Horton (1978) reported leaf temperatures of oats under water-stressed environment being 2.5-4.0ºC (4.5-7.2ºF) warmer than well-watered plants. Bandaru et al. (2006) found leaf temperature of ESPs was about 2ºC (3.6ºF) and 4ºC (7.2ºF) warmer than clumped plants when measured at 42 and 60 DAP, respectively. Similarly, Kapanigowda et al. (2010a) reported leaf temperature of ESPs was about 2ºC (3.6ºF) warmer than that of clumps during the hottest part of the day.

4.2.3 Vapor Pressure Deficit

Clumps consistently showed lower VPD than ESPs at different growth stages. VPDs for clumps and ESPs did not differ during the night hours. However, as the day progressed, different VPDs were observed. The VPD in both studies was the lowest at 5:00-6:00 h CST and the highest at 14:00 – 15:00 h CST (Figures 14 and 15). For GFS, mean VPD for clumps with LIT was 1.50 (±0.08 se) kPa, while it was 1.59 (±0.09 se) kPa for ESPs. A similar trend was recorded for MIT and HIT. Clumps and ESPs with MIT showed a mean VPD of 1.13 (±0.05 se) and 1.22 (±0.06 se) kPa, respectively. With HIT, a mean VPD for clumps was 0.95 (±0.05 se) kPa, and 1.09 (±0.05 se) kPa for ESPs (60-64 DAP; Figure 14A). **S**imilarly, for 75-79 DAP, mean VPD for clumps with LIT was 1.93 (±0.07 se) kPa, while it was 2.08 (±0.08 se) kPa for ESPs. With MIT, clumps and ESPs had the mean VPD of 1.44 (±0.05 se) kPa and 1.56 (±0.05 se) kPa, respectively. Clumps with HIT had the mean VPD of 1.28 (±0.04 se) and ESP had 1.41 (±0.05 se) kPa (Figure 14B). For BFS, clumps showed the mean VPD of 1.43 (±0.06 se) kPa, which was lower than the mean VPD of 1.50 (±0.07 se) kPa for ESPs (70-74 DAP; Figure 15A). Similarly, for 80-84 DAP, ESPs had the greater VPD of 2.18 (±0.09 se) kPa than clumps, 2.10 (±0.08 se) kPa (Figure 15B).

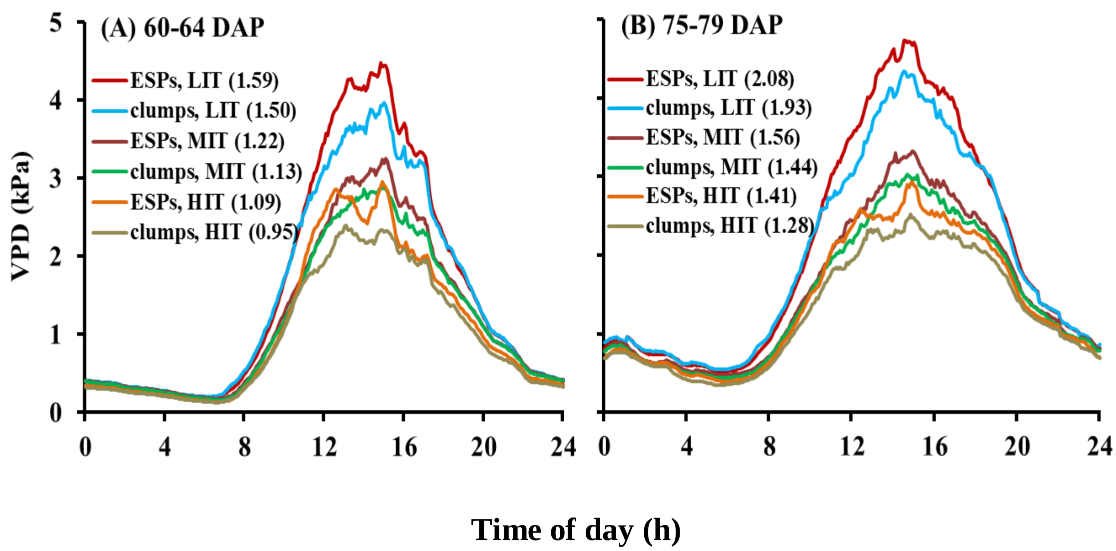

Figure 14. Five-day vapor pressure deficit (VPD) means within crop canopy recorded every five minutes for different treatments correspond to the reproductive and grain filling growth stages for Gruver field study (GFS), 2014. Number in the parenthesis indicates the mean VPD in kPa for each treatment. For both DAPs, VPDs increased from high irrigation treatment (HIT) to medium irrigation treatment (MIT) to low irrigation treatment (LIT). ESPs = evenly spaced plantings.

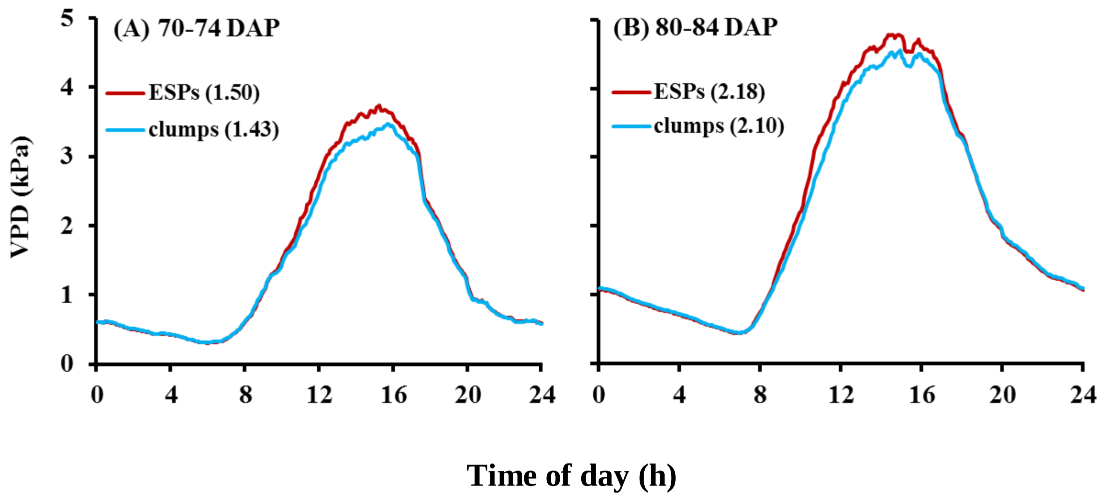

Figure 15. Five-day vapor pressure deficit (VPD) means within crop canopy recorded every five minutes for different treatments correspond to the reproductive and grain filling growth stages for Bushland field study (BFS), 2015. Number in the parenthesis indicates the mean VPD in kPa for each treatment. VPDs measured at 70-74 days after planting (DAP) were lower than those measured at 80-84 DAPs because of the rain events. ESPs = evenly spaced plantings.

As water stress increased by decreasing the irrigation level, VPD within the crop canopy also increased. This was because under the water stressed environments, when plants were unable to meet their transpiration demands, stomata might be closed, thereby increasing the leaf temperature. Aston and Van Bavel (1972), and Jackson et al. (1977) also reported similar results. Since carbon dioxide (CO_2) diffuses through the stomata, closing of stomata is also related to the reduced rate of photosynthesis. So, under the water limiting environments, plants having less leaf area but opened stomata are preferred over plants having more leaf area but closed stomata (Glenn et al., 2008; Rajan et al. 2010). Compared to clumps, LAI for ESPs was significantly ($P < 0.05$) higher in GFS and relatively greater ($P = 0.1468$) in BFS, hence ESPs might lose more water through transpiration, which triggered stomata to be closed and increased VPD within the crop canopy. However, since soil moisture was not limiting under irrigated conditions, despite having higher LAI, corn plants with MIT and HIT had lower VPD compared to the plants with LIT. Similar to Istanbulluoglu et al. (2002), a positive linear relationship was found between irrigation and LAI (Table 7).

4.2.4 Tiller Number

For GFS, planting geometry and irrigation showed the main effects as well geometry × irrigation interaction ($P < 0.05$) to the production of tillers (Table 5). With LIT, ESPs produced a significantly higher number of tillers (1.13 tillers plant^{-1}) than clumps (0.03 tillers plant^{-1}). Both geometries with MIT and HIT had a similar number of tillers ranging from 0.01 (clumps, MIT) to 0.17 (ESPs, MIT) per plant (Table 8). For BFS, the effect of geometry on tiller production was marginal ($P = 0.1243$). There was a clear trend that tiller number was greater for ESPs (0.13 tillers plant^{-1}) than those for clumps (0.04 tillers plant^{-1}) (Table 7). In both studies, none of the tillers produced harvestable grains; however, there were tillers with naked ears and few under-sized grains in GFS.

Table 7. Corn tiller number, leaf area index (LAI), aboveground biomass (AGB), grain yield (GY), harvest index (HI), and grain water use efficiency (WUEg) as affected by irrigation and planting geometry in Gruver field study (GFS), 2014 and planting geometry in Bushland field study (BFS), 2015.

Geometry	Irrigation	Tillers§ (plant^{-1})	LAI§ (m^2 m^{-2})	AGB‡ (Mg ha^{-1})	GY# (Mg ha^{-1})	HI¶	WUEg* (kg m^{-3})
GFS							
Clump		0.01 b†	3.7 b	16.61 a	11.27 a	0.56 a	1.50 a
ESP		0.44 a	4.0 a	15.91 a	10.56 a	0.54 b	1.42 a
	High	0.01 b	4.6 a	21.80 a	14.97 a	0.58 a	1.34 b
	Medium	0.08 b	4.2 b	18.88 b	13.09 b	0.58 a	1.83 a
	Low	0.58 a	2.8 c	8.08 c	4.68 c	0.49 b	1.22 b
BFS							
Clump		0.04 a	2.1 a	6.29 a	3.61 a	0.48 a	0.94 a
ESP		0.13 a	2.5 a	6.79 a	3.64 a	0.45 a	0.93 a

Note: ESP = evenly spaced planting.

†For each study and column, means with different letters within geometry and irrigation represent significant differences at $P < 0.05$.

§Tiller number and LAI was determined at flag leaf stage.

‡Aboveground biomass was expressed as oven-dried.

#Grain yield was adjusted at 15.5% moisture.

¶Harvest index is based on weight of dry grain divided by aboveground dry matter.

*WUE for GFS was computed based on the dry grain yield per unit of water added through irrigation and precipitation. For BFS, it was calculated based on the dry grain yield per unit of water used in ET.

Table 8. Corn tiller number, leaf area index (LAI), aboveground biomass (AGB), grain yield (GY), harvest index (HI), and grain water use efficiency (WUEg) as affected by geometry × water interaction in Gruver field study (GFS), 2014.

Irrigation	Geometry	Tillers§ (plant^{-1})	LAI§ (m^2 m^{-2})	AGB‡ (Mg ha^{-1})	GY# (Mg ha^{-1})	HI¶	WUEg$ (kg m^{-3})
HIT	Clump	0.01 a†	4.4 a	22.88 a	15.40 a	0.57 b	1.36 a
	ESP	0.02 a	4.7 a	20.73 a	14.64 a	0.59 a	1.31 a
MIT	Clump	0.01 a	3.9 b	19.41 a	13.95 a	0.60 a	1.95 a
	ESP	0.17 a	4.5 a	18.35 a	12.24 b	0.56 b	1.71 b
LIT	Clump	0.03 b	2.6 a	8.74 a	4.57 a	0.52 a	1.20 a
	ESP	1.13 a	2.8 a	7.43 a	4.72 a	0.46 b	1.24 a

Note: LIT = low irrigation treatment, MIT = medium irrigation treatment, HIT = high irrigation treatment, ESP = evenly spaced planting.

†Different letters within a column and each irrigation level represent significant differences at $P < 0.05$.

§Tiller number and LAI were determined at flag leaf stage.

‡Aboveground biomass was expressed as oven-dried.

#Grain yield was adjusted at 15.5% moisture.

¶Harvest index is based on weight of dry grain divided by aboveground dry matter.

$WUE was computed based on the dry grain yield per unit of water added through irrigation and precipitation.

Low density planting and skip-row configurations are the major strategies that have been practiced in the US Great Plains for conserving soil water for use by crops during the grain-filling growth stages when soil water is often inadequate. However, for crops such as grain sorghum and corn, reducing the plant population often results in an increased number of tillers that use water and nutrients but often end up with little or no grain (Stewart, 2009). In both studies, plants in clumps produced lower number of tillers compared to the plants in ESPs, which was also observed by Krishnareddy et al. (2006) in sorghum and Kapanigowda et al. (2010a) in corn. Less available growing space in a high density planting reduces the number of tillers (Liddle et al., 1982; Casal et al., 1986). Tiller emergence is also related to the quality of light that hits the plant (Lafarage et al., 2002). For instance, tiller production was reduced under the conditions of low red light to far-red light ratio (R:FR) (Casal et al., 1985; Davis and Simmons, 1994; Gautier et al., 1999; Krishnareddy et al., 2009; Finlayson et al., 2010). With low density planting, but adequate supply of soil fertility and moisture, most of the corn hybrids produced one or more tillers during the early growth stage (Thomison, 2009), which was likely be the reason for having significantly higher number of tillers per plant in ESPs with LIT. Further, lower plant density with LIT might allow higher R:FR light ratio reaching at the base of the plants triggering more tiller formation.

4.2.5 Aboveground Biomass

Aboveground biomass was not significantly affected ($P > 0.05$) by the planting geometry for both studies (Table 5). For GFS, ESPs had 4.2% (0.70 Mg ha^{-1} [0.31 ton ac^{-1}]) lesser biomass than clumps on average. In contrast, for BFS, ESPs produced 12.0% (0.68 Mg ha^{-1} [0.30 ton ac^{-1}]) more biomass compared to clumps (Table 7). Aboveground biomass in BFS was significantly ($P < 0.05$) influenced by the irrigation. The average biomass production reduced by 13.4% (2.92 Mg ha^{-1} [1.30 ton ac^{-1}]) from HIT to MIT and by 62.9% (13.7 Mg ha^{-1} [6.1 ton ac^{-1}]) from HIT to LIT, which was 21.80, 18.88, and 8.08 Mg ha^{-1} (9.72, 8.42, and 3.60 ton ac^{-1}), respectively for HIT, MIT, and LIT (Table 7).

Bandaru et al. (2006) compared clumps and ESPs in sorghum in Bushland, Texas and found significantly lower biomass in clumps at harvest. In contrast, Kapanigowda et al. (2010a) in the same location grew corn and found significantly higher biomass in clumps compared with ESPs at harvest, which was found true in our GFS, though the difference was not significant. Moisture stress can affect growth, development, and physiological processes of corn plants differently at different growth stages resulting in lesser biomass production (Doorenbos and Kassam, 1979; Traore et al., 2000). For GFS too, the magnitude of decline in aboveground biomass production was largely influenced by the level of irrigation, indicating that plants with LIT had higher water stress at different growth stages followed by plants with MIT and HIT. Many early studies also demonstrated that water stress significantly reduced corn growth and development (Denmead and Shaw, 1960; Claassen and Shaw, 1970; Jurgens et al., 1978; Musick and Dusek, 1980; Bryant et al., 1992; Jama and Ottman, 1993).

4.2.6 Grain Yield

Grain yield in GFS was significantly different between clump and ESP geometries at $P = 0.0695$ (Table 5) with a mean of 11.27 Mg ha^{-1} (5.03 ton ac^{-1}) for clumps and 10.56 Mg ha^{-1} (4.71 ton ac^{-1}) for ESPs, averaging across three irrigation levels. Grain yield was significantly ($P < 0.05$) affected by irrigation (Table 5). The mean grain yield for HIT, MIT, and LIT was 14.97, 13.09, and 4.68 Mg ha^{-1} (6.68, 5.84, and 2.10 ton ac^{-1}), respectively. This result suggested that grain yield reduced by 12.6% (1.88 Mg ha^{-1} [0.84 ton ac^{-1}]) and 68.7% (10.3 Mg ha^{-1} [4.6 ton ac^{-1}]) from HIT to MIT and HIT to LIT, respectively (Table 6). HIT received 100% more water than MIT, but it increased the grain yield only by 14.4%. For BFS, both geometries produced the same amount of grains, 3.61 Mg ha^{-1} (1.61 ton ac^{-1}) for clumps and 3.64 Mg ha^{-1} (1.62 ton ac^{-1}) for ESPs (Table 7).

Plants with LIT used most of the soil water during the vegetative growth stage, and when they reached the reproductive stage, soil moisture was already limited to the point plants could not fulfill their water demand. Hence, a significant reduction in dry matter accumulation occurred, which eventually reflected into poor grain yield. Reduced grain yield as a result of increased water stress was also reported by Hergert et al. (1993), who found corn yields of 11.8, 10.1, and 5.6 Mg ha^{-1} (5.3, 4.5, and 2.5 ton ac^{-1}) under the conditions of high irrigation, limited irrigation, and dryland, respectively. Similarly, Yildirim et al. (1996) studied the effects of different levels of soil moisture on corn yield and reported the highest yield of 10.85 Mg ha^{-1} (4.84 ton ac^{-1}) under well-watered conditions, while the lowest yield was 3.47 Mg ha^{-1} (1.56 ton ac^{-1}) under water-limiting conditions. Overall, CTs and within canopy VPDs were consistently lower, but grain yields were often higher for clumps compared to ESPs. Blum et al. (1989), Ayeneh et al. (2002), and Pradhan et al. (2014) also reported higher grain yields from the wheat cultivars having cooler canopies than genotypes having warmer canopies.

4.2.7 Harvest Index

HI in GFS was significantly ($P < 0.05$) affected by the main effects of geometry and irrigation, and geometry × irrigation interaction (Table 5). Clumps had higher HI with LIT (0.52 vs. 0.46 for ESPs) and MIT (0.60 vs. 0.56 for ESPs), while ESPs had higher HI with HIT (0.59 vs. 0.57 for clumps). HI sharply decreased from HIT and MIT to LIT, and the magnitude of decline was larger in ESPs compared to clumps. More clearly, ESP geometry with HIT had mean HI of 0.59, while the same geometry with LIT had a mean HI of 0.46, which was the lowest of all (Table 8). For BFS, the HI was significantly higher for clumps at *P* = 0.0950 with HI of 0.48 and 0.45 for clumps and ESPs, respectively (Table 7).

Crop sensitivity to water stress varies according to the growth stages (Doorenbos and Kassam, 1979). For instance, as reported by Traore et al. (2000) the HI was affected when water stress was imposed during anthesis stage of corn. Prihar and Stewart (1990) reported that HI in sorghum was reduced due to the environmental stress. Raun et al. (1989) found the corn HI ranging from 0.57 to 0.60 with fully irrigated condition, which was also true in this study. Other researchers (Fairbourn et al., 1970; Francis et al., 1978; Bennet et al., 1989; and Kiniry et al., 1997) reported minimum HI of 0.40 to maximum of 0.55 for different growing conditions. As a whole, clump geometry had higher HI in both of our studies. Kapanigowda et al. (2010a and 2010b) and Mohammed et al. (2012) also found increased HI for clumps (about 10-33%) compared to ESPs in corn. Reduced HI for ESPs was mainly associated with their increased number of tillers per plant, while higher number of tillers coupled with water stress resulted lower HI in LIT than in MIT and HIT.

4.2.8 Water Use Efficiency

For GFS, geometry had no effect on WUE (Table 5). However, when analyzing the data from each irrigation level, clumps had significantly ($P < 0.05$) higher WUEg, 1.95 kg m^{-3} than ESPs, 1.71 kg m^{-3} with MIT. Further, compared to ESPs, clumps had WUEg relatively higher with HIT (1.36 vs. 1.31 kg m^{-3} for ESPs), but lower with LIT (1.20 vs. 1.24 kg m^{-3} for ESPs). WUEg was significantly ($P < 0.05$) affected by the main effect of irrigation. Plants growing with MIT had higher WUEg (1.83 kg m^{-3}) followed by plants with HIT (1.34 kg m^{-3}), and LIT (1.22 kg m^{-3}) (Tables 7 and 8). For the BFS, clumps and ESPs had the similar WUEg values (0.94 vs. 0.93 kg m^{-3} for ESPs).

Since clump geometry leaves more free space between the clumps, the evaporative loss could be higher in clump fields than the fields with ESP, especially under low density planting. However, WUE values were comparable or even higher for clumps than those for ESPs. As in case of grain yield, WUE was higher with MIT than with HIT and LIT. Despite higher grain yield, the lower WUE for HIT was likely because of an excess irrigation, and soil water contents at planting and harvest were not obtained. Yazar et al. (1999) found the lowest WUE for the plants grown without irrigation when compared to the irrigated plants. They reported WUE (dry weight basis) of corn ranging from 0.97 to 1.42 kg m^{-3} for different water levels. In contrast, Meyers et al. (1984) found higher WUE in grain sorghum when water stress was increased. Howell et al. (1998) reported WUEs (dry weight basis) of corn ranging from 1.52 kg m^{-3} for short-season hybrid to1.57 kg m^{-3} for full-season hybrid under well-irrigated conditions. Howell (2001) summarized the work of different scholars in Texas High Plains and reported WUEs (15.5% grain moisture) ranging from 0.34 kg m^{-3} for dryland to 1.39 kg m^{-3} for fully irrigated corn. Hao et al. (2015) grew five corn hybrids in the Texas High Plains for three years and mentioned WUE (15.5% grain moisture) as 1.19 to 2.40 for different water regimes. Overall, lower WUE for the plants having higher CT was found in both studies. Araus et al. (1993), Read et al. (1991), and Zong et al. (2008) also reported this.

4.2.9 Conclusions

Corn plants in clumps created mutual shading and exposed less leaf area per plant to the environment. Moreover, clumps may have reduced the effect of wind, which helped to decrease the rate of transpiration. Compared to ESPs, clumps consistently showed lower CT and VPD within crop canopy. Overall, clumps did not reduce the grain yield, but decreased the vegetative mass resulting significantly higher HI compared to ESPs. Due to the increased free space available between and among the clumps, potential evaporative loss could be greater for clump geometry. However, clumps did not decrease the WUE. HIT in GFS received 100% more water than MIT, but it increased the grain yield only by 14.4% with significantly lower WUE indicating that only increasing water application does not increase the WUE, which is more important in water limited areas. Therefore, the development of water management strategies is extremely important for maintaining agricultural profitability. Though clumps produced grain yield similar to ESPs, improved microclimate, decreased number of tillers, and increased HI associated with clump geometry were some of the important attributes to be considered, especially when plants are grown under water limited environments, where despite of low plant populations, water deficits are common during the reproductive and grain filling growth stages. Hence, clump geometry appears to be a potential alternative strategy for growing corn, and possibly other crops, under semi-arid climatic environments.

STUDY 3: Grain Sorghum Transpiration Efficiency at Different Growth Stages As Affected by Growing Period Vapor Pressure Deficit

4.3.1 Plant Growing Environment

The GH and GC temperatures were maintained between 20ºC (68ºF) (night minimum) and 32ºC (90ºF) (day maximum). Plants in GH1 were grown under natural lights, but for GH2 supplemental light was provided using 600 W SONT bulbs fixed at 2.0-2.5 m (6.5-8.2 ft) height. Mean RH values for crop growing period were 51.4 (±12.7 s.d.), 47.0 (±9.0 s.d.), 54.5 (±11.2 s.d.), and 31.5 (±8.0 s.d.) % for GH1, GH2, GC1, and GC2 studies, respectively. The decreased RH from the first study (GH1 and GC1) to the second study (GH2 and GC2) was likely due to the seasonal weather conditions, because the GH and GC used in the studies had no capability to regulate humidity. Higher RH resulted in greater VPDs for second studies than those for first studies. At different growth stages, crop growing period mean VPDs within each study were similar (except GH2), but were different from one study to the other. Mean VPDs from emergence to final harvesting (physiological maturity of grains) were 2.28 (±0.42 s.d.), 2.32 (±0.61 s.d.), 1.38 (±0.41 s.d.), and 2.41 (±0.23 s.d.) kPa for the GH1, GH2, GC1, and GC2 studies, respectively.

4.3.2 Cumulative Water Used in Transpiration

Since plants were harvested at different growth stages, cumulative water used in transpiration was significantly ($P < 0.05$) different from one growth stage to the other (Tables 9 and 12). Plants in GH studies transpired an average of 6.11, 18.56, 49.97, and 58.65 L of water at S1, S2, S3, and S4, respectively (Tables 10). Total water used from seedling emergence to final harvest was 51.67 L for GH1 and 65.38 L for GH2 (Table

11). Plants in GC studies transpired an average of 3.07, 6.42, 14.66, and 18.64 L of water at S1, S2, S3, and S4, respectively (Table 13). Total water used from seedling emergence to final harvest was 17.76 kg for GC1 and 19.53 L for GC2 (Table 14).

Table 9. P-values of total water transpired by sorghum plants, shoot dry weight (DW), root dry weight (DW), total dry weight (DW), shoot:root (S:R) ratio, shoot transpiration efficiency (TE_{shoot}), and total transpiration efficiency (TE_{total}) as affected by the environment and plant growth stage at harvest for the greenhouse studies as determined by analysis of variance (ANOVA).

Effect	Water used	Shoot DW	Root DW	Total DW	S:R ratio	TE_{shoot}	TE_{total}
Environment (E)‡	<.0001	0.0470	<.0001	<.0001	<.0001	<.0001	0.0200
Growth stage (GS)	<.0001	<.0001	<.0001	<.0001	<.0001	0.0910	<.0001
E × GS	<.0001	<.0001	<.0001	<.0001	0.0009	0.8740	0.0871

‡Environment represents study 1 and study 2.

Table 10. Means of total water transpired by sorghum plants, shoot dry weight (DW), root dry weight (DW), total dry weight (DW), shoot:root (S:R) ratio, shoot transpiration efficiency (TE_{shoot}), and total transpiration efficiency (TE_{total}) as affected by plant growth stage at harvest and environment for the greenhouse studies.

Effect	Water used (L)	Shoot DW (g box^{-1})	Root DW (g box^{-1})	Total DW (g box^{-1})	S:R ratio (g g^{-1})	TE_{shoot} (kg m^{-3})	TE_{total} (kg m^{-3})
Growth stage at harvest							
S1	6.11 d†	25.4 d	9.2 c	34.6 d	2.40 d	4.12 a	5.63 b
S2	18.65 c	81.6 c	36.3 b	117.8 c	2.81 c	4.35 a	6.35 a
S3	49.97 b	213.6 b	64.4 a	278.1 b	3.78 b	4.29 a	5.54 b
S4	58.65 a	251.6 a	62.7 a	314.3 a	4.31 a	4.32 a	5.37 b
Environment							
GH1 study	-§	-	-	-	4.17 a	4.47 a	5.60 b
GH2 study	-	-	-	-	2.48 b	4.08 b	5.85 a

Note: S1 = seedling emergence to six leaf stage, S2 = seedling emergence to flag leaf stage, S3 = seedling emergence to grain filling stage, S4 = seedling emergence to grain physiological maturity stage.

†In each column, for growth stage and environment, means with different letters were significantly different at $P < 0.05$.

§Mean values cannot be calculated.

Table 11. Means of total water transpired by sorghum plants, shoot dry weight (DW), root dry weight (DW), total dry weight (DW), shoot:root (S:R) ratio, shoot transpiration efficiency (TE_{shoot}), and total transpiration efficiency (TE_{total}) as affected by plant growth stage at harvest × environment interaction for the greenhouse studies.

Effect	Water used (L)	Shoot DW (g box^{-1})	Root DW (g box^{-1})	Total DW (g box^{-1})	S:R ratio (g g^{-1})	TE_{shoot} (kg m^{-3})	TE_{total} (kg m^{-3})
GH study 1							
GH1 × S1	7.19 d†	30.8 d	4.5 c	40.7 d	3.22 b	4.29 a	5.66 ab
GH1 × S2	20.71 c	94.6 c	30.1 b	124.7 c	3.20 b	4.57 a	6.02 a
GH1 × S3	44.51 b	197.7 b	39.8 a	237.6 b	4.97 a	4.44 a	5.34 b
GH1 × S4	51.67 a	233.8 a	44.2 a	278.1 a	5.32 a	4.52 a	5.38 b
GH study 2							
GH2 × S1	5.04 d	20.0 d	8.5 d	28.5 d	2.40 b	3.94 a	5.60 b
GH2 × S2	16.59 c	68.5 c	42.5 c	111.0 c	1.61 c	4.12 a	6.68 a
GH2 × S3	55.42 b	229.2 b	89.0 a	318.5 b	2.58 b	4.14 a	5.75 b
GH2 × S4	65.38 a	269.5 a	81.2 b	350.5 a	3.31 a	4.11 a	5.36 b

Note: S1 = seedling emergence to six leaf stage, S2 = seedling emergence to flag leaf stage, S3 = seedling emergence to grain filling stage, S4 = seedling emergence to grain physiological maturity stage.

†In each column, for each study, means with different letters were significantly different at $P < 0.05$.

Table 12. P-values of total water transpired by sorghum plants, shoot dry weight (DW), root dry weight (DW), total dry weight (DW), shoot:root (S:R) ratio, shoot transpiration efficiency (TE_{shoot}), and total transpiration efficiency (TE_{total}) as affected by the environment and plant growth stage at harvest for the growth chamber studies as determined by analysis of variance (ANOVA).

Effect	Water used	Shoot DW	Root DW	Total DW	S:R ratio	TE_{shoot}	TE_{total}
Environment (E)‡	0.232	0.0001	0.6372	0.0025	0.0003	<.0001	0.0023
Growth stage (GS)	<.0001	<.0001	<.0001	<.0001	<.0001	0.3178	0.0932
E × GS	0.0005	0.0308	0.3420	0.1024	0.1300	0.1502	0.1178

‡Environment represents study 1 and study 2.

Table 13. Means of total water transpired by sorghum plants, shoot dry weight (DW), root dry weight (DW), total dry weight (DW), shoot:root (S:R) ratio, shoot transpiration efficiency (TE_{shoot}), and total transpiration efficiency (TE_{total}) as affected by the plant growth stage at harvest and environment for the growth chamber studies.

Effect	Water used (L)	Shoot DW (g box^{-1})	Root DW (g box^{-1})	Total DW (g box^{-1})	S:R ratio (g g^{-1})	TE_{shoot} (kg m^{-3})	TE_{total} (kg m^{-3})
Growth stage at harvest							
S1	3.07 d†	14.3 d	4.4 c	18.7 d	3.28 c	4.64 a	6.09 a
S2	6.42 c	28.6 c	8.9 b	37.5 c	3.21 c	4.43 a	5.82 a
S3	14.66 b	69.3 b	17.2 a	86.5 b	4.06 b	4.69 a	5.86 a
S4	18.64 a	84.6 a	17.3 a	101.8 a	5.00 a	4.55 a	5.48 a
Environment							
GC1 study	-§	-	-	-	4.23 a	4.89 a	6.09 a
GC2 study	-	-	-	-	3.55 b	4.27 b	5.54 b

Note: S1 = seedling emergence to six leaf stage, S2 = seedling emergence to flag leaf stage, S3 = seedling emergence to grain filling stage, S4 = seedling emergence to grain physiological maturity stage, GC1 = growth chamber first study, GC2 = growth chamber second study.

†In each column, for growth stage and environment means with different letters were significantly different at $P < 0.05$.

§Mean values cannot be calculated.

Table 14. Means of total water transpired by sorghum plants, shoot dry weight (DW), root dry weight (DW), total dry weight (DW), shoot:root (S:R) ratio, shoot transpiration efficiency (TE_{shoot}), and total transpiration efficiency (TE_{total}) as affected by the growth stage at harvest × environment interaction for the growth chamber studies.

Effect	Water used (L)	Shoot DW (g box^{-1})	Root DW (g box^{-1})	Total DW (g box^{-1})	S:R ratio (g g^{-1})	TE_{shoot} (kg m^{-3})	TE_{total} (kg m^{-3})
GC study 1							
GC1 × S1	3.50 d†	16.5 c	4.5 c	21.0 c	3.72 c	4.75 a	6.02 a
GC1 × S2	6.76 c	32.3 b	10.2 b	42.5 b	3.21 c	4.78 a	6.27 a
GC1 × S3	15.35 b	79.1 a	17.7 a	96.8 a	4.57 b	5.14 a	6.29 a
GC1 × S4	17.76 a	86.7 a	16.3 a	103.0 a	5.42 a	4.88 a	5.79 a
GC study 2							
GC2 × S1	2.65 d	12.0 d	4.2 c	16.2 d	2.85 c	4.54 a	6.16 a
GC2 × S2	6.08 c	24.7 c	7.8 b	32.5 c	3.21 bc	4.08 a	5.37 ab
GC2 × S3	13.98 b	59.5 b	16.7 a	76.2 b	3.56 b	4.25 a	5.44 ab
GC2 × S4	19.53 a	82.5 a	18.2 a	100.7 a	4.61 a	4.22 a	5.18 b

Note: S1 = seedling emergence to six leaf stage, S2 = seedling emergence to flag leaf stage, S3 = seedling emergence to grain filling stage, S4 = seedling emergence to grain physiological maturity stage, GC1 = growth chamber first study, GC2 = growth chamber second study.

†In each column, for each study, means with different letters were significantly different at $P < 0.05$.

4.3.3 Biomass Production and Shoot: Root Ratio

For GH and GC studies, shoot biomass was significantly ($P < 0.05$) affected by the main effects of environment and plant growth stage, and environment × growth stage interaction (Tables 9 and 12). Plants produced consistently higher shoot mass from S1 through S4 for each study (Tables 11 and 14). Shoot mass at final harvest (S4) was higher for GH2 (269.5 g box^{-1}) than for GH1 (233.8 g box^{-1}) (Table 11). This was mainly because of the sorghum plants in GH2 producing more tillers (1.87 tillers plant^{-1} in average) than in GH1 (0.62 tillers plant^{-1} in average). None of the plants in GC studies produced tillers. However, at each growth stage, shoot mass was greater for GC1 than for GC2 (Table 14).

Root mass was significantly ($P < 0.05$) affected by the main effects of environment and plant growth state, and environment × growth stage interaction for GH studies (Table 9), but only by the main effect of growth stage in GC studies (Table 12). For each study, mean root mass was different among S1, S2, and S3, but similar between S3 and S4 (except GH2), but total biomass (shoot + root) increased consistently from S1 through S4 (Tables 11 and 14).

For GH studies, S:R ratio was significantly ($P < 0.05$) affected by the main effects of environment and plant growth stage, and environment × growth stage interaction (Table 9). Mean S:R ratio was higher for GH1 (4.23) than for GH2 (2.48), and it was highest for S4 (4.43) followed by S3 (3.78), S2 (2.81), and S1 (2.40) (Table 10). For GC studies, S:R ratio was significantly ($P < 0.05$) affected by the main effects of environment and plant growth stage. S:R ratio was higher for GC1 (4.23) than for GC2 (3.55), and was highest for S4 (5.00) followed by S3 (4.06), S1 (3.28), and S2 (3.21). S1 and S2 were statistically similar (Table 13). Overall, S:R ratio increased from earlier (S1 and S2) to later (S3 and S4) growth stages (Tables 10 and 13).

In the current study, at later growth stages (S3 and S4), root weight was more or less constant, but shoot growth continued to increase throughout the growth period.

Hence, the S:R ratio increased with the advancement of the age of plants. This was also observed by Fageria et al. (1992) in their greenhouse studies on rice, wheat, common bean, and cowpea. They suggested that S:R ratios were influenced by soil phosphorus (P) levels, cultivars, and plant age. Amanullah and Stewart (2013) grew grain sorghum in the greenhouse and found S:R ratios of 1.10, 4.34, and 3.47 at 30, 60, and 90 days after emergence, respectively. Yang (2010) grew sorghum in the pots, harvested shortly after flowering, and found S:R ratios ranging from 3.09 to 4.59 for different pot sizes, which were comparable to the current S:R ratios at S2 and S3 growth stages. Though rooting behavior is different between sorghum and rice, similar to the current results, Yoshida (1981) and Ten Berge et al. (1994) found higher S:R ratio at grain maturity compared to the seedling stage in rice at the International Rice Research Institute (IRRI), Philippines. According to Waldren (1983), during early growth stages, roots grow rapidly and few, if any, die, so the size of the root system increases exponentially. As the plant reaches flowering, roots began to die as fast as new roots are produced so that the size of the root system remains constant. As the plant reaches later growth stages, the number of roots dying exceeds the number being produced and the overall size of the root system declines.

4.3.4 Transpiration Efficiency

For GH and GC studies, TE_{shoot} was significantly (P < 0.05) influenced by the main effect of environment (Tables 9 and 12). For GH studies, TE_{shoot} was higher for GH1 (4.47 kg m^{-3}) than for GH2 (4.08 kg m^{-3}). Plant growth stage showed a tendency of significance (P = 0.0910) with higher ET_{shoot} at S2 (4.35 kg m^{-3}) and lower at S1 (4.12 kg m^{-3}) (Tables 9 and 10). TE_{total} was significantly (P < 0.05) affected by the main effect of environment and plant growth stage (Table 9). Mean TE_{total} was higher for GH2 (5.85 kg m^{-3}) than for GH1 (5.60 kg m^{-3}), and similar at S1 (5.63 kg m^{-3}), S3 (5.54 kg m^{-3}), and S4 (5.37 kg m-3), but was higher at S2 (6.35 kg m^{-3}) (Table 10). For GC studies, mean ET_{shoot} and ET_{total} values were similar among different growth stages, but they were significantly ($P < 0.05$) influenced by the main effect of environment (Table 12). Both values were higher for GC1 than those for GC2 (Table 13). For all studies, aboveground dry matter (shoot) increased linearly with cumulative water used in transpiration (Figures 16 and 17).

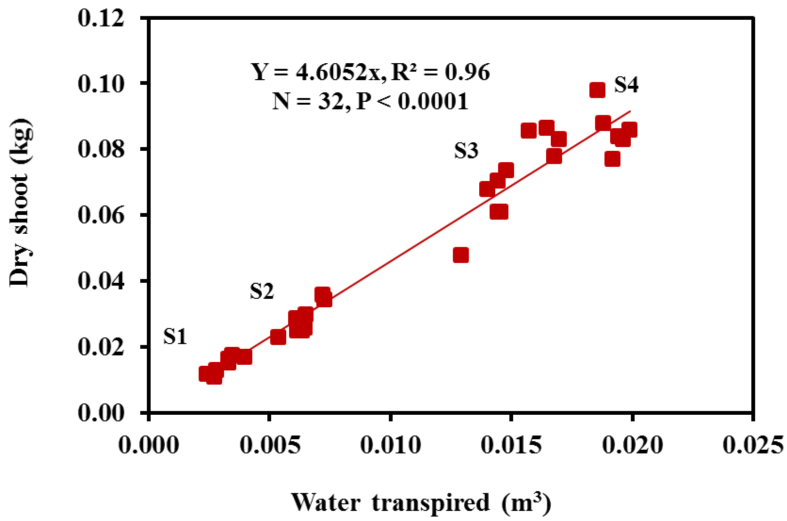

Figure 16. A linear regression between sorghum dry shoot mass and cumulative water used in transpiration during the crop growing period for the growth chamber studies. S1 = seedling emergence to six leaf stage, S2 = seedling emergence to flag leaf stage, S3 = seedling emergence to grain filling stage, S4 = seedling emergence to grain physiological maturity stage.

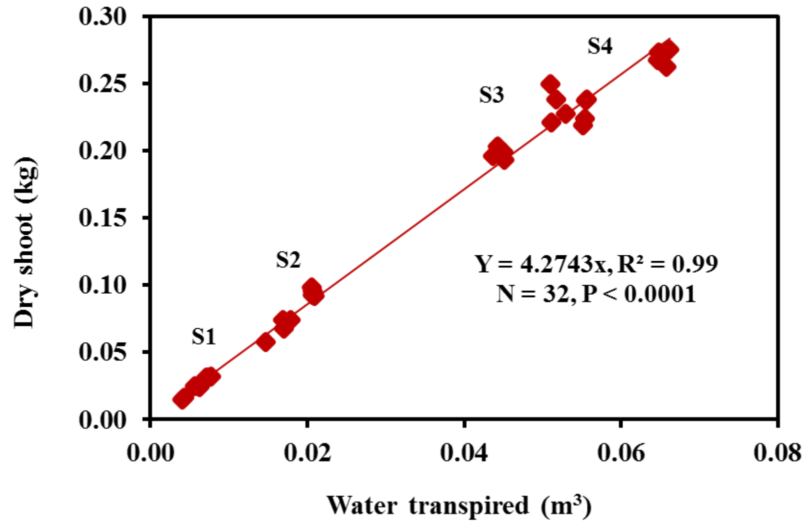

Figure 17. A linear regression between sorghum dry shoot mass and cumulative water used in transpiration during the crop growing period for the greenhouse studies. S1 = seedling emergence to six leaf stage, S2 = seedling emergence to flag leaf stage, S3 = seedling emergence to grain filling stage, S4 = seedling emergence to grain physiological maturity stage.

TE_{total} values were greater than TE_{shoot} values due to the inclusion of root biomass. Reported TE_{shoot} values for small grain crops vary from 3.1 to 6.7 kg m^{-3} for wheat and 3.2 to 5.7 kg m^{-3} for barley (Kemanian et al., 2005), 2.9 to 4.5 kg m^{-3} for oat (Ehlers and Goss, 2003; Ehlers, 1989), and 2.5 to 5.4 kg m^{-3} for rice (Impa et al., 2005). TE values in the current studies were a bit lower than those reported by Xin et al. (2009), who grew 25 sorghum lines in the greenhouse over two seasons and found mean TE_{shoot} of 5.7 (±0.58 s.d.) kg m^{-3} and mean TE_{total} of 8.08 (±0.51 s.d.) kg m^{-3}. Similar to the current results, early studies have shown a linear relationship between aboveground dry matter (shoot) and total water transpired by crops during the growing season (Ben-Gal and Shani, 2002; Kemanian et al., 2005; Haefele et al., 2009; Xin et al., 2009; Mantovani et al., 2014). The crop growing period mean VPDs, which are explained below, likely triggered the differences in TEshoot between two GH or GC studies.

4.3.5 Transpiration Efficiency Vs. Vapor Pressure Deficit

Crop growing period mean VPDs for S1, S2, S3, and S4 were 2.37, 2.25, 2.31, and 2.18 kPa for GH1, 2.78, 1.91, 2.25, and 2.32 kPa for GH2, 1.18, 1.26, 1.37, and 1.45 kPa for GC1, and 2.36, 2.32, 2.43, and 2.52 kPa for GC2 studies, respectively. VPDs within each study were close to each other (except GH2; Figure 18). For GH2 (Figure 17B), mean VPDs for S1 and S2 were considerably different due to the problem with greenhouse system. S1 had the highest VPD (2.78 kPa), but lowest TE_{shoot} (3.94 kg m^{-3}). Within each study, mean TE_{shoot} values at different growth stages were similar (Tables 11 and 14). Mean VPD values varied from one study to the other, which increased from GC1 to GH1 to GH2 to GC2. When data from all studies were combined, TE_{shoot} was significantly ($P < 0.05$) affected by the crop growing period VPD. TE_{shoot} decreased linearly as the VPD increased (Figure 19).

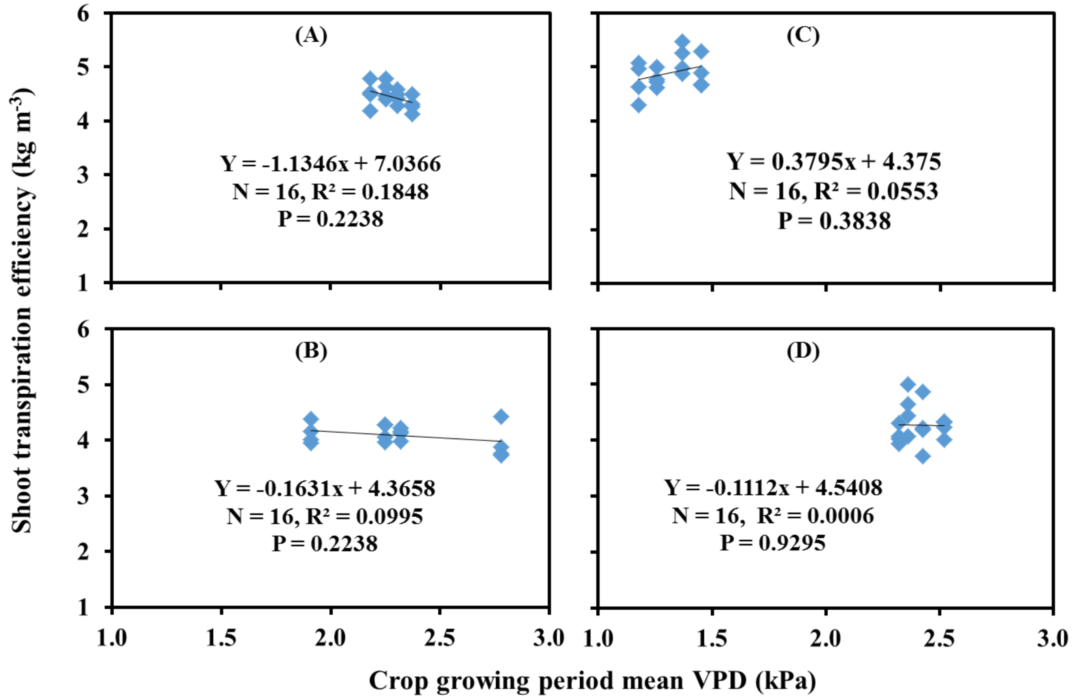

Figure 18. A linear regression between sorghum growing period mean vapor pressure deficits (VPDs) and shoot transpiration efficiency for the greenhouse studies, GH1 (A), GH2 (B), and the growth chamber studies, GC1 (C) and GC2 (D).

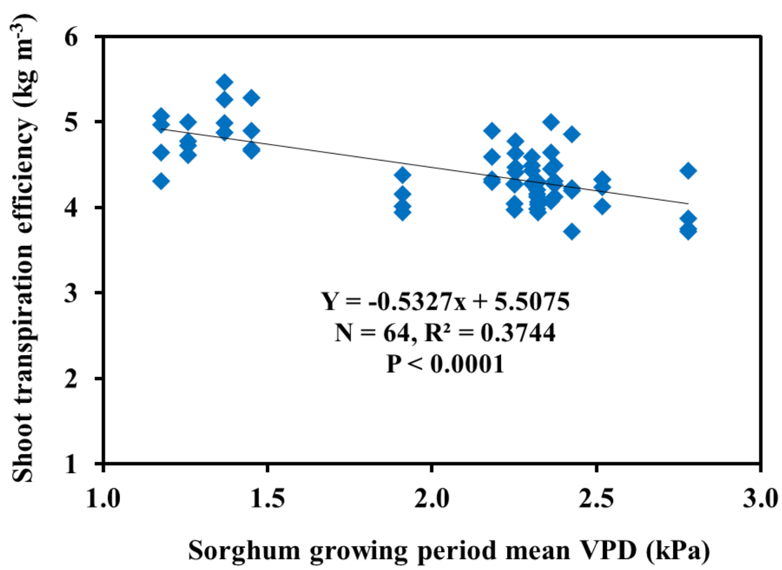

Figure 19. A linear regression between sorghum growing period mean vapor pressure deficits (VPDs) and shoot transpiration efficiencies for all (two greenhouse and two growth chamber) studies.

Bierhuizen and Slatyer (1965) grew cotton plants under adequate fertilizer and soil moisture conditions in a glasshouse and reported that TE_{shoot} was decreased linearly with increasing leaf-air VPD. Kemanian et al. (2005) graphed TE_{shoot} vs. daytime VPD for their barley study and pervious 10 studies in barley and wheat, and found that TE_{shoot} seems to be an inverse function of VPD, which was well represented by the model ($P <$ 0.0001, R^2 = 0.97, N = 38). Haefale et al. (2009) did not find a significant decrease in TE_{shoot} in rice with increasing VPD, but noticed a trend of decline. Cotton, barley, wheat, and rice are C_3 crops, and their TE response against VPD was similar to the current sorghum (C_4 crop) results. As shown in Figure 19, relationships between growing period VPD and shoot transpiration efficiency was highly significant ($P < 0.0001$), suggesting that changes in TE values were highly dependent on the changes in VPD values. Xin et al. (2009) also mentioned that TE based on biomass accumulated per unit of water transpired was greatly influenced by VPD.

For the GH1, GH2, GC1, and GC2 studies, on average, sorghum plants produced 1 g of biomass for every 224.6, 245.6, 205.3, and 235.3 g of water transpired, when the crop growing period mean VPDs were 2.28, 2.32, 1.31, and 2.41 kPa, respectively. These values are close to the findings of Sinclair and Weiss (2010). They reported that C_4 crops grown in an “average” transpiration environment of 2 kPa VPD will produce 1 g of biomass for every 220 g of water transpired, but for an arid region with a transpiration environment of 2.5 kPa VPD, crops use about 280 g for each g of biomass production.

4.3.6 Conclusions

Shoot biomass increased linearly with cumulative water transpiration. Plants in GH and GC produced significantly higher shoot mass with the advancement of the age, while root mass increased from S1 through S3, and remained constant thereafter. However, total biomass (root + shoot) increased consistently from S1 through S4, thereby increasing the S:R ratio from earlier (S1 and S2) to later (S2 and S3) growth stages. Overall, within each study, mean VPD as well as TE_{shoot} values at different growth stages were similar. However, different VPDs were recorded from one study to the other. When data from all studies were combined, TE_{shoot} values showed an inverse linear relationship with crop growing period mean VPDs. Sinclair et al. (2005) conducted simulations of sorghum growth in four locations in Australia and found that imposition of a maximum transpiration rate at high VPD results in sorghum yield increases of 9-13% in years with yield less than 4.5 Mg ha^{-1} (2.0 ton ac^{-1}). Hence, improvement in TE is likely to have a positive impact on sorghum yield under semiarid climatic conditions.

STUDY 4: Transpiration Efficiency of Old and Modern Wheat Cultivars During Vegetative Growth

4.4.1 Plant Height

None of the measured parameters showed cultivar × water interaction. Plant heights were significantly (*P* < 0.05) affected by the main effects of cultivar and water (Table 15). Overall, old cultivars had higher plant height than the modern cultivars, where the mean plant height was highest for Triumph 64, 45.3 cm (1.5 ft) and lowest for TAM 105, 33.5 cm (1.1 ft). Greater plant height was measured at high water, 41.7 cm (1.4 ft) than at low water level, 36.0 cm (1.2 ft) (Table 16). The modern wheat cultivars are (semi)-dwarf (medium-tall) genetically, and hence, they were expected to be shorter than the older cultivars such as Triumph 64 and Scout 66.

Table 15. P-values of wheat plant height, leaf chlorophyll content (LCC), leaf relative water content (LRWC), aboveground biomass, cumulative water use, and biomass water use efficiency (WUEb) as determined by analysis of variance (ANOVA).

Treatments	Plant height	LCC at 40 DAP	LRWC at 25 DAP	LRWC at 35 DAP	Above-ground biomass	Cumulative water use	WUEb
Cultivar (C)	0.0004	0.0329	0.4683	0.3699	0.4599	0.3152	0.2013
Water (W)	0.0006	0.0066	0.0571	0.0307	0.0004	0.0009	0.0046
C × W	0.2157	0.7206	0.8079	0.6127	0.4945	0.4757	0.9896

Note: DAP = days after planting.

4.4.2 Leaf Chlorophyll Content

Chlorophyll content in wheat leaves was significantly (*P* < 0.05) affected by main effect of cultivar and water (Table 15). As a whole, modern cultivars had higher leaf chlorophyll compared to the old cultivars, where TAM 111 had the highest chlorophyll

(55.8) and Scout 66 had the lowest (52.0). Plants growing at high water had significantly higher leaf chlorophyll (55.0) compared to the plants at low water level (52.6) (Table 16).

Table 16. The mean plant height, leaf chlorophyll content (LCC), leaf relative water content (LRWC), aboveground biomass, cumulative water use, and biomass water use efficiency (WUE) in wheat as affected by cultivar and water level.

Effects	Plant height at harvest (cm)	LCC at 40 DAP	LRWC at 25 DAP (%)	LRWC at 35 DAP (%)	Above-ground biomass¶ (g box^{-1})	Cumulative water use (L)	WUEb (kg m^{-3})
Cultivars							
Triumph 64	45.5 a†	53.6 ab	88.8 a	94.8 a	93.7 a	38.60 a	2.38 a
Scout 66	42.3 ab	52.0 c	94.2 a	86.2 a	74.1 a	30.83 a	2.40 a
TAM W 101	33.8 cd	54.4 ab	91.8 a	95.6 a	86.1 a	35.67 a	2.37 a
TAM 105	33.5 d	54.8 ab	93.2 a	87.5 a	66.8 a	29.82 a	2.19 a
TAM 111	38.7 bcd	55.8 a	89.3 a	97.0 a	78.0 a	35.60 a	2.15 a
TAM 112	39.4 bc	53.4b	88.3 a	97.3 a	86.0 a	38.66 a	2.16 a
Water levels							
High	41.7 a	55.0 a	93.0 a	94.2 a	96.4 a	39.85 a	2.40 a
Low	35.9 b	52.6 b	88.9 b	91.7 b	65.1 b	29.74 b	2.15 b

Note: DAP = days after planting.

†Within cultivars and water levels, means with different lowercase letter in each column were significantly different at $P < 0.05$.

¶Aboveground biomass is expressed as oven-dried.

For wheat, LCC for a healthy green flag leaf at the time of anthesis is typically 40-60 (Pask et al., 2012). This range was true for the current study, though leaf chlorophyll was measured at 40 DAP (before anthesis). Talebi (2011) found that drought tolerant genotypes had higher LCC compared with other genotypes under different moisture conditions. In this study, LCC was higher for the newer cultivars suggesting that the newer cultivars were more drought tolerant. LCC decreased from high to low water level, which agrees with Changhai et al. (2010), who grew four varieties of winter wheat in Northern China and found that the total LCC of all cultivars was significantly decreased as the water level decreased or the drought condition increased. Zaharieva et al. (2001) reported that LCC before initiation of leaf senescence in wheat was positively correlated to biomass and grain yield per plant. This type of relation was not found, which might be because plants were harvested at vegetative growth stage. In most natural plant communities, total leaf area is positively correlated with leaf N and chlorophyll concentrations, and there is a close link between LCC and leaf N content (Yoder and Pettigrew-Crosby, 1995). Hence, having more chlorophyll, plants at high water might be able to utilize soil nitrogen more effectively, thereby producing more biomass than the plants at low water. Also, higher levels of chlorophyll, and hence, the photosynthesis might trigger plants at high water level to produce more biomass. Total chlorophyll content per leaf area unit may be a good indicator of the strength of photosynthetic tissue (Nageswara et al., 2001; Fotovat et al., 2007). Higher LCC associated with the modern cultivars indicates that they have the better photosynthetic capacity compared to the old cultivars; however, aboveground biomass was not different among the cultivars.

4.4.3 Leaf Relative Water Content

Leaf relative water content, a measure of water deficit in the leaf was significantly ($P < 0.05$) influenced by the main effect of water (Table 15). At 25 DAP, LRWC for plants growing at high and low water was 93% and 88.9%, respectively. Similarly, it was 94.2% for plants at high water and 91.7% for plants at low water at 35 DAP. LRWC among wheat cultivars was neither significantly different for each DAP, nor consistent between two DAPs (Tables 15 and 16).

Drought resistant plants have been described as those having a relatively small change in leaf water content per unit change in leaf water potential. Typical values of LRWC range between 98% in turgid and transpiring leaves to about 40% in severely desiccated and senescing leaves (Pask et al., 2012). Since none of the plants were severely water stressed, LRWC values in the current study ranged from 88 to 97%. Leaf RWC is related to transpiration rate (Nordin, 1976), an important indicator of water status under drought conditions (Sinclair and Ludlow, 1985). The current study did not find differences in LRWC among the wheat cultivars, though modern cultivars had relatively higher LRWC than intermediate and old cultivars at 35 DAP. Fischer (1973) found that LRWC was directly related to soil water content and suggested that LRWC might also be used to indicate soil water content. In our study, since high water treatment had more soil water, associated plants had significantly higher LRWC than the plants growing at low water level.

4.4.4 Aboveground Biomass

Aboveground biomass was significantly ($P < 0.05$) affected by water treatment, (Table 15), where plants growing at high water produced mean biomass of 96.4 g box^{-1}, and plants at low water produced 65.1 g box^{-1}. Though there was no statistical difference ($P > 0.05$) among the cultivars, Triumph 64 produced highest amount of biomass, 93.7 g box^{-1}, while TAM 105 produced the lowest, 66.8 g box^{-1} (Table 16).

Much of the significant yield improvement in many modern crops and cultivars has been associated with increase in HI. By developing plants of shorter structure and large grain heads the HI, and consequently the yield, of many cereals has been substantially increased. The approach of Green Revolution in 1960s was also associated with the development of widely adapted cultivars of wheat and rice that had significant increased HI (Sinclair and Weiss, 2010). Slafer and Andrade (1989) grew six wheat cultivars released between 1912 and 1980 in Argentina and reported no difference in aboveground biomass among them. In the U.K., release of successive wheat cultivars has not resulted in increased biomass production, but HI was increased from about 0.35 before 1940 to about 0.5 in 1980 (Sinclair and Weiss, 2010). Perry and D'Antuono (1989) grew 28 Australian wheat cultivars released from 1860s to 1982 in 20 field trials over four years. Grain yields were measured on all trials, and six trials were also sampled for biomass and yield components. When comparing older to newer cultivars, aboveground biomass appeared to have increased slightly, but over 80% of the overall increase in grain yield was due to increase in HI. Austin et al. (1989) grew 13 winter wheat cultivars over three years and reported that modern wheat cultivars yielded 59% more grain yield, but only 6% more total aboveground biomass than very old cultivars. After comparing old and modern cultivars, similar results (higher grain yield and HI in modern cultivars) were reported by (Riggs et al., 1981) in barley and Lawes (1977) in oat.

Above mentioned studies reported biomass at harvest after grain maturity and they suggested that there was little or no increase in aboveground biomass from older to newer wheat cultivars. In the current study too, statistically significant differences were not found in biomass production among wheat cultivars during vegetative growth.

4.4.5 Water Use Efficiency and Transpiration Efficiency

Biomass water use efficiency was significantly ($P < 0.05$) affected by the main effect of water (Table 15). Plants growing at high and low water levels had WUEs of 2.40 kg m^{-3} and 2.15 kg m^{-3}, respectively. Though WUEb was not different ($P > 0.05$) among the cultivars, there was a trend that the WUEb increased from modern to the older cultivars. Scout 66 had the highest WUEb of 2.40 kg m^{-3} and TAM 111 had the lowest WUEb of 2.15 kg m^{-3} (Table 16). Cumulative water used during the crop period was not significantly different ($P > 0.05$) among the cultivars (Table 15 and 16).

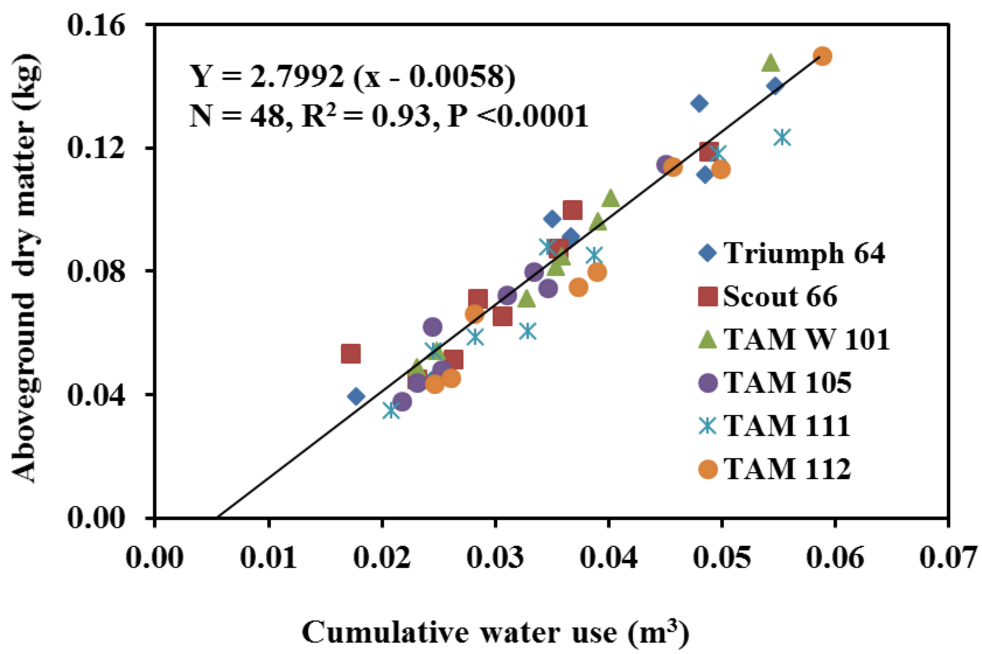

Figure 20. A linear regression between aboveground dry matter and cumulative water used for all cultivars at vegetative growth (i.e. 62 days after planting).

The data presented in Figure 20 did not result in the regression line passing through the origin indicating that there was some evaporation, mainly because boxes were not well sealed with lids. As a result, the original regression equation ($Y = 2.7992x - 0.0164$) had a negative intercept. Since output (aboveground biomass) cannot be negative even at zero level of input (water) used, Y value was set to zero to find the value of x. The transformed equation was Y = 2.7992 (x – 0.0058), which indicated that on average 0.0058 m^3 (5.8 L) of water was lost from each box in the form of evaporation. Hence, total water used during the crop season could not be attributed to transpiration, and data were reported as WUE values rather than TE values. WUE values were comparable to previous wheat field studies such as, 2.3-3.3 kg m^{-3} (Zhang et al., 1998) and 1.8-2.0 kg m^{-3} in first experiment and 1.9-3.4 kg m^{-3} in second experiment (Huang et al., 2005). However, good evaporation control in the present study is indicated by a small y-axis intercept, and the high regression coefficient suggests a good fit of the observed data and the liner regression (Haefele et al., 2009). Therefore, the slope of the line has been used as an estimate of TE. On average, wheat plants produced ~2.8 kg of aboveground dry matter for every cubic meter of water used (i.e. 1 g of dry matter per 357 g of water). This value is close to the TR value suggested by Sinclair and Weiss (2010). They state that the TR of C_4 crops (sorghum, corn) is about 220 g water for each gram of biomass produced, when growing in an average transpiration environment of 2 kPa, but for C_3 crops like wheat, the TR is about 1.5 times greater than that for C_4 crops. According to Ehlers and Goss (2003), as neither the growth period, nor the total biomass production have changed decisively in modern wheat cultivars, the cumulative transpiration as well the TE are left more or less untouched. However, because of the increase in harvest index in modern cultivars, the TE related to grain yield has been improved. This argument about TE can be supported to the current study, because plants were grown under similar environmental conditions, evaporation was minimized, and WUE values among the cultivars were not different.

4.4.6 Conclusions

Leaf chlorophyll, aboveground biomass, and WUE were significantly higher for the plants growing at high water level than those at low water level. Aboveground biomass had a linear relationship with cumulative transpiration. Adoption of plant cultivars with higher yield and WUE under drought conditions is paramount. Early studies indicate that an increase in grain yield for modern cultivars is mainly derived from the increase in harvest index keeping the total aboveground biomass constant. Since the harvest index of wheat is as high as 0.36 in the U.S. Southern High Plains (Xue et al., 2014), WUE values for each cultivar may differ from vegetative growth stage to reproductive and grain formation growth stage. Hence, this study suggests for further studies evaluating wheat WUE at grain maturity stage.

CHAPTER V

THINKING IN SYSTEMS

5.1 Systems Thinking in Agriculture

Systems can be defined as a group of interacting components that conserve some identifiable set of relations with the sum of the components plus their relationships (i.e. a system itself) conserving some identifiable set of relations to other entities (Laszlo and Krippner, 1998). Systems thinking is a transdisciplinary framework for seeing interrelationships rather than only the components, and patterns of changes rather than static snapshots (Nguyen and Bosch, 2012). Compared to other approaches, use of a systems thinking approach helps to leverage management complexity more effectively (Bosch et al., 2013). Stakeholders and decision-makers use it to move from the event level to deeper levels of thinking and develop a systematic framework to deal with complex problems (Bosch et al., 2007).

Systems approach has been used as a tool for problem solving, by viewing "problems" as parts of an overall system, rather than reacting to specific parts, outcomes or events, and thereby potentially contributing to further development of unintended consequences (Wikipedia, 2015). It does not jump to solutions quickly, rather it takes time to think and analyze the issue fully before reaching a conclusion. Identification of leverage points, “the point of power”, is the key part of the problem solving (Bertalanffy, 1972; Vayghan, 2012). Systems approach further helps to distinguish between the theoretical concepts and their interrelationships, and to build ideas useful for handling real-world situations (Laszlo and Krippner, 1998).

According to Meadows (2008), the basic characteristics of systems that work well are resilience, self-organization, and hierarchy. Resilience is the ability for a system to bounce back into shape or adjust to change. Modern farming practices such as monoculture of crops makes the system vulnerable to disease and pest, hence may not be considered resilient. Self-organization is the ability of a system to organize itself and build complex structures from simple building blocks (i.e. DNA and RNA as building blocks of life), and hierarchy describes how complex systems can be broken into smaller, simpler organization that can function autonomously (Meadows, 2008). Today, systems approach has been adopted extensively in the fields of agriculture, environment, education, health, business, policy analysis, natural resource management, and various aspects of organizational management (Cavana et al., 1999; Rosser, 2001; Wilson, 2004; Elias, 2008).

Agriculture in the 21st century faces multiple challenges. It has to produce 70% more food to feed an estimated nine billion people by 2050 (FAO, 2009). Addressing these challenges requires moving from a conventional "linear" way of thinking to "systems thinking" that brings thought and behavior into line with the natural laws of sustainability (Banson et al., 2014). Bawden (1991) explained the importance of systems thinking and practice in agriculture, and the need of innovative research design, agro-ecosystem analysis, and extension to solve the multiple agricultural problems. Ikerd (1993) suggested that systems approach helps in designing sustainable farming strategies that take care of every component/sub-system of farming and balances environmental soundness, economic viability, and social equity. Further, systems thinking is a way to conceptualize and act towards the integration of economic, social, and environmental dimensions of agricultural sustainability, which support farming communities to improve both human and ecosystem well-being (Nguyen and Bosch, 2012).

Everything starts with a cause, a cause leads to effect, and the effect leads to another cause, another cause leads to another effect, and the process goes on and on (Banson et al., 2014). Feedback loops describe the cause and effect relationships between various components of a system (Bettis and Prahalad, 1995). Reinforcing feedback is when changes in elements of the system are fed back and result in an amplification of the change. Balancing feedback is when changes in elements of the system are fed back opposing the original change result in a dampening effect (Banson et al., 2014). Because of the complex nature of interactions and multiple feedback loops, conditions of farming in a particular farm change continuously. Changes may occur in bio-physical properties (soil fertility), ecological processes (insect populations), economic variables (market prices), characteristics of individuals (farmers' interest in experimenting), and social dynamics (cohesion and trust in a group). It means various interactions jointly affect the behavior of farming system over time (Noe and Alroe, 2012).

The first step in a systems approach to farm management is to identify the boundaries of the system to be managed (Bird et al., 1984). The purpose in establishing boundaries is to separate those things which are considered as part of a system from those things which are considered as an external environment. However, things in the external environment may affect the system or be affected by the system. Thus, system boundaries do not imply mutual independence between things inside and outside them, rather it serve to sharpen the perception of interdependence between systems and their external environment (Ikerd, 1993). Further, systems approach focuses on the farm as a whole, as well as on the interrelationships among its components (Bawden, 1991; Laszlo and Krippner, 1998). Though farm planning and management in systems agriculture is complex, potential for synergistic gains lies within this complexity (Ikerd, 1993).

Systems are the key distinction from traditional reductionist approaches, which focuses on analyzing each part of the system individually such as, animal nutrition, animal health, fertilizer application, and plant growth. These separate parts are conceptualized as an assemblage of fairly isolated mechanistic elements that are determined by linear cause and effect relationships. For example, an appropriate fertilizer when applied in adequate rate may lead to better plant growth. Similarly, in reductionist approaches, a farmer is considered as agent who works individually and makes farming decisions independently, while systems approach seeks to understand how a group of farmers interact and influence the behavior of one another (Roling and Jiggins, 1998).

It has been widely accepted that the reductionist approach failed in developing appropriate technologies for resource-poor farmers in less favorable production environments. This led to the incorporation of a systems perspective in the identification, development, and evaluation of relevant improved technologies (Norman, 2002). A wide range of approaches to agricultural innovation has emerged over the past few decades, including Participatory Research (Farrington and Martin, 1988), Farming Systems Research (Norman, 2002), Training and Visit System (Hulme, 1992), Induced Innovation (Ruttan and Hayami, 1984), Farmer First (Chambers et al., 1989), and Agricultural Knowledge and Information Systems (Roling, 2009).

5.2 Systems Approach in Dryland Study

Every component of systems is connected to each other in such ways that their complex interrelationships give rise to a sense of wholeness (Laszlo and Krippner, 1998). The strength that emerges through the interrelationships of the parts makes system different from the sum of its parts. This means every system is a collection of interacting subsystems. It is important to note that not only does the farming system as a whole have a purpose, but its parts may also have purposes of their own. The dynamics and interactions, thus lead to emergent properties and behaviors of the system as a whole (Darnhofer et al., 2012). In dryland agriculture, numerous factors are constantly interacting, so there is no easy way to clearly explain how all of these interactions produce a result. It means research in dryland agriculture consists of two or more interacting and influencing factors that largely determine the outcome of the study.

Increasing concerns related to degradation of biophysical, socioeconomic environments, and cultural environments are often associated with agricultural practices (Bawden, 1991; Ikerd, 1993). Addressing these problematic relationships between agriculture and the environmental factors is complex. Introduction of systems thinking and practices helps researchers to think about the wholeness of a particular farming system, find the interrelationship between and among the components, design innovative research methods, and potentially rebuild the farming system. Systems approach challenges researchers to seek alternative ideas on farm planning, management, and technology innovation that could be new experiences for them (Bawden, 1991).

Sustainable dryland farming requires a holistic approach to farm planning and management. Whole systems have qualities and characteristics not present in any of their constituent parts; therefore, one must seek to understand the greater whole in order to understand its parts, not vice-versa (Savory, 1988). Systems take on values in and of themselves through the process of synergism. Synergism then is a process by which resources and inputs are rearranged spatially, temporally, physically, and individually in order to create more valuable wholes. In reality, the dimensions of time, space, form, and ownership are inseparable. Thus, a holistic systems approach to farming is a matter of managing the temporal, spatial, physical, and individual arrangements of interrelated sets of resources, inputs, products, markets, people, and processes (Ikerd, 1993).

Sustainable dryland agriculture must be capable of maintaining its productivity and usefulness to society indefinitely. Such agriculture must use farming systems that conserve resources, protect the environment, produce efficiently, compete commercially, and enhance the quality of life for farmers and society overall. Systems, which fail to conserve and protect their resource base, will degrade its productivity and eventually lose their ability to produce. Not only the dryland, but also any farming system, which fails to provide the people with adequate supplies of safe and healthy food at reasonable costs and otherwise enhance the quality of life, cannot be considered sustainable (Ikerd, 1993).

Fallowing, seed rate, cultivar selection, planting date, and planting geometry are some of the key aspects that largely determine crop growth and yield in dryland agriculture. Dryland agriculture is considered more challenging than any other farming system mainly due to the lack of adequate water. Addressing the problematic relationships between agriculture and the environmental factors is not an easy task. Compared to other research, dryland research may be more complex, more expensive, and usually time consuming to identify such relations and the nature of interaction. The researcher should understand this complexity and be able to define the pattern of relationship, which is only possible through the systems approach (Bawden, 1991). The researcher should ask himself/herself - which system is being investigated? What are the environmental impacts associated with that system (for example, a commercial farm)? How can the impacts be minimized? How to measure the impact or the improvements? Similarly, what should be and what could be are some of the other basic questions that should be analyzed critically (Bawden, 1991). Addressing these questions should help to understand the interaction among the various components, address the problems, and improve the farm productivity.

Systems thinking provides a model of decision-making that helps researchers or organizations effectively deal with problems. Understanding the concepts and approaches of systems helps researchers to realize why they need to know the connections among different components of farming. For example, agriculture is not only about plant, soil and water, but it has vital connections with economics, management, animal husbandry, and the environment. Without understanding the interconnections among them, a researcher may not be able to work effectively in identifying and solving agricultural issues, which are often vague and complex. Similarly, one has to begin with understanding the problems of farmers from the perspectives of farmers; and the solutions should be based on a proper understanding of their objectives and their environments, including both biophysical and socioeconomic components. Systems thinking in research advocates that the farmer, a part of a whole system, should participate in research and innovation processes not only because they have a right to be involved, but also their knowledge and experiences play a vital role during the entire process of investigation and result dissemination. Further, scientists involved in the process should represent both technical and social scientists, and the process should by nature be iterative (Norman, 2002).

Most of the approaches or models that are used today are of linear types. However, system thinking focuses on cyclical rather than linear cause and effect (Sherwood, 2002). Remaining other factors constant, what we often think is if 25 kg fertilizer within a unit of land gives 1,000 kg grain yield, 50 kg would give 2,000 kg grains. This only happens in linear models, which are often furnished with mathematical equations, and are applied in the areas where resources (mainly water and soil nutrients) are not limiting for growing crops. But in dryland areas, 50 kg fertilizer could end up with less than 2,000 kg grains, because water became limiting or we might have damaged the soil and plant health using too much fertilizer, or it can be higher than 2,000 kg because it might have achieved the output maximization level of inputs (water and nutrient). Meadow (2008) in her book "Thinking in Systems" explained this phenomenon as a "Linear Minds in a Nonlinear World" and pinpointed it as one of the reasons for why systems surprise us. Some of the current innovations in systems approach such as farming system research and participatory research that recognizes farmers' experiences, knowledge, and skills are important in dryland areas to be introduced to make the production system viable.

5.3 Systems Approach in Current Studies

An agricultural system is an assemblage of components, which are united by some form of interaction and interdependence and operate within a prescribed boundary to achieve a specified agricultural objective on behalf of the beneficiaries of the system (FAO, 2015). Current studies evaluate how microclimate and transpiration efficiency in dryland crops are influenced by the planting geometry, growth stage, and cultivar at different water levels and soil surface types. Interrelationship (feedback loops) of these factors forms a system with a pattern of behavior regarding the crop growth and yield. It has a pre-set boundary and the components inside the boundary as given in Figure 21, which determine the behavior of the system, though the factors that are outside the boundary can also influence the system. For example, the market price and government policy are not included in the model, but they directly or indirectly influence crop production. Current studies include systems hierarchy; several other small subsystems lie within the whole system. For example, a plant within a big system (research project) is a sub-system. Plants are composed of tiny cells and each cell represents another sub-system.

As drought increases, soil moisture decreases, then, use of mulch, plantation of drought resistant cultivars, and adoption of clump geometry are expected to increase. Clump geometry reduces the vegetative growth, and increases the harvest index. However, because of the increased free space (soil surface) between clumps, soil evaporation could be increased (Figure 21). Drought is largely influenced by precipitation, so as the precipitation increases, drought decreases. It is generally understood that a drought is a prolonged water shortage relative to the climatic norm at a location, but the necessary length of time for a dry period to become a drought is not universally defined and may ultimately depend upon local circumstances and impacts (Maliva and Missimer, 2012). Increase in precipitation increases soil moisture and decreases drought (Figure 21).

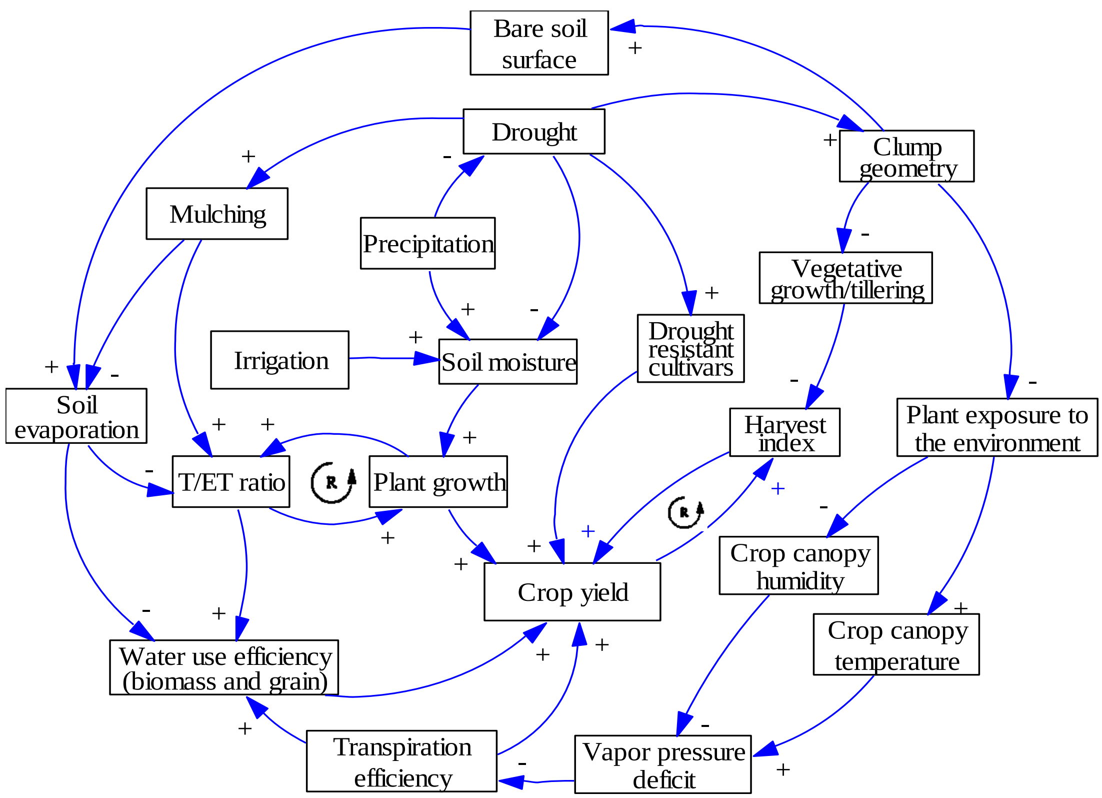

Figure 21. Causal loop diagram for the current studies. T = transpiration, ET = evapotranspiration.

Plant growth and development in water deficit areas largely depend on the availability of soil moisture. Irrigation increases the soil moisture and finally the plant growth and crop yield (Figure 21). For example, in study 1 (2-yr greenhouse study), compared to low water level, average sorghum grain yield at high water level was significantly higher by 47.3 g box^{-1} (63%). Similarly, in study 2 (Gruver field study), corn grain yield significantly increased from low (4.67 Mg ha^{-1} [2.08 ton ac^{-1}]) to medium (13.09 Mg ha^{-1} [5.84 ton ac^{-1}]) to high irrigation (14.97 Mg ha^{-1} [6.68 ton ac^{-1}]) treatments. Dryland crops often face challenges in obtaining an adequate supply of water to meet their metabolic demands. Soil properties like texture and structure, pH, and compaction may influence the soil environments for plants obtaining water. In fact, many plants have evolved water uptake mechanisms even during the drought condition that are adapted to local environmental conditions and producers in the area adopt them as drought resistant cultivars (Figure 21). Though modern wheat cultivars used in study 4 (wheat study) were more drought tolerant than other cultivars, their production performances under different (low and high) water regimes were not known because plants were harvested at vegetative growth stage.

Although finding sufficient mulching materials such as vegetation or crop debris is challenging in the dryland farming areas, mulch helps to reduce evaporation and make more water available for plant transpiration (i.e. higher T/ET ratio). As the transpiration increases, plant growth increases and as the plant growth increases, there would be more transpiration, so a reinforcing feedback loop exists here. Similarly, when the transpiration increases, WUEb also increases, which leads to better crop yield (Figure 21). For straw mulch and bare surface treatments, the mean biomass water use efficiency (WUEb) values were 3.60 kg m^{-3} and 2.08 kg m^{-3} and grain water use efficiency (WUEg) values were 1.64 kg m^{-3} and 0.97 kg m^{-3}, respectively, suggesting a 42.2% and 40.7% reduction in WUEb and WUEg, respectively, when soil surface was changed from straw mulch to bare. As a result, grain yield with straw mulched treatment was significantly higher by 59% compared to bare soil surface with the same plant population.

Clump geometry in studies 1 and 2 increased grain yield relatively but the harvest index (HI) significantly. Greater HI in clumps was mainly because of clumps producing fewer tillers compared to the conventional evenly spaced planting (ESP). Further, clump geometry showed potential in improving the microclimate within the crop canopy by decreasing temperature and increasing humidity, thereby decreasing the vapor pressure deficit (VPD). As hypothesized, plants in clumps were less exposed to the environmental conditions (wind, temperature, and solar radiation) compared to the plants in ESP. This is important when plants are grown under hot, dry, and windy environments. In study 3 (greenhouse and growth chamber studies), as the VPD increased, transpiration efficiency decreased (Figures 19 and 21). That was likely be a reason for clumps producing relatively higher grain yields compared to ESPs in studies 1 and 2.

CHAPTER VI

SUMMARY AND PERSPECTIVES

Improvements in microclimate within plant canopy while growing sorghum and corn plants in clumps are the key findings of the current study (Studies 1 and 2). Similar TE at different growth stages of sorghum, which is significantly affected by the growing period VPD is the second important knowledge delivered by the study (Study 3). Thirdly, the study shows that there was no difference in water use efficiency between old and modern wheat cultivars (Study 4).

The challenge of increasing crop productivity and production stability while conserving the resources and, at the same time, maintaining economic viability as well as environmental quality is the primary concern for agriculture researchers. In order to improve crop yields, various production systems and management practices have evolved, and this is also true for semi-arid regions, where some forms of dryland farming occur. Since dryland agriculture is water-limited, majority of the improvements are focused on improving the efficiency of water use, particularly how to use a high proportion of the limited precipitation for transpiration.

Results suggest that plants providing shade for each other is the primary mechanism for improving the microclimate when crops are grown in hot and water deficit environments. As hypothesized, plants in clumps created mutual shading and exposed less leaf area per plant to the environment. Consequently, clumps consistently showed lower canopy temperature and within canopy VPD than conventional ESPs under different water regimes and soil surface types. Overall, compared to ESPs, clumps produced less biomass, mainly by reducing the number of tillers and increased relatively the grain yield, but significantly increased the HI. Hence, clump geometry appeared to be a potential alternative for commercial production.

Implementation of clump geometry requires no additional inputs, though it does require adjusting or modifying some equipment such as seed plates, which can drop required number of seeds (usually three seeds for corn and four seeds for sorghum) at a time or very close together. Due to the increased surface area between and among the clumps, potential evaporative loss as well as weed pressure could be greater for clump geometry. Hence, adoption of crop management practices such as using mulch, or growing crops in fields covered with crop residues is suggested when adopting clump geometry to make it more viable. Further, minimum tillage (no-till) may help conserve the soil moisture and make it available to plants. These practices also reduce runoff by increasing retention time and the soil infiltration rate.

Current studies (except wheat study) were conducted with a single cultivar in sorghum (DK-S36), and Pioneer (P1151AM) and Syngenta (N42Z-3111A) hybrids in corn. So, it could be interesting to grow different cultivars and study if cultivar × planting geometry interaction exists. Though there are plenty of studies investigating cultivar × row spacing interaction with mixed results, adding geometry could give some useful scientific evidence. Based on the past and current results, one of the main reasons for having higher grain yield and HI in clump geometry was the production of fewer tillers, because tillers utilize water and nutrient but, in drylands, often produce little or no grains.

Since the formation of tillers differs from hybrid to hybrid (Caravetta et al., 1990), different hybrids could perform differently in clump geometry.

Transpiration environment mainly depends on four factors; namely how hot it is, how sunny it is, how windy it is, and how dry the air is (Stewart and Peterson, 2015). Current studies documented and analyzed the temperature and humidity data from clumps and ESPs. There is still room to study and compare differences in wind pressure or wind speed within the plant canopy for the clumps and ESPs. Research questions for clump geometry associated with the methods and timing of fertilizer application, nutrient use efficiency, and grain nutrient content would add value in further studies.

The challenge for global agriculture in the 21st century is to produce 70% more food and fiber by 2050 for a growing and more prosperous population, while implementing more sustainable methods of farming and responding to climate change (FAO, 2009). Dryland agriculture continues to be the main engine for food production and economic growth in many parts of the world. However, recent years have been tumultuous for the agricultural sector, mainly due to the increasing climatic abnormalities. Though risks faced by farmers are numerous and varied, and are specific to the country, climate, and local agricultural production systems, dryland producers are exposed to a high degree of production risk. Further, price volatility has increased with sharp swings in product and input prices, and pest and disease outbreaks are reported increasing. Hence, risk management in dryland agriculture should be a vital tool for farmers to plan, avoid, and react to shocks. Favorable government policies are essential that support dryland growers to implementing risk management strategies namely risk mitigation (crop diversification, cultivar selection, use of mulch, vertical integration, integrated pest and nutrient management, etc.), risk transfer (insurance, contracting, hedging, etc.), and risk coping (off-farm income, selling assets, borrowing from banks, etc.).

The most vulnerable regions to drought are located in Sub-Saharan Africa and Central Asia where the vast majority of the poor people depend on agriculture. Farmers often have very few options in terms of crop choice. The agriculture in these regions is less mechanized and most of the agronomic practices right from land preparation to planting, weeding to harvesting and threshing are done manually. Promotion of clump geometry could be worthy in these dry regions to minimize the production risk. Further, growing plants in clumps may save planting time, where planting is done manually.

The intercropping of beans or cowpeas with corn is a common farming practice in the tropics (Kyamanywa, 1988). With the same plant populations, compared to ESPs, clumps leave more free space for other crops. Hence, inter-crops may perform better due to increased light interception into the field as well as less competition with the major crops for space, light, nutrient, and water. Intercropping, on the other hand may help to reduce weed pressure, one of the limitations of clump geometry. Further, since shading in crop plants creates unfavorable environment for insect colonization resulting increased emigration and mortality (Perrin and Phillips, 1978; Baliddawa, 1985), compared to conventional ESPs, clumps may have lesser insect infestation, where insect/pest results considerable yield loss in sorghum and corn.

Finally, there was no overwhelming evidence to suggest that clump geometry would result in large changes in crop yield, but it consistently improved the microclimate and increased the grain yield and HI with no additional input costs. Dryland agriculture is considered more fragile than any other farming systems, where even a small improvement in grain yield is hard to achieve, but it may be possible through growing plants in clumps. However, there is no single and effective strategy for successful dryland agriculture, and developing recommendations for optimizing crop yield is not an easy task. Based on the resource availability, crop diversity, and local problems and potentialities, dryland farming systems necessitate a holistic systems approach combined with different good practices to the level best. A systems approach is further essential to analyze the complexity of interaction among the various components of dryland farming, and find the leverage point, where actions and changes in structures can lead to significant, enduring improvements. The ultimate goal is how to make dryland farming system more adoptable, profitable, and less risky business in times of climate change.

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APPENDIX

Table 1. Raw data for sorghum greenhouse study (STUDY 1).

Rep.	Geo.	Water level	Soil surface	Leaf area (cm^2 $plant^{-1}$)	Dry biomass (g)	Dry grain (g)	HI	WUEb (g kg^{-1})	WUEg (g kg^{-1})	TEb (kg m^{-3})	TEg (kg m^{-3})
R1	Clump	High	lid	998.4	294.2	144.4	0.49	5.25	2.58	5.49	2.58
R1	Clump	High	straw	806.3	233.4	117.8	0.50	3.93	1.99	-	-
R1	Clump	High	bare	410.0	91.3	54.0	0.59	1.55	0.92	-	-
R1	Clump	Low	lid	1015.9	214.4	91.3	0.43	6.32	2.69	5.54	2.69
R1	Clump	Low	straw	194.9	69.5	32.8	0.47	1.89	0.89	-	-
R1	Clump	Low	bare	150.0	36.3	14.5	0.40	0.96	0.38	-	-
R1	ESP	High	lid	1053.1	348.0	146.8	0.42	6.00	2.53	6.16	2.53
R1	ESP	High	straw	730.4	237.2	121.4	0.51	4.08	2.09	-	-
R1	ESP	High	bare	309.1	131.2	60.9	0.46	2.30	1.07	-	-
R1	ESP	Low	lid	881.6	212.4	87.9	0.41	6.37	2.64	5.87	2.64
R1	ESP	Low	straw	277.3	94.3	47.4	0.50	2.50	1.26	-	-
R1	ESP	Low	bare	190.6	30.3	11.9	0.39	0.82	0.32	-	-
R2	Clump	High	lid	1190.5	292.2	140.4	0.48	5.03	2.42	5.35	2.38
R2	Clump	High	straw	790.8	227.2	118.9	0.52	3.81	1.99	-	-
R2	Clump	High	bare	425.9	105.7	38.1	0.36	1.70	0.61	-	-
R2	Clump	Low	lid	1006.3	177.2	76.7	0.43	4.92	2.13	4.73	2.13
R2	Clump	Low	straw	327.8	96.0	42.2	0.44	2.58	1.13	-	-
R2	Clump	Low	bare	106.6	38.0	14.7	0.39	1.04	0.40	-	-
R2	ESP	High	lid	1158.8	281.1	141.1	0.50	4.78	2.40	5.42	2.40

Table continued……

Rep.	Geo.	Water level	Soil surface	Leaf area (cm^2 plant^{-1})	Dry biomass (g)	Dry grain (g)	HI	WUEb (g kg^{-1})	WUEg (g kg^{-1})	TEb (kg m^{-3})	TEg (kg m^{-3})
R2	ESP	High	straw	753.3	225.0	105.8	0.47	3.68	1.73	-	-
R2	ESP	High	bare	339.3	118.2	47.5	0.40	1.99	0.80	-	-
R2	ESP	Low	lid	1036.7	185.4	89.3	0.48	5.25	2.53	4.91	2.53
R2	ESP	Low	straw	451.1	85.4	38.2	0.45	2.38	1.06	-	-
R2	ESP	Low	bare	168.2	47.0	18.0	0.38	1.38	0.53	-	-
R3	Clump	High	lid	1044.4	301.0	129.6	0.43	5.12	2.21	4.91	2.21
R3	Clump	High	straw	781.9	210.4	101.0	0.48	3.55	1.70	-	-
R3	Clump	High	bare	278.2	120.4	59.3	0.49	2.08	1.02	-	-
R3	Clump	Low	lid	864.9	190.1	76.9	0.40	5.09	2.06	4.88	2.06
R3	Clump	Low	straw	436.1	103.4	43.1	0.42	3.13	1.31	-	-
R3	Clump	Low	bare	144.1	41.0	19.1	0.46	1.11	0.52	-	-
R3	ESP	High	lid	1170.3	304.0	112.2	0.37	5.35	1.97	4.75	1.97
R3	ESP	High	straw	806.5	211.3	107.1	0.51	3.50	1.78	-	-
R3	ESP	High	bare	287.3	106.0	54.9	0.52	1.78	0.92	-	-
R3	ESP	Low	lid	1034.4	195.2	62.8	0.32	5.36	1.72	5.06	1.72
R3	ESP	Low	straw	607.3	100.5	26.1	0.26	2.85	0.74	-	-
R3	ESP	Low	bare	204.5	36.2	12.9	0.36	0.96	0.34	-	-

Table 2. Raw data for sorghum greenhouse study (STUDY 1).

Rep.	Geo.	Water level	Soil surface	Leaf area (cm^2 $plant^{-1}$)	Tiller no. ($plant^{-1}$)	Dry biomass (g)	Dry grain (g)	HI	WUEb (g kg^{-1})	WUEg (g kg^{-1})	TEb (kg m^{-3})	TEg (kg m^{-3})
R1	Clump	high	lid	1767.9	0.50	404.31	203.5	0.50	5.49	2.76	5.49	2.76
R1	Clump	high	straw	1516.5	1.00	317.32	136.7	0.43	4.17	1.86	-	-
R1	Clump	high	bare	1352.5	0.00	217.19	105.8	0.49	2.82	1.39	-	-
R1	Clump	low	lid	1309.9	0.00	322.31	161.3	0.50	5.54	2.09	5.54	2.77
R1	Clump	low	straw	1260.2	1.50	259.76	108.6	0.42	4.25	1.87	-	-
R1	Clump	low	bare	550.8	0.00	149.15	84.6	0.57	2.45	1.38	-	-
R1	ESP	high	lid	2098.5	1.33	453.66	228.7	0.50	6.16	3.65	6.16	3.11
R1	ESP	high	straw	2473.0	1.83	371.67	141.0	0.38	4.93	1.92	-	-
R1	ESP	high	bare	1062.9	0.50	223.67	110.0	0.49	2.90	1.46	-	-
R1	ESP	low	lid	2280.8	1.50	349.24	151.6	0.43	5.87	1.96	5.87	2.55
R1	ESP	low	straw	1717.6	1.83	285.78	123.8	0.43	4.68	2.08	-	-
R1	ESP	low	bare	1264.7	1.00	197.55	87.9	0.44	3.22	1.44	-	-
R2	Clump	high	lid	1558.7	1.00	397.03	211.0	0.53	5.35	3.46	5.35	2.84
R2	Clump	high	straw	1187.0	0.17	273.46	143.1	0.52	3.62	1.93	-	-
R2	Clump	high	bare	874.2	0.17	213.76	101.7	0.48	2.77	1.35	-	-
R2	Clump	low	lid	1218.6	0.50	282.73	132.6	0.47	4.73	1.72	4.73	2.22
R2	Clump	low	straw	990.2	0.33	215.69	108.8	0.50	3.52	1.82	-	-
R2	Clump	low	bare	741.2	0.33	143.18	76.3	0.53	2.30	1.25	-	-
R2	ESP	high	lid	2187.2	1.50	413.39	176.6	0.43	5.42	2.88	5.42	2.32
R2	ESP	high	straw	1829.9	1.50	313.31	129.6	0.41	4.11	1.70	-	-

Table continued……

Rep.	Geo.	Water level	Soil surface	Leaf area (cm^2 plant^{-1})	Tiller no. (plant^{-1})	Dry biomass (g)	Dry grain (g)	HI	WUEb (g kg^{-1})	WUEg (g kg^{-1})	TEb (kg m^{-3})	TEg (kg m^{-3})
R2	ESP	high	bare	1169.2	0.83	251.15	111.9	0.45	3.22	1.47	-	-
R2	ESP	low	lid	1953.3	2.00	294.56	111.6	0.38	4.91	1.43	4.91	1.86
R2	ESP	low	straw	1584.5	1.50	259.47	115.2	0.44	4.18	1.92	-	-
R2	ESP	low	bare	755.9	0.50	149.62	69.0	0.46	2.42	1.11	-	-
R3	Clump	high	lid	1342.5	0.17	361.38	195.2	0.54	4.91	3.13	4.91	2.65
R3	Clump	high	straw	1283.1	0.33	294.64	130.9	0.44	3.84	1.78	-	-
R3	Clump	high	bare	993.6	0.50	203.25	100.4	0.49	2.62	1.31	-	-
R3	Clump	low	lid	1694.4	0.33	297.23	123.1	0.41	4.88	1.59	4.88	2.02
R3	Clump	low	straw	1491.5	1.00	237.05	102.5	0.43	3.85	1.68	-	-
R3	Clump	low	bare	643.4	0.00	144.43	68.8	0.48	2.31	1.12	-	-
R3	ESP	high	lid	2118.4	2.00	359.33	154.6	0.43	4.75	2.50	4.75	2.04
R3	ESP	high	straw	1809.9	1.00	299.68	128.2	0.43	3.87	1.70	-	-
R3	ESP	high	bare	1647.9	1.17	218.61	97.1	0.44	2.81	1.25	-	-
R3	ESP	low	lid	1675.1	1.00	307.98	127.3	0.41	5.06	1.63	5.06	2.09
R3	ESP	low	straw	1208.6	0.83	210.73	83.4	0.40	3.39	1.37	-	-
R3	ESP	low	bare	895.3	0.33	149.89	60.6	0.40	2.39	0.97	-	-

Table 3. Raw data for corn Gruver field study (STUDY 2).

Rep.	Geo.	Irrigation treatment	Dry biomass (Mg ha^{-1})	Grain at 15% moisture (Mg ha^{-1})	HI	Leaf area index (m^{2} m^{-2})	Tiller no. (plant^{-1})	WUEg (kg m^{-3})
R1	ESP	low	7.53	3.40	0.38	2.64	0.42	0.88
R1	ESP	medium	18.65	12.59	0.57	4.69	0.21	1.76
R1	ESP	high	19.68	13.87	0.60	4.7	0.00	1.24
R1	Clump	low	8.23	5.06	0.52	2.57	0.04	1.32
R1	Clump	medium	20.35	14.53	0.60	3.94	0.00	2.03
R1	Clump	high	24.52	16.04	0.55	4.32	0.00	1.44
R2	ESP	low	8.47	4.22	0.42	3.29	1.88	1.10
R2	ESP	medium	20.02	12.99	0.55	4.33	0.04	1.81
R2	ESP	high	21.87	15.59	0.60	4.99	0.00	1.39
R2	Clump	low	7.74	3.90	0.43	3.22	0.00	1.01
R2	Clump	medium	19.39	13.69	0.60	3.59	0.00	1.91
R2	Clump	high	22.07	14.89	0.57	3.97	0.04	1.33
R3	ESP	low	10.15	5.97	0.50	2.45	1.00	1.55
R3	ESP	medium	17.22	11.28	0.55	4.49	0.13	1.58
R3	ESP	high	20.59	14.81	0.61	4.28	0.04	1.33
R3	Clump	low	6.44	4.16	0.55	2.02	0.04	1.08
R3	Clump	medium	17.22	14.12	0.62	4.24	0.00	1.97
R3	Clump	high	21.71	15.12	0.59	4.59	0.00	1.35
R4	ESP	low	8.80	5.55	0.53	2.99	1.21	1.44
R4	ESP	medium	17.51	12.13	0.59	4.52	0.29	1.69

Table continued……

R4	ESP	high	20.38	14.30	0.59	4.90	0.00	1.28
R4	Clump	low	7.33	5.14	0.59	3.14	0.04	1.34
R4	Clump	medium	18.58	13.45	0.61	4.17	0.00	1.88
R4	Clump	high	23.63	15.14	0.54	4.81	0.00	1.35

Table 4. Raw data for corn Bushland field study (STUDY 2).

Rep.	Geo.	Tiller no. (plant^{-1})	LAI (m^2 m^{-2})	Dry biomass (Mg ha^{-1})	Grain at 15% moisture (Mg ha^{-1})	HI	WUEg (kg m^{-3})
R1	Clump	0.05	2.5	6.69	3.68	0.47	0.99
R1	ESP	0.08	2.7	7.27	4.00	0.47	1.04
R2	Clump	0.00	2.0	5.37	3.20	0.50	0.83
R2	ESP	0.20	2.5	6.34	3.42	0.46	0.86
R3	Clump	0.06	1.8	6.72	3.65	0.46	0.93
R3	ESP	0.20	2.2	6.84	3.43	0.42	0.87
R4	Clump	0.05	2.2	6.38	3.91	0.52	1.01
R4	ESP	0.03	2.7	6.72	3.71	0.47	0.95

Table 5. Raw data for sorghum greenhouse first study (STUDY 3).

Rep.	Plant growth stages	Water used kg)	Dry shoot (g box^{-1})	Dry root (g box^{-1})	Dry biomass (g box^{-1})	R:S ratio (g g^{-1})	TEshoot (kg m^{-3})	TEtotal (kg m^{-3})
R1	Six leaf stage	6.70	28.6	7.9	36.3	3.63	4.26	5.44
R1	Flag leaf stage	20.65	95.7	37.1	132.8	2.58	4.63	6.43
R1	Grain filling stage	44.95	198.8	43.5	242.3	4.57	4.42	5.39
R1	Grain maturity stage	50.95	259.4	47.5	306.9	5.46	5.09	6.02
R2	Six leaf stage	7.30	31.4	9.9	41.3	3.19	4.30	5.65
R2	Flag leaf stage	20.60	98.4	28.1	126.5	3.50	4.78	6.14
R2	Grain filling stage	45.10	192.9	38.1	231.0	5.06	4.28	5.12
R2	Grain maturity stage	52.90	237.4	48.4	285.8	4.90	4.49	5.40
R3	Six leaf stage	7.05	31.7	8.8	40.5	3.61	4.49	5.74
R3	Flag leaf stage	20.90	92.1	28.0	120.1	3.28	4.41	5.75
R3	Grain filling stage	43.70	196.1	37.6	233.7	5.22	4.49	5.35
R3	Grain maturity stage	51.75	247.7	42.3	290.0	5.86	4.79	5.60
R4	Six leaf stage	7.70	31.8	12.9	44.7	2.47	4.13	5.80
R4	Flag leaf stage	20.70	92.5	26.9	119.4	3.43	4.47	5.77
R4	Grain filling stage	44.30	203.2	40.3	243.5	5.04	4.59	5.50
R4	Grain maturity stage	51.10	231.1	38.8	269.9	5.96	4.52	5.28

Table 6. Raw data for sorghum greenhouse second study (STUDY 3).

Rep.	Plant growth stages	Water used kg)	Dry shoot (g box^{-1})	Dry root (g box^{-1})	Dry biomass (g box^{-1})	R:S ratio (g g^{-1})	TEshoot (kg m^{-3})	TEtotal (kg m^{-3})
R1	Six leaf stage	6.20	24.0	11.0	35.0	2.18	3.87	5.65
R1	Flag leaf stage	4.00	15.0	6.0	21.0	2.50	3.75	5.25
R1	Grain filling stage	5.65	25.0	11.0	36.0	2.27	4.42	6.37
R1	Grain maturity stage	4.30	16.0	6.0	22.0	2.67	3.72	5.12
R2	Six leaf stage	16.90	74.0	43.0	117.0	1.72	4.38	6.92
R2	Flag leaf stage	16.95	68.0	44.0	112.0	1.55	4.01	6.61
R2	Grain filling stage	17.80	74.0	47.0	121.0	1.57	4.16	6.80
R2	Grain maturity stage	14.70	58.0	36.0	94.0	1.61	3.95	6.39
R3	Six leaf stage	55.20	219.0	91.0	310.0	2.41	3.97	5.62
R3	Flag leaf stage	55.35	224.0	81.0	305.0	2.77	4.05	5.51
R3	Grain filling stage	55.50	237.0	95.0	332.0	2.49	4.27	5.98
R3	Grain maturity stage	55.65	238.0	89.0	327.0	2.67	4.28	5.88
R4	Six leaf stage	64.85	273.0	84.0	357.0	3.25	4.21	5.51
R4	Flag leaf stage	64.75	267.0	82.0	349.0	3.26	4.12	5.39
R4	Grain filling stage	66.20	275.0	84.0	359.0	3.27	4.15	5.42
R4	Grain maturity stage	65.75	262.0	75.0	337.0	3.49	3.98	5.13

Table 7. Raw data for sorghum growth chamber first study (STUDY 3).

Rep.	Plant growth stages	Water used (kg)	Dry shoot (g box^{-1})	Dry root (g box^{-1})	Dry biomass (g box^{-1})	S:R ratio (g g^{-1})	TEshoot (kg m^{-3})	TEtotal (kg m^{-3})
R1	Six leaf stage	3.30	16.4	4.4	20.8	3.77	4.98	6.29
R1	Flag leaf stage	3.95	17.0	4.4	21.4	3.91	4.31	5.42
R1	Grain filling stage	3.45	17.5	5.0	22.5	3.53	5.08	6.52
R1	Grain maturity stage	3.30	15.3	4.2	19.4	3.67	4.62	5.88
R2	Six leaf stage	7.20	36.0	12.2	48.1	2.96	5.0o	6.68
R2	Flag leaf stage	7.25	34.6	11.0	45.6	3.16	4.78	6.29
R2	Grain filling stage	6.50	30.0	9.2	39.2	3.26	4.61	6.03
R2	Grain maturity stage	6.10	28.8	8.3	37.1	3.47	4.73	6.09
R3	Six leaf stage	15.70	85.8	20.7	106.5	4.15	5.46	6.78
R3	Flag leaf stage	14.45	70.4	14.1	84.5	5.00	4.87	5.84
R3	Grain filling stage	14.80	73.8	14.5	88.3	5.11	4.99	5.97
R3	Grain maturity stage	16.45	86.5	21.5	108.1	4.02	5.26	6.57
R4	Six leaf stage	16.95	83.0	15.0	98.0	5.53	4.90	5.78
R4	Flag leaf stage	18.55	98.0	21.0	119.0	4.67	5.28	6.42
R4	Grain filling stage	18.80	88.0	16.0	104.0	5.50	4.68	5.53
R4	Grain maturity stage	16.75	78.0	13.0	91.0	6.00	4.66	5.43

Table 8. Raw data for sorghum growth chamber second study (STUDY 3).

Rep.	Plant growth stages	Water used (kg)	Dry shoot (g box^{-1})	Dry root (g box^{-1})	Dry biomass (g box^{-1})	S:R ratio (g g^{-1})	TEshoot (kg m^{-3})	TEtotal (kg m^{-3})
R1	Six leaf stage	2.70	12.0	4.0	16.0	3.00	4.44	5.93
R1	Flag leaf stage	2.40	12.0	5.0	17.0	2.40	5.00	7.08
R1	Grain filling stage	2.80	13.0	4.0	17.0	3.25	4.64	6.07
R1	Grain maturity stage	2.70	11.0	4.0	15.0	2.75	4.07	5.56
R2	Six leaf stage	6.15	25.0	8.0	33.0	3.13	4.07	5.37
R2	Flag leaf stage	6.35	25.0	7.0	32.0	3.57	3.94	5.04
R2	Grain filling stage	5.35	23.0	8.0	31.0	2.88	4.30	5.79
R2	Grain maturity stage	6.45	26.0	8.0	34.0	3.25	4.03	5.27
R3	Six leaf stage	14.00	68.0	17.0	85.0	4.00	4.86	6.07
R3	Flag leaf stage	14.45	61.0	17.0	78.0	3.59	4.22	5.40
R3	Grain filling stage	12.90	48.0	14.0	62.0	3.43	3.72	4.81
R3	Grain maturity stage	14.55	61.0	19.0	80.0	3.21	4.19	5.50
R4	Six leaf stage	19.40	84.0	16.0	100.0	5.25	4.33	5.15
R4	Flag leaf stage	19.60	83.0	20.0	103.0	4.15	4.23	5.26
R4	Grain filling stage	19.20	77.0	15.0	92.0	5.13	4.01	4.79
R4	Grain maturity stage	19.90	86.0	22.0	110.0	3.91	4.32	5.53

Table 9. Raw data for wheat greenhouse study (STUDY 4).

Rep.	Cultivars	Water level	Plant height (cm)	Leaf chl. at 40 DAP	LRWC at 25 DAP	LRWC at 35 DAP	Water used (kg)	Dry biomass (g)	TE (kg m^{-3})
R1	Triumph 64	high	52.8	49.8	91.9	104.6	54.67	140.1	2.56
R1	Scout 66	high	54.0	45.9	87.3	102.6	48.82	118.9	2.44
R1	TAM W 101	high	35.0	52.5	96.8	105.6	35.37	81.6	2.31
R1	TAM 105	high	29.8	49.2	98.9	-	25.27	48.3	1.91
R1	TAM 111	high	48.0	51.0	88.4	104.0	49.67	118.4	2.38
R1	TAM 112	high	45.0	47.8	89.1	103.1	49.82	113.2	2.27
R1	Triumph 64	low	45.3	51.9	83.5	93.3	36.68	91.3	2.49
R1	Scout 66	low	39.3	53.3	91.1	106.8	30.57	65.5	2.14
R1	TAM W 101	low	34.3	52.2	73.1	100.6	32.72	71.4	2.18
R1	TAM 105	low	35.0	60.3	80.4	95.8	34.57	74.8	2.16
R1	TAM 111	low	31.0	55.1	96.1	105.0	20.77	35.1	1.69
R1	TAM 112	low	38.8	53.4	87.3	100.9	37.32	74.9	2.01
R2	Triumph 64	high	54.8	49.8	86.8	104.3	49.52	111.6	2.25
R2	Scout 66	high	35.5	54.3	104.8	103.7	26.27	51.5	1.96
R2	TAM W 101	high	36.0	51.6	92.4	101.9	40.17	103.9	2.59
R2	TAM 105	high	34.3	51.4	95.2	101.3	33.37	80.0	2.40
R2	TAM 111	high	46.0	53	87.4	97.4	55.37	123.6	2.23
R2	TAM 112	high	30.3	53.3	96.6	102.8	24.62	43.7	1.77
R2	Triumph 64	low	42.8	55.6	74.0	99.5	36.62	90.3	2.47
R2	Scout 66	low	37.0	49.9	95.8	101.9	23.12	45.0	1.94

Table continued……

R2	TAM W 101	low	27.0	54.2	-	99.4	23.07	49.0	2.12
R2	TAM 105	low	29.3	53.8	88.2	101.3	21.77	37.8	1.74
R2	TAM 111	low	31.8	56.6	85.9	101.1	32.87	60.8	1.85
R2	TAM 112	low	39.0	56.0	79.7	99.5	38.92	80.0	2.06
R3	Triumph 64	high	44.5	55.0	92.3	100.8	36.02	96.9	2.69
R3	Scout 66	high	31.5	49.8	102.4	-	17.22	53.5	3.11
R3	TAM W 101	high	40.3	54.9	92.4	98.4	54.32	148.0	2.72
R3	TAM 105	high	33.3	54.7	95.3	100.2	31.02	72.4	2.33
R3	TAM 111	high	34.3	59.9	89.0	100.3	24.52	54.2	2.21
R3	TAM 112	high	47.8	54.2	76.9	100.1	58.79	150.3	2.56
R3	Triumph 64	low	31.0	58.2	97.0	102.0	18.72	39.3	2.10
R3	Scout 66	low	47.3	49.6	91.3	97.7	35.52	87.5	2.46
R3	TAM W 101	low	28.0	59.5	96.5	102.8	24.82	54.2	2.18
R3	TAM 105	low	28.8	56.5	95.1	106.7	23.12	44.0	1.90
R3	TAM 111	low	34.8	58.9	89.9	101.5	28.27	58.7	2.08
R3	TAM 112	low	33.8	52.4	91.8	101.1	26.02	45.6	1.75
R4	Triumph 64	high	54.3	52.3	92.7	101.1	48.02	134.4	2.80
R4	Scout 66	high	47.0	56.0	94.5	98.4	28.42	71.1	2.50
R4	TAM W 101	high	34.8	53.3	97.3	100.6	35.87	84.9	2.37
R4	TAM 105	high	45.5	54.5	92.9	102.5	45.02	114.8	2.55
R4	TAM 111	high	45.0	58.2	87.2	97.1	38.72	85.2	2.20
R4	TAM 112	high	42.0	54. 5	103.3	104.4	45.62	114.2	2.50
R4	Triumph 64	low	36.8	53.6	92.5	100.3	25.37	44.8	1.76
R4	Scout 66	low	46.8	54.1	86.5	95.9	36.77	100.0	2.72

Table continued……

R4	TAM W 101	low	35.3	57.5	86.5	99.8	39.02	96.2	2.47
R4	TAM 105	low	32.0	57.9	100.0	100.4	24.42	62.2	2.55
R4	TAM 111	low	38.5	54	90.8	100.1	34.67	88.0	2.54
R4	TAM 112	low	39.0	55.6	81.7	103.8	28.17	66.3	2.35