EFFECT OF PLANTING GEOMETRIES AND FERTILIZER PLACEMENT ON NUTRIENT UPTAKE BY GRAIN SORGHUM

By

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ABSTRACT

Grain sorghum [*Sorghum bicolor* (L.) Moench] is an important dryland crop in the Texas Panhandle. Productivity of grain sorghum depends on climatic conditions, plant available soil water, and soil fertility. Previous research has shown growing grain sorghum in clumps instead of Equal Spaced Planting (ESP) reduced plant stress, reduced production of tillers, and increased harvest index and grain yield under dryland conditions. The current study was conducted in the greenhouse and field to investigate the effect of fertilizer application on sorghum plants grown in clump and ESP geometries. The objectives of the research were to (a) compare fertilizer (nitrogen and phosphorus) uptake in grain sorghum plants in clumps and ESP geometries (b) observe root growth patterns in clump and ESP plants (c) and determine the fertilizer effect on tiller formation and harvest index.

The greenhouse experiment was conducted at West Texas A&M University during 2014 and 2015. Grain sorghum was grown in clump and ESP geometries with two and three fertilizer levels in 2014 and 2015, respectively. Plants were grown in wooden boxes, with a transparent side, covered by a removable wooden board, so that root growth could be observed. All experiments were conducted in a Randomized complete block design (RCBD) and fertilizer was applied in a band beneath clump and ESP plants. The field experiment was conducted at the USDA Conservation and Production Research Laboratory at Bushland, Texas, during 2014 and 2015. Grain sorghum was grown in clump and ESP planting geometries in unfertilized and fertilized (68 kg N ha^{-1} and 10 kg P ha^{-1}) plots. Planting density in both geometries was 62,000 plants ha^{-1}. In 2015 corn was grown in clump and ESP planting geometries without using fertilizer. N and P concentrations in grain and stover were obtained from laboratory analysis and data are reported as N uptake in aboveground biomass and P uptake in aboveground biomass

In the 2014 greenhouse study, ESP plants had significantly higher N uptake in aboveground biomass, stover yield, and tillers per plant. However, harvest index was higher in clumps. The interaction between planting geometry and fertilizer showed a significantly higher N uptake in ESP with high fertilizer level. In 2015, clump plants had significantly higher grain yield, aboveground N uptake, nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE). Increasing fertilizer level increased P uptake in aboveground biomass. Plants in ESP produced deeper and well developed root systems while clump plants produced roots that developed angularly and then downward.

In the 2014 field study, clump plants had lower N and P uptake in aboveground biomass than ESP, but had higher NUE and PUE. Though clump plants had significantly fewer tillers per plant than ESPs, harvest index was not different. In the 2015 field study, planting geometry did not have a significant effect on N and P uptake in aboveground biomass, NUE or PUE. However, the interaction between planting geometry and fertilizer level showed higher N uptake in clump fertilized plants. Clump plants produced fewer tillers per plant. Harvest index was significantly higher in clumps. Fertilized plots had significantly higher N uptake in aboveground biomass but fertilizer had no effect on P uptake.

Overall, data suggest N and P uptake in aboveground biomass varies by soil nutrient condition, and level of fertilizer. Increasing fertilizer level increases tiller production in the plants. Application of fertilizer has shown mixed results on N uptake and grain yield in clump and ESP plants. Further investigation is necessary to draw a conclusion on aboveground N and P uptake in plants grown in clump and ESP planting geometries at different fertilizer rates and placement methods.

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DEDICATION

TO MY BELOVED GRANDMOTHER

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CHAPTER I

INTRODUCTION

Grain sorghum (*Sorghum bicolor* (L.) Moench) is a major crop grown in the tropical, subtropical, and semi-arid regions of the world. It ranks third in production among most important cereals after maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) in the USA and fifth most important in the world after maize, rice (*Oryza sativa* L), wheat, and barley (*Hordeum vulgaris* L.) (US Grain Council, 2016). The USA is the top producer and exporter of grain sorghum in the world. USA produced 9,882,000 Mg on 2,643,000 ha and 10,988,000 Mg on 2,590,000 ha in 2013 and 2014 respectively (FAOSTAT, 2016).

Grain sorghum is well adapted to a wide range of climatic and soil fertility conditions. Its ability to perform well in high temperature, low rainfall, and frequent drought has made it the most important summer crop in the Central and Southern Great Plains regions of the USA (Stewart, 2006). It is one of the most economically important crops in the Southern Great Plains (Almas, 2004). It also plays a vital role in the economy and cropping system of the Southern Great Plains. Nearly 90% of the grain sorghum in the USA is used as feedstock in livestock industries (Alternative Field Crops Manual, 2016). Recently, grain sorghum has also been used in ethanol production. It is widely grown under both irrigated and non-irrigated (dryland) conditions. However, as irrigated lands are being reverted to dryland due to rapid depletion of the Ogallala aquifer and decreased precipitation, the crop is becoming increasingly important in the Great Plains of the USA (Almas, 2004). Due to the changing climatic conditions, grain sorghum's ability to yield under dryland growing conditions will hold a great importance to agriculture (Stewart and Burnett, 1987).

Soil water content at planting, growing season rainfall (Unger and Baumhardt, 1999), planting date, planting density (Stewart and Steiner, 1990), planting geometry and effective utilization of radiation (Steiner, 1986) strongly influence grain sorghum yield. Other influencing factors include weather conditions, crop hybrid, tillering, soil fertility, and water use efficiency (grain yield per unit of water consumed) (Schneider, 2009). Manipulating planting geometries could significantly reduce crop stress and increasing yield (Stewart and Burnett, 1987). Abunyewa et al. (2010) reported grain sorghum planted in skip row configuration (planting one or group of rows alternated with rows not planted) at a low growing season precipitation site (319 mm) increased grain yield. Skip row configuration also showed higher grain yield stability. Bandaru et al. (2006) reported a higher grain yield when planted in clumps than equally spaced plants in grain sorghum in the 1000 kg ha^{-1} to 3000 kg ha^{-1} range, and suggested increased grain yield may have resulted from improved water use efficiency. Haag (2013) reported cumulative water use at flowering and grain filling stage was higher in clumps than skip row configuration. Author further reported grain yield in clump geometry was higher than conventional and skip row planting geometries in two out of three year study. Kapanigowda et al. (2010) reported increase in grain yield of corn grown at clump planting geometry than ESP in dryland conditions.

The efficient use of water, nutrients, and other resources has always been critical in dryland agriculture. Effective irrigation and proper fertilization may have a significant effect on crop yield in the Great Plains (Wienhold et al. 1995: Al-Kaisi and Yin, 2003). The agronomic practices such as managing nutrients and irrigation water are vital factors to increase yield and efficient use of applied nitrogen (Hao et al., 2014). Myers (1978c) suggested different methods of placement may alter the effectiveness of applied fertilizer by changing susceptibility of leaching and volatilization losses by modifying the pattern of plant uptake. Myers (1978a) reported that applying nitrogen fertilizer as a band application resulted in higher N uptake in aboveground biomass compared to broadcasting and mixing with topsoil.

Prior studies of planting sorghum in clump geometries resulted in higher grain yield and improved water use efficiency. The hypothesis of the study is that fertilizer uptake in aboveground biomass will be greater for sorghum plants grown in clumps than for ESP. Greenhouse and field studies were conducted in 2014 and 2015.

The objectives of the greenhouse study were

1. To compare fertilizer (nitrogen and phosphorus) uptake in grain sorghum plants in clump and ESP geometries
2. To observe root growth pattern in clump and ESP plants

The objectives of field study at USDA-ARS, Bushland were

1. To compare fertilizer (nitrogen and phosphorus) uptake in grain sorghum plants in clumps and ESP geometries
2. To determine the fertilizer effect on tiller formation and harvest index

CHAPTER II

REVIEW OF LITERATURE

The United Nations Conference on Diversification (UNESCO, 1977) divided bioclimatic zones into four different zones based on the aridity index (the ratio of precipitation (P) and potential evapotranspiration (PET) namely hyperarid zone, arid zone, semiarid zone, and sub humid zone. The semiarid zone has an aridity index (P/PET) between 0.20 and 0.50 where most of the dryland farming system is practiced (Stewart, 1988). Due to low precipitation and high PET, water is the most limiting factor in vegetation growth and development in the semiarid regions (Koohafkan and Stewart, 2008).

2.1 Dryland Farming

Stewart and Burnett (1987) defined dryland farming as the rainfed system that emphasized water conservation, sustainable crop yield, limited inputs for soil fertility maintenance, and wind and water erosion constraints. The semi-arid region is characterized by cool dry seasons followed by relatively hot and dry seasons, and a moderate and rainy season (Koohafkan and Stewart, 2008). The short rainy season cannot supply enough water for crops throughout the year. Thus, summer fallowing is often practiced to some extent in dryland areas of North America (Stewart, 1988). The success or failure of dryland crops depends on stored soil moisture during the planting and growing season as well as growing season rainfall, planting date, planting density, and the water managed from modifying planting geometry (Steiner, 1986). Enough soil moisture present during germination and the early growth phase promote vegetative growth in plants but low precipitation or drought may lead to significant yield loss or complete failure of crops (Bandaru et al. 2006).

The soils in dryland regions are very diverse in physiochemical properties. Low water holding capacity and the ability to supply nutrients directly influence the crop production in drylands (Koohafkan and Stewart, 2008). Thus, application of a balanced amount of nutrients and water supply results in higher grain yield. There is little or no research being conducted on manipulating planting geometry and method of fertilizer placement. This section reviews the effect of planting grain sorghum in clumps and applying nutrients with different methods.

2.2 Planting Geometry and Clump Planting

Planting geometry refers to the arrangement of plants during planting. Research has shown planting geometry is also an important factor determining grain sorghum yield (Bandaru et al., 2006: Kapanigowda et al., 2010). Equally spaced planting, skip-row, and double skip-row are common practices in use (Abunyewa et al., 2010). Clump planting is a new strategy for dryland agriculture where three or four plants are grown together (Bandaru et al., 2006: Kapanigowda et al., 2010: Krishnareddy et al., 2010: Stewart and Peterson, 2015).

In an experiment in Bushland, TX Steiner, (1986) reported narrow row spacing (38 cm) and high (18 plants m^{-2}) and medium (12 plants m^{-2}) planting density resulted in higher seasonal evapotranspiration (ET) than normal row spacing (76 cm) and low planting density because of higher ET, which ultimately reduced the grain yield in 1983. In 1984, grain sorghum in a narrow row increased total biomass yield but did not improve grain yield. However, regular row plots resulted in greater harvest index. Krishnareddy et al. (2010) planted grain sorghum in clumps (1, 2, 4, and 6 plants per clump) at planting densities of 1.8 plants m^{-2}, 3.6 plants m^{-2}, 7.1 plants m^{-2}, and 10.7 plants m^{-2} respectively and reported decreased tillers per plant with the increase in planting density which averaged 0.6 tillers per plant and 0.3 tillers per plant with 4 and 6 plant clumps respectively. Additionally, the fertility of tillers with high planting density was low. Prior research showed the advantage of modifying planting geometry in grain sorghum. Higher planting density increased the possibility of decrease in grain yield.

Planting in clumps while keeping the same plant density reduced tiller production during the vegetative growth stage, leading to a greater percentage of water use in the grain filling stage, and increased grain yield (Bandaru et al., 2006 and Kapanigowda et al., 2010). Planting grain sorghum in clumps rather than in uniformly spaced planting helped to minimize stress and improved yield by reducing water stress.

2.3 Nitrogen Uptake in Aboveground Biomass

Nitrogen, a macro-nutrient, is highly susceptible to volatilization, leaching, and denitrification. Therefore, it is one of the most yield-limiting nutrients for crop production in the world (Mahama, 2012). Low nitrogen supply causes underdevelopment of crop plants, resulting in low yield or crop failure (Zhao et al., 2005). Rates of nitrogen fertilizer application in excess of plant requirement are also harmful to the plants and environment (Al-Kaisi and Yin, 2003). Authors further suggested that excess nitrogen accumulates in the soil profile in the form of nitrate nitrogen. Finding a more efficient way to fertilize the crop may reduce the increasing use of nitrogen (Smil, 1997). Shoot N concentration decreases with increasing nutrient deficiency and crop age (Jones, 1983).

Myers (1978c) reported increased nitrogen uptake in aboveground biomass with band application compared to broadcasting and mixing with topsoil. Myers (1978a) reported N uptake in aboveground biomass was also higher at optimum fertilizer rate.

Nitrogen use efficiency (NUE) is defined in various ways. Fageria and Baligar (2005) defined NUE as the maximum economic yield per unit of nitrogen applied, absorbed, or utilized by plants to produce grain and straw. Moll et al. (1982) defined NUE as ratio of grain weight produced per unit of plant available nitrogen in the soil. NUE = Gw/Ns (where Gw is grain weight and Ns it nitrogen supplied). NUE is also calculated based on the applied nitrogen (Dobermann, 2005). It is calculated as the ratio of crop yield (Y_N) with applied nitrogen and amount of fertilizer nitrogen (F_N) applied. NUE= Y_N (kg ha^{-1})/ (kg N ha^{-1}). The author further suggested 40-70 kg grain kg^{-1}N is considered common. Research has shown NUE is higher in low nitrogen rate and lower in high N application rate (Fageria and Baligar, 2005). Plants may not be able to uptake all applied nitrogen because their absorption mechanism might have been saturated (Moll et al., 1982). In this study N use efficiency is defined as the dry grain yield produced per unit of fertilizer N applied.

2.4 Phosphorus Uptake in Aboveground Biomass

Phosphorus is the second most important macronutrient after nitrogen. Phosphorus fertilizers are mainly derived from rock phosphate. Phosphorus deficiency is one of the major growth factors limiting crop productivity in various parts of the world (Johnston et al. 2014). Modifying surface soil properties, managing phosphorus sources, optimizing phosphorus application rates in specific cropping systems are common strategies to improve its efficient use (Syers et al., 2008). Phosphorus is highly susceptible to fixation. Plants generally absorb only 10-30% of applied phosphorus. Nearly 70-90% of applied phosphorus remains in the soil (Hemwall, 1957).

Fageria et al. (1988) conducted an experiment with rice cultivars. Three treatments low, medium, and high phosphorus (1.1 mg kg^{-1}, 10.2 mg kg^{-1} and 87 mg kg^{-1} of soil) were used. Plant height, root length, tillers, dry root and shoot weight, P concentration in root and shoot and total P uptake in root and shoot were highly significant with the level phosphorus. Growth parameters increased with the increasing level of phosphorus supply. In another experiment Power et al., (1961) reported dry matter and grain production increased with the increase in soil moisture and P fertilization in winter red wheat in Montana. Myers (1978b) reported increased P concentration in grain and vegetative parts with increase in rate of application.

Phosphorus use efficiency (PUE) is defined in various ways. PUE can be defined as the economic yield produced per unit of phosphorus applied (Dobermann 2005; Hussein 2009). PUE can also be defined in terms of yield increase per unit of P applied (Syers et al., 2008). Authors further suggested when efficiency of P use is calculated as kilograms of grain per kilogram of P uptake, the largest values were for the crops given N, because without N, yields were very small and not financially viable. In the current study P use efficiency is defined as the dry grain yield produced per unit of fertilizer P applied.

Conservation and effective utilization of plant available soil moisture is important for plant growth and development in dryland. Nutrient uptake efficiency is affected by crop, their genotype and growing conditions such as fertilizer application rate, time of application, and available soil moisture.

2.5 Tillering

Tillering is an important mechanism for yield compensation in many cereal crops. It is affected by genotype and environmental factors such as temperature, photoperiod, light intensity, soil moisture, fertility and planting density (Gerik and Neely 1987). When planting density was increased, tiller number per plant decreased. Tillers normally produced fewer leaves than the main stalk and matured 7-10 days later. Downes (1967) reported the effect of temperature on tillering in sorghum. Sorghum plants were grown at different day and night temperatures and photoperiods. Photoperiod did not change tillering but temperature regime affected the process. Sorghum produced no tiller at 30/25°C or 25/20°C with 12 or 14 hours of photoperiod but plants produced tillers well at 20/15°C and 20/10°C.

2.6 Harvest Index

Harvest index describes the plant's capacity to allocate assimilates into the formed reproductive parts (Wnuk et al., 2013). Harvest index, an important yield component in agronomy, is the ratio of grain yield to dry matter yield (Donald, 1962). Prihar and Stewart (1991) reported harvest index is independent of the size of the mature plant but in some cases harvest index increased with decreased plant size. The authors suggested that the harvest index may vary with the environmental condition, planting date, irrigation regimes, and population densities. Fageria et al. (2006) reported harvest index showed a positive correlation with grain yield in cereals. Another research in grain sorghum and maize showed higher harvest index when they were planted in clumps (Bandaru et al., 2006 and Kaponigowda et al., 2010). Bandaru et al. (2006) conducted an experiment by planting grain sorghum in clumps and reported an increase in harvest index and grain yield. Kadasrivenkata (2007) and Kaponigowda et al. (2010) also reported an increase in harvest index of corn plants grown in clumps in dryland plots due to the reduction in tiller number.

2.7 Root Growth and Development

Myers (1980) in Australia conducted an experiment in grain sorghum with two sorghum hybrids (Texas 610 and Pioneer 846) in 1971 and 1972. Samples were taken at floral initiation, mid elongation (between floral initiation and anthesis, nearly 45 days after emergence), anthesis and at physiological maturity stage. The author reported the highest root concentration of nitrogen and phosphorus in during mid elongation. After this stage, the nitrogen concentration declined. Root length and root weight followed the same trend. Root length reached 80 cm by mid elongation stage; however, there was minor growth until anthesis. In another experiment in Australia, Broad and Hammer (2004) planted sorghum in chambers mimicking skipped row configuration. They found the sorghum plants with tillers produced extensive root exploration and water extraction from the soil. Authors further suggested tiller manipulation may provide an idea about water management in that particular environment. The higher root volume indicates the ability of roots to pass through a large volume of soil and ability to absorb water and nutrient in an efficient way (Nour and Weibel, 1978). Thus, a better understanding of root systems and their architecture helps to improve water use efficiency and nutrient uptake in crops (Fageria et al., 2006).

Schneider (2009) conducted an experiment in a greenhouse at West Texas A&M University using boxes with plexiglas on the front to observe root growth and pattern. The author reported distinct rooting patterns in the plants grown in clumps versus ESP.

Roots in the plants grown in clumps developed angularly, but in ESP roots extended straight down. Total root length did not show any difference. Visual observation during the growth stages suggested plant roots in ESP penetrated deeper and earlier than clump plants. Singh et al. (2010) reported root angle is affected by the genotype and is independent of plant size which could be used in screening of genotype. The author also suggested root angle may help to predict the water extraction tendency in mature plants.

2.8 Root-Shoot Ratio

Root-shoot ratio is the amount of plant tissues that have a supportive function to the amount of those that have a growth function. Generally, the proportion of shoots is higher in the beginning of the vegetative phase, and decreases until the end of the vegetative phase, when the proportion of roots reach the maximum (Allaby, 2016). Roots are also a vital component of plant performance and nutrient requirement. Rao (1991) reported the addition of nitrogen fertilizer to soil stimulated root growth. But when there is enough nutrient, plants tend to allocate less to the roots (Aegren and Franklin, 2003). Myers (1980) also reported nitrogenous fertilizer increased the growth of tops without markedly affecting root growth which tends to lower root shoot ratio when there is sufficient nutrient supply.

2.9 Water Use Efficiency

Water use efficiency in agronomy is defined as the ratio of economic crop yield to the water used to produce that yield (Viets, 1962). Sinclair et al. (1984) defined water use efficiency as a ratio of biomass accumulation, expressed as carbon dioxide assimilation (A), total crop biomass (B), or crop grain yield (G) to water consumed, expressed as transpiration (T), evapotranspiration (ET) or total input to the system (I).

The available plant water is directly correlated with the grain yield. In extremely dry growing conditions plants produce very little or no grain. The highest water use efficiency (kg grain m^{-3} ET) occurs at the highest water level (Stewart et al., 1983). The authors also reported an additional 10 mm of ET above the threshold ET of 143 mm increases approximately 145 kg ha^{-1} of grain yield. Blum and Naveh (1976) reported a significant increase in grain yield when grain sorghum plants were planted in double rows compared to regularly spaced rows with the same number of plants per unit area. This view is supported by Krishnareddy (2010), who found that plant spacing and planting densities in dryland grain production may influence water use efficiency. Maintaining wider spacing under dryland conditions helps to conserve water during the early vegetative growth stage and use in later growth stages (Steiner, 1986). Unger and Jones (1981) reported that mulching increased water used efficiency. As an aside, the authors indicated the possibility of reduction in harvest index if planted at higher planting density. Using the same plant density per unit area and modifying spacing may allow grain sorghum roots to explore and utilize soil moisture (Blum and Naveh, 1976). Improving water use efficiency in grain sorghum by modifying plant spacing, density, and planting geometries may result in higher grain yield in dryland farming systems.

2.10 Evapotranspiration

Of total available water in soil, the plant absorbs water through roots and uses it for physiological activities. Some portion of absorbed water escapes through stomata during gaseous exchange. The process of movement of water through stomata is transpiration (T). When part of soil moisture goes to the atmosphere as water vapor it is known as evaporation. These two processes occur simultaneously, which is referred as evapotranspiration (ET) (Allen et al., 1988). Transpiration is an important physiological phenomenon which regulates the leaf temperature and draws water and soluble nutrients from soil through roots (McMahon et al., 2002). Transpiration is sometimes described as a necessary evil because it is an inevitable process. Loss of water can lead to wilting, serious desiccation, and often the death of a plant. Therefore, water management in dryland agriculture is very important. In the dryland farming system, ET is calculated as the sum of growing season precipitation and water extracted from plant available water in the root zone (Stewart and Peterson, 2015). Growing season precipitation is less than 50% of potential evapotranspiration in the Southern Great Plains (Bandaru et al., 2006: Stewart and Peterson, 2015). Thus, grain production in the Great Plains relies on managing soil water and growing season precipitation. Evapotranspiration is affected by weather parameters, crop factors such as variety, development stage and management, and environmental conditions such as soil salinity, soil water content, and plant density (Allen et al., 1988).

2.11 Transpiration/Evapotranspiration Ratio

Transpiration/Evapotranspiration ratio (T/ET) is the fraction of total evapotranspiration which mainly contributes to biomass production. It is affected by many factors and fluctuates within a short period of time and over the season (Stewart and Peterson, 2015). The authors stated, only about half of the total growing season evapotranspiration is transpiration in dryland crops in the semiarid region. However, a study in semi-humid regions of China, in maize and winter wheat, showed T/ET as low as zero at the planting time and as high as 0.9 at the mid vegetative growth stage when leaf area index (LAI) (leaf area per unit ground surface) was 3.0 (Kang et al., 2003).

Residue covered soil surface shows greater influence in T/ET. Unger and Jones (1981) suggested the shading effect of plant leaves work as mulch and improves transpiration. Growing sorghum plants in clumps does not cover the soil surface as much as plants in ESP, but foliage creates mutual shading (Stewart, 2006). Stewart and Peterson (2015) also suggested mulching primarily helps in conserving water before planting and helps to increase the fraction of T in T/ET.

CHAPTER III

MATERIALS AND METHODS

3.1 Greenhouse Studies

The greenhouse experiments were conducted at West Texas A&M University during 2014 and 2015. Effects of planting geometries (equally spaced planting (ESP) and clump) and fertilizer levels were tested using the DK-S36-06 grain sorghum hybrid in the experiments. Plants were grown in wooden boxes. One side of each box had a transparent Plexiglas cover with a removable wooden board, so that root growth could be observed periodically without continuous exposure to sunlight.

3.1.1 2014 (Grain Sorghum)

3.1.1.1 Experimental Design

The greenhouse experiment was a Randomized Complete Block Design (RCBD). It consisted of four treatments and three replications in 12 boxes. Two planting geometries; ESP and clump, and two fertilizer levels; Level 1(4.32 g N and 0.63 P) and level 2 (8.64 g N and 1.25 g P) were used. Fertilizer rates were estimated based on the average N content in aboveground biomass. Average aboveground biomass was estimated as 400 grams for four sorghum plants per box (Schneider, 2009) and N concentration as 1.25%. Nitrogen fertilizer recovery was assumed 60% (Varvel and Peterson, 1991) and the optimum rate (Level 2) was determined. Lower rate (Level 1) was determined as half of the optimum rate. Grain sorghum seeds (variety DK-S36-06) were planted on May 25, 2014 and harvested on September 20, 2014; 118 Days After Planting (DAP).

Wooden boxes of length 75 cm, width 10 cm, and height 100 cm were used to grow plants. Weight of each box was taken and pebbles were added to each of them to maintain the same initial weight at 21 kg. Calcined clay was added to the height of 85 cm. Calcined clay is a plant growing medium, widely used in greenhouse experiments. It has a relatively high cation exchange capacity and water holding capacity (nearly 45% by volume) compared to other growing media. It was tested for nitrogen and phosphorus concentration. Calcined clay was not a significant source of plant available nitrogen (<1 ppm nitrate-nitrogen) but it was rich in plant available phosphorus (70 ppm P).

Thirty liters of water were poured into each box. The fertilizer was applied in a thick band at the center of boxes for clump treatments and regular band running through the box length in boxes for ESP treatments (Figure 3.1). After applying fertilizer, the rest of the box volume was filled with the additional Calcined clay. The final height of the growing medium was maintained at 95 cm to allow some space for mulching and watering. An additional 3.4 liters of water were added in all boxes.

Figure 3.1 Fertilizer application in a thick band for clump treatments (left) and regular band for ESP treatment (right).

Filled box weights were slightly different (from 114 kg to 117 kg) because the front boards (Plexiglas) were slightly bulging out in some boxes. Soil moisture in all boxes was maintained at near field capacity (42% by growing medium volume).

Four plants were grown in each box. Seeds were planted 5 cm below the surface. Three seeds were planted per hill in ESP treatment boxes and six seeds per hill in clump treatment boxes. Planting distance was 18 cm between plants in ESP, whereas all four seeds were planted at the center of the box length for clumps. The top surface of each box was covered with chopped wheat straw at 26 g box^{-1}. Extra plants were removed at the three leaf stage, keeping only four plants at 18 cm apart for the ESP treatment and four plants together for the clump treatment.

3.1.1.2 Irrigation

Soil moisture in all boxes was started with near field capacity (42% by growing medium volume). Irrigation was started 8 DAP and continued to physiological maturity. Irrigation water was applied to all the boxes at the same rate. Boxes were weighed every two to four days, using a common balance, depending on the moisture in the top growing medium layer and plant stress signs. Boxes were weighed regularly to determine amount of water used by the plants. The volumetric amount of water used was determined by subtracting the box weight from initial level. The volumetric amounts of water were recorded for each box and water per box was added in such a way that the box with the maximum weight did not exceeding the weight at the beginning.

3.1.2.3 Observation and Growth Measurement

The primary focus of the experiment was to compare the grain and biomass yield, N and P uptake in aboveground biomass at different planting geometries and fertilizer levels. Tillers per plant were also determined when plants were at flag leaf stage.

3.1.1.4 Insect Pest Management

Plants became infested with spider mites in the early flowering stage. Plants were sprayed with isopropyl alcohol diluted with water at the ratio of 1:10. Initially, this technique seemed effective. However, mite infestation increased in later growth stages. They created webs around panicles during the hard dough stage, but there were no severely damaged plants. Plants were also infested with green aphids. The same treatment method of mite control was used, which was effective to control aphids.

3.1.1.5 Crop Harvesting and Sample Processing

Plants were harvested by cutting at ground level. Panicle heads were cut at their base and removed from the stalks. Head and stover samples were kept in separate paper bags and labeled. All boxes were allowed to dry for a few weeks in the greenhouse after being harvested. Roots were extracted by removing the plexiglas cover and removing growing medium by tapping the boxes. After the roots were extracted, they were washed, cleaned, and sun dried. Head and grain samples were dried in an oven at 70°C. Stover and root samples were allowed to dry in air for a week and then transferred to an oven at 65°C for drying. Weight was recorded when weights of the samples were constant.

Grain was extracted by manual threshing. Seed, stem (stover) and root samples were weighed and later ground in a Thomas-Wiley laboratory mill, with 2.0 mm screen. Ground samples were labeled and sent to Servi-Tech laboratories in Amarillo, TX to determine nitrogen and phosphorus concentration.

3.1.1.6 Nitrogen and Phosphorus Uptake Calculation

The following equations were used to determine N and P uptake in aboveground biomass, nitrogen use efficiency, and phosphorus use efficiency.

N Uptake in aboveground biomass (g box^{-1}) = (Dry grain weight* N concentration in grain) + (Dry stover weight*N concentration in stover)

P uptake in aboveground biomass (g box^{-1}) = (Dry grain weight* P concentration in grain) + (Dry stover weight*P concentration in stover)

Nitrogen Use Efficiency (kg kg^{-1}N) = Dry grain yield /fertilizer N applied

Phosphorus Use Efficiency (kg kg^{-1}P) = Dry grain yield /fertilizer P applied

3.1.1.7 Statistical Analysis

Statistical Analyses were performed using SAS version 9.4 (SAS Inst, Cary, NC). The mixed models were used to evaluate the effect of planting geometry and level of fertilizer on data for growth, yield parameters, nutrient uptake in aboveground biomass, and fertilizer (nitrogen and phosphorus) use efficiencies. Alpha level was at 0.05 and means of significant variables were separated using the least significant difference (LSD) procedure. The data analyzed for growth were tillers per plant at flag leaf stage, grain yield, stover yield, harvest index (kg dry grain/kg dry aboveground biomass), root weight, and root shoot ratio. The data analyzed for nutrient uptake in aboveground biomass were N uptake in aboveground biomass, P uptake in aboveground biomass, N and P use efficiencies.

3.1.2 2015 (Grain Sorghum)

3.1.2.1 Experimental Design

The experiment in the greenhouse was a Randomized Complete Block Design (RCBD). It consisted of six treatments and three replications. Planting geometries were ESP and clump, and three fertilizers levels were: Level 1(3 g N, 0.44 g P), Level 2 (6 g N, 0.88 g P) and Level 3 (9 g N, 1.32 g P). Fertilizer levels were determined using same methods as in the 2014 greenhouse study (Section 1.1.1.1). In the 2014 greenhouse experiment, fertilizer levels did not have a significant effect on grain yield, thus three rates were used in 2015. Optimum rate (Level 3) was similar to the optimum rate in 2014, medium rate (Level 2) was 66% of the level 3 and lowest rate (Level 1) was 33% of level 3. Grain sorghum (variety DK-S36-06) seeds were planted on Feb 18, 2015 and harvested on July 04, 2015; 136 DAP.

The number of boxes were not sufficient to conduct the experiment with three rates of fertilizer. Also the transparent plexiglas side was bulged due to higher growing medium weight thus, new boxes were made in 2015. The boxes used in the experiment were similar in length and width but height was reduced to make them easy to handle. Wooden boxes of length 75 cm, width 10 cm and height 85 cm with transparent plexiglas and a removable wooden board and base were used in the experiment. Peebles were added to make the same initial weight of 23 kg for each box. All boxes were filled with calcined clay to 65 cm of their height and 21L water was added. Fertilizer was applied as in the 2014 experiment (section 3.1.1.1) The remaining volume was filled with calcined clay and additional 4.8L water was added in each box. Each box had the same initial weight of 93 kg.

Seeds were planted 5 cm below the growing medium surface and 2.5 cm to the side of the fertilizer band. Seed number and plant spacing were the same as 2014. Mulch was applied at the same rate as in 2014. The temperature in the greenhouse was set with a maximum temperature of 32°C and a minimum temperature of 18°C. Light in the greenhouse was also turned on to mimic the day length (nearly 12 hours) in the month of May-June. The lighting system was set to be turned on at 6 am and turned off at 6 pm.

3.1.2.2 Irrigation

Soil moisture in all boxes was started with near field capacity (42% by growing medium volume). Irrigation was started 13 DAP and continued to physiological maturity. Each box received the same amount of water for the first 76 DAP. Plants in high fertilizer treatments were stressed but the plants in the low fertilizer treatments did not show any stress symptoms. Moreover, box weight also showed that the plants with the low level of fertilizer treatments consumed less water compared to high and medium level treatments. After 76 DAP different rates of irrigation water were applied to the boxes with different fertilizer levels. All boxes with the same fertilizer rates were weighed to determine amount of water used by the plants. The volumetric amount of water used was determined by subtracting the box weight from initial level. The volumetric amounts of water were recorded for each box and water per box was added in such a way that the box with the maximum weight did not exceeding the weight at the beginning.

3.1.2.3 Observation and Growth Measurement

The number of tillers was determined at flag leaf stage. Roots and their development were observed by removing the board from the Plexiglas side of each box. Regular observations were made to note the growing pattern in different treatments. Photographs were taken at different stages of plant growth such as early vegetative growth stage, flowering stage, at plant harvest, and after removing growing media from the boxes as shown in Figure 3.2 and Figure 3.3.

Figure 3.2 Observation of root growth by removing the board on the front

Figure 3.3 Sorghum roots after removing growing media by removing bottom of the box

3.1.2.4 Insect Pest Management

Plants became infested with spider mites in the early flowering stage. The same method as in 2014 was used to manage mite infestation (section 3.1.1.4).

3.1.2.5 Crop Harvesting and Sample Processing

Crop was harvested and samples were processed using same methods as in 2014 (section 3.1.1.5)

3.1.2.6 Nitrogen and Phosphorus Uptake Calculation

N and P uptake in aboveground biomass, nitrogen use efficiency, and phosphorus use efficiency were calculated using same formulas as in 2014 (section 3.1.1.6).

3.1.2.7 Statistical Analysis

The same statistical procedure as in 2014 was used (section 3.1.1.7).

3.2 Field Studies

The field studies were conducted at the USDA Conservation and Production Research Laboratory, Bushland, TX (35° 11′ N, 102° 5′ W) on Pullman clay loam (US soil taxonomy: fine, mixed, superactive, thermic Torrertic Paleustoll; FAO: Kastanozems) in 2014 and 2015.

3.2.1 2014 (Grain Sorghum)

3.2.1.1 Experimental Design

The experiment was conducted as a Randomized Complete Block (RCBD) with four treatments and four replications on a land that had been planted to grain sorghum in 2013. Each plot was 6 m long and 3 m wide (4 rows) with row spacing of 76 cm. There were a total of 16 plots. The experiment consisted of two planting geometries; ESP and Clump, and two fertilizer levels; fertilized (68 kg N ha^{-1} and 10 kg P ha^{-1}) and unfertilized. Grain sorghum (variety DK-S36-06) was planted on June 11 and harvested on October 16, 2014; 126 DAP. Plant population for each plot was maintained at 62,000 plants per hectare. The precipitation during the crop growing period is shown in Table 3.1.

Fertilizer was applied in the row by making a trench with a hoe. Fertilizer was applied evenly in a band for ESP treatments and applied as a thick band for clump treatments. Seeds were planted with a hand planter at a depth of 5 cm, 4 cm to the side of the trench where fertilizer was applied. Three to four seeds per hill and 7-8 seeds per hill were planted in ESP and in clump plots respectively. The planting distance was 21 cm between plants and 84 cm between clumps. Extra plants in the hills were removed at the four leaf stage, keeping one plant per hill in ESP and four plants per hill in a clump.

Table 3.1 Growing season precipitation data at Bushland, Texas, 2014 (Grain Sorghum)

Month	Growing season precipitation (mm) †
June	34
July	98
August	26
September	114
October	31
Total	303

† Precipitation records were obtained from U.S. climate data website

3.2.1.2 Observation and Growth Measurement

The primary focus of the field experiment was to compare the grain and biomass yield in fertilized and unfertilized plots with different planting geometries. Tillers per plant, and productive tillers per plant were also recorded. Data for tillers per plant were recorded on July 29 (48 DAP). The number of productive tillers per plant was recorded 114 DAP.

3.2.1.3 Weed Management

Weeds in the field were managed before planting by spraying Roundup [Glyphosate (N-phosphonomethyl) glycine)] at the concentration of 24 ml per liter of water. After plant germination, weeds were controlled by manual hoeing.

3.2.1.4 Crop Harvesting and Sample Processing

Sorghum plants were harvested from the middle two rows with an area of 3.75 m^2 (2.5 m X 1.5 m) in each plot. Two rows on the side were not harvested to eliminate border effects. Stalks (stover) and panicle heads were harvested separately. Harvested samples were preliminarily dried in the greenhouse. Head samples were threshed manually. Seed and stover samples were dried in an oven at 70°C and 65°C respectively. The measurement was taken when weights were constant.

Seed and stover samples were ground in a Thomas-Wiley laboratory mill, with a 2.0 mm screen. Ground samples were labeled and sent to Servi-Tech laboratories, Amarillo, TX to analyze nitrogen and phosphorus concentration.

2.2.1.5 Nitrogen and Phosphorus Uptake Calculation

The following equations were used to determine N and P uptake in aboveground biomass, nitrogen use efficiency, and phosphorus use efficiency. N and P use efficiencies were determined for fertilized plots only.

N uptake in aboveground biomass (kg ha^{-1}) = (Dry grain weight* N concentration in grain) + (Dry stover weight*N concentration in stover)

P uptake in aboveground biomass (kg ha^{-1}) = (Dry grain weight* P concentration in grain) + (Dry stover weight*P concentration in stover)

Nitrogen Use Efficiency (kg kg^{-1}N) = Dry grain yield /fertilizer N applied

Phosphorus Use Efficiency (kg kg^{-1}P) = Dry grain yield /fertilizer P applied

3.2.1.6 Statistical Analysis

Statistical Analyses were performed using SAS version 9.4 (SAS Inst, Cary, NC). The mixed models were used to evaluate the effect of planting geometry and level of fertilizer on data for growth, yield parameters, nutrient uptake in aboveground biomass, and fertilizer (nitrogen and phosphorus) use efficiencies. Alpha level was at 0.05 and means of significant variables were separated using the least significant difference (LSD) procedure. The data analyzed for growth were tillers per plant, tillers with panicle per plant, grain yield, stover yield, and harvest index. The data analyzed for nutrient uptake in aboveground biomass were N uptake in aboveground biomass, P uptake in aboveground biomass, N and P use efficiencies.

3.2.2 2015 (Grain Sorghum)

3.2.2.1 Experimental Design

The experiment was designed as a Randomized Complete Block (RCBD) with four treatments and four replications. Each plot was 6 m long and 4.5 m wide (6 rows) with row spacing of 76 cm. There were a total of 16 plots. Seed was planted on June 22, 2015 and plants were harvested on October 16; 115 DAP. Fertilizer levels, method of fertilizer application, planting geometries, plant spacing, and plant population were same as the field study in 2014 (section 3.2.1.1). The precipitation during crop growing period is shown in Table 3.2.

Table 3.2 Growing season precipitation data at Bushland, Texas, 2015 (Grain Sorghum)

Month	Growing season precipitation (mm) †
June	-
July	73
August	114
September	10
October	23
Total	220

† Precipitation records were obtained from Crop Stress Laboratory, Bushland, TX

3.2.1.2 Observation and Growth Measurement

The main focus of the field study was the same as the field study in 2014 (section 3.2.1.2). Tillers per plant, and productive tillers per plant were recorded 66 DAP and 114 DAP respectively.

3.2.2.3 Weed Management

Weeds in the field were managed using the same methods as in the field study 2014 (section 3.2.1.3).

3.2.2.4 Insect Pest Management

A grasshopper infestation was noticed in the sorghum and corn plots during the vegetative growth stage. DuPont Pervathon[†] was sprayed at 1000 ml ha^{-1} to manage the infestation. Sugarcane aphid infestation occurred in the grain sorghum plots in the early flowering stage. Sivanto[††] was sprayed at 730 ml ha^{-1} to manage aphid infestation.

Pervathon[†]: (Chlorantraniliprole) [3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)phenyl]-1-(3-chloro-2-pyridinyl)-1Hpyrazole-5-carboxamide

Sivanto[††]: (Flupyradifurone) 4-[[(6-chloropyridin-3-yl)methyl](2,2-difluoroethyl) amino]furan-2(5H)-one

3.2.2.5 Birds and Rodent Management

Bird damage was noted during the hard dough stage. Nets were installed and covered using concrete reinforcement bar at four corners of each plot (Figure 3.4). Rodent infestations were noticed in some of the ESP treatment plots, they were managed by using non-poisonous sticky plates.

Figure 3.4 Nets installed in the field to prevent bird damage. Bushland 2015

3.2.2.6 Crop Harvesting and Sample Processing

Sorghum plants were harvested from the middle two rows with a total area of 6.5 m^2 (4.3 m X 1.5 m) in each plot. The middle two rows were harvested to eliminate border effects. Main stalk, tiller stalk, and their heads were harvested separately. Harvested samples were air dried and head samples were threshed using a mechanical thrasher. Seed moisture was measured using a Dickey John moisture tester. Stover samples were dried in an oven at 65°C and weights were recorded when weights were constant. Seeds moisture for small samples, when moisture tester couldn’t be used, were determined by drying grain at 130°C for 18 hours. Seeds and stover samples for laboratory analysis were prepared as in the 2014 field study (section 3.2.1.4).

3.2.2.7 Soil Moisture Measurement

Soil samples were taken in the field before planting (June 24, 2015) the crop and after harvest (October 19, 2015). Samples were taken by using a tractor mounted probe (tip diameter: 1.9 cm) to a depth of 120 cm. A total six samples across a line of the field width were taken from two different sides of the field in the beginning. Samples were taken between the two innermost rows from each plot after harvest. The soil cores were divided based on soil profile depth into increment of 0 cm -15 cm, 15 cm -30 cm, 30 cm - 60 cm, 60 cm -90 cm, and 90- 120 cm. Samples were weighed, dried in an oven at 105°C for 24 hours, and then weighed again to calculate percent moisture content by weight.

3.2.2.8 Estimation of T/ET

T/ET was estimated using an equation GY = ET× T/ET × 1/TR × HI as described by Stewart and Peterson, 2015. Where GY is dry grain yield (kg ha^{-1}); ET is evapotranspiration (kg ha^{-1}) (water use by evaporation from soil surface and transpiration by the crop between seeding and harvest); T/ET is the portion of evapotranspiration transpired by the crop; TR is transpiration ratio (number of kilogram of water transpired to produce 1 kg of aboveground biomass); HI is the harvest index (kg dry grain/kg aboveground dry biomass).

ET was calculated as the sum of growing season precipitation and extracted plant available soil water to a depth of 120 cm. Growing season precipitation was the sum of precipitation from the date of planting to date of harvest. Plant extracted water was calculated by subtracting soil moisture at harvest from soil moisture at planting. Soil moisture in the beginning and at plant harvest was determined gravimetrically. To estimate T/ET values, TR of 239 was assumed for all treatments, which is the average value estimated by Stewart and Peterson (2015) for grain sorghum of similar yield for multiple years at Bushland, TX. By assuming a TR value, the T/ET could be estimated since there were measured values for each of the other factors in the equation.

3.2.2.9 Nitrogen and Phosphorus Uptake Calculation

N and P uptake in aboveground biomass, nitrogen use efficiency, and phosphorus use efficiency were calculated in the same way as in the 2014 grain sorghum field study (section 3.2.1.5).

3.2.2.10 Statistical Analysis

Statistical analysis for growth, yield parameters, and nutrient uptake were done using the same procedure as in the 2014 grain sorghum field study (section 3.2.1.6). Additional analyses were done for soil water content and estimated T/ET ratio using the mixed models of SAS.

3.2.3 2015 (Corn)

3.2.3.1 Experimental Design

The experimental design, plot size, and row spacing were the same as the grain sorghum field study 2015. There were two treatments, ESP and clump, and four replications. Plants were grown without using any fertilizer. Seed was planted on June 24, 2015 and harvested on October 2; 100 DAP. Seeds were planted in rows with the hand planter. Two seeds were planted per hill in ESP and 4 seeds per hill were planted in clump treatment plots. Plant to plant spacing was maintained for ESP at 37 cm and clump to clump was 112 cm. Extra plants per hill were removed at the four leaf stage keeping 1 plant per hill in ESP and 3 plants per hill in a clump. Plant population in each plot was maintained at 39,000 plants per hectare. The precipitation during the crop growing period is shown in Table 3.3.

Table 3.3 Growing season precipitation data at Bushland, Texas, 2015 (corn)

Month	Growing season precipitation (mm) †
June	-
July	73
August	114
September	10
October	-
Total	197

† Precipitation records were obtained from Crop Stress Laboratory, Bushland, TX

3.2.3.2 Observation and Growth Measurement

The main focus of the study was to measure and compare grain and biomass yield in the corn plants grown in clump and ESP planting geometries. Yield data were obtained after plant harvest.

3.2.3.3 Weed Management

Weeds in the field were managed by hand hoeing for the first month and thereafter by spraying Roundup [Glyphosate (N-phosphonomethyl) glycine)] as per need at the concentration of 24 ml per liter of water.

3.2.3.4 Insect Pest Management

A grasshopper infestation was noticed in the corn plots during the vegetative growth stage. Grasshopper infestation was managed using the same methods as in 2015 grain sorghum field study (section 3.2.2.4).

3.2.3.5 Crop Harvesting and Sample Processing

Corn plots were harvested on October, 02 (100 DAP). Plants from the middle four rows 13 m^2 (4.3 m X 3 m) in each plot were harvested and biomass yield was calculated. Ears and stover were harvested separately for the two innermost rows [6.5 m^2 (4.3 m X 1.5 m)] and harvest index was calculated. Seed moisture was measured using a Dickey John moisture tester. Stover samples were dried in an oven at 60°C and weight was recorded when weights were constant.

3.2.3.6 Soil Moisture Measurement

Soil moisture measurements were taken and data were obtained using the same method as in the 2015 grain sorghum field study (section 3.2.2.7).

3.2.3.7 Estimation of T/ET

T/ET was in the corn plots were estimated as in the 2015 grain sorghum field study (section 3.2.2.8). TR for corn was assumed same as grain sorghum.

3.2.3.8 N and P Uptake in Aboveground Biomass

N and P uptake in aboveground biomass were calculated in the same way as in the 2014 grain sorghum field study (section 3.2.1.5).

3.2.3.9 Statistical Analysis

Statistical analysis for yield parameters, nutrient uptake, and soil moisture content were done as in the 2015 grain sorghum field study (section 3.2.2.10).

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Greenhouse Studies

4.1.1 2014 (Grain Sorghum)

4.1.1.1 Yield parameters

Fertilizer level or planting geometry did not significantly affect grain yield. However, planting geometry had a significant effect ($P \leq 0.05$) on stover yield (Table 4.1). ESP plants produced higher stover yield (126 g box $^{-1}$) than clump plants (86 g box $^{-1}$) (Table 4.2). ESP plants produced tillers (1.05 tillers plant^{-1}) but clump plants did not have any tillers, at flag leaf stage, when the number of tillers was determined (Table 4.2). More tillers per plant in the ESP treatment significantly ($P \leq 0.05$) affected harvest index (Table 4.1). ESP plants had lower harvest index (0.50) than clump plants (0.58) (Table 4.2).

Planting geometry and interaction between planting geometry and fertilizer level had a significant effect ($P \leq 0.05$) on total nitrogen uptake in aboveground biomass, while planting geometry and fertilizer levels had no significant effect ($P \leq 0.05$) on phosphorus uptake in aboveground biomass (Table 4.1). ESP plants had higher nitrogen uptake (4.22 g box $^{-1}$) than clump plants (3.73 g box^{-1}) (Table 4.2). ESP-level 2 had the highest (4.66 g box $^{-1}$) and clump-level 2 had the lowest (3.69 g box^{-1}) amount of fertilizer nitrogen uptake ($P \leq 0.05$) (Table 4.3). Result shows higher rate of fertilizer increased tillers in ESP planting geometry and increased total nitrogen uptake in aboveground biomass but did not increase total yield.

No significance difference in grain yields were observed due to fertilizer rates and planting geometries, indicating that amounts of N and P at the high fertilizer rate were higher than required by plants for grain. Fertilizer burn, in high fertilizer rate, observed during early vegetative growth may also had an effect on grain yield (A Table 1).

Stover yield in ESP was significantly higher than clump geometry. Significantly more tillers in ESP plants increased stover yield in ESP resulting in significantly lower harvest index compared to clump plants. Planting grain sorghum in clumps than ESP helps to minimize tiller production (Krishnareddy et al., 2010). Bandaru et al. (2006) and Kapanigowda et al., (2010) reported higher harvest index in clump plants under dryland condition. While grain yields were same, higher aboveground biomass in ESP planting geometry may have increased total N uptake, since the growing medium was a significant source of P, it resulted in no effect on P uptake in aboveground biomass.

Table 4.1: Summary table of P>F values for grain weight, stover weight, harvest index, tillers per plant, and N and P uptake in aboveground biomass

Parameter	Fertilizer	Geometry	Fertilizer X Geometry
Grain weight	0.0939	0.5672	0.3039
Stover weight	0.2457	0.0013	0.2974
Harvest index	0.7418	0.0328	0.9122
Tillers per plant	0.1027	- §	-
N uptake in aboveground biomass	0.0777	0.0408	0.0448
P uptake in aboveground biomass	0.9778	0.4318	0.9778

§ Sorghum plants in clumps did not have any tillers at flag leaf stage

Table 4.2: Effect of planting geometry and fertilizer level on grain weight, stover weight, harvest index, tillers per plant, and N and P uptake in aboveground biomass

Treatment	Dry grain wt. (g box^{-1})	Dry stover wt. (g box^{-1})	Harvest index (ratio)	Tillers (tillers plant $^{-1}$)	N uptake (aboveground biomass) (g box^{-1})	P uptake (aboveground biomass) (g box^{-1})
Fertilizer¶						
Level 1	128	126	0.54	0.63	3.77	0.54
Level 2	112	125	0.53	0.41	4.17	0.54
Geometry						
Clump	118	86b	0.58a	0 §	3.73b	0.51
ESP	122	126a	0.50b	1.05	4.22a	0.56

Numbers within a column followed by the different letters are statistically significant at $P \leq 0.05$
¶: fertilizer level [Level 1(4.32 g N and 0.63 P) box^{-1}, level 2 (8.64 g N and 1.25 g P) box^{-1}]
§ Sorghum plants in clumps did not have any tillers at flag leaf stage

Table 4.3: Effect of interaction between planting geometries and fertilizer levels on N uptake in aboveground biomass

Geometry	Fertilizer	N uptake in aboveground biomass (g box^{-1})
ESP	Level 1	3.78b
	Level 2	4.66a
Clump	Level 1	3.76b
	Level 2	3.69b

Numbers within a column followed by the different letters are statistically significantly at $P \leq 0.05$

Fertilizer level and planting geometry had no significant effect ($P \leq 0.05$) on root-shoot ratio (ratio of dry root weight to dry aboveground biomass weight) (Table 4.4). Fertilizer level had a highly significant effect ($P \leq 0.001$) on fertilizer Nitrogen Use Efficiency (NUE) and fertilizer Phosphorus Use Efficiency (PUE) (kilogram of grain produced per kilogram of fertilizer N or P applied) (Table 4.4). Planting geometry did not have a significant effect ($P \leq 0.05$) on NUE and PUE (Table 4.4). NUE in the level 1 (30 kg kg^{-1} N) was more than double in level 2 (13 kg kg^{-1} N) (Table 4.5). PUE in level 1 (204 kg kg^{-1} P) was significantly higher than in level 1 (90 kg kg^{-1} P) (Table 4.5).

Fertilizer level did not significantly affect root weight and root shoot ratio. Indicating that root shoot ratio is independent of fertilizer levels. The another possibility could be the higher fertilizer rate may have affected root and shoot growth in early vegetative growth phase resulting in no difference in root weight and root shoot ratio. Low fertilizer resulted higher fertilizer N and P use efficiency. It indicates low fertilizer treatment used the applied fertilizer nitrogen and phosphorus more efficiently to produce grain.

Table 4.4 Summary table of P>F values for root weight, and root-shoot ratio, N use efficiency and P use efficiency

Parameter	Fertilizer	Geometry	Fertilizer X Geometry
Root weight	0.6376	0.7479	0.4341
Root-shoot ratio	0.2168	0.2816	0.2168
N use efficiency	<0.0001	1.0000	0.1987
P use efficiency	<0.0001	0.7326	0.2319

Table 4.5 Effect of fertilizer level and planting geometry on root weight, root-shoot ratio, N use efficiency and P use efficiency

Treatment	Dry root wt. (g box^{-1})	Root-shoot ratio	N use efficiency † (kg kg^{-1} N)	P use efficiency †† (kg kg^{-1} P)
Fertilizer				
Level 1	47	0.19	30a	204a
Level 2	49	0.24	13b	90b
Geometry				
Clump	47	0.24	21	146
ESP	49	0.20	21	149

Numbers within a column followed by the different letters are statistically significant at P≤0.05
† Nitrogen use efficiency = Dry grain yield (kg)/fertilizer N applied (kg)
†† Phosphorus use efficiency = Dry grain yield (kg grain)/fertilizer P applied (kg)

4.1.1.2 Nutrient Deficiency Symptoms

Plants grown in ESP planting geometry showed yellowing in leaves in the beginning of grain filling stage (Figure 4.1). However, the leaves on the plants grown in clump geometry were greener than those on the plants in ESP in all fertilizer levels. ESP plants produced more tillers, absorbed more nitrogen during early vegetative growth stage and showed the early sign of nutrient deficiency.

Figure 4.1 Nitrogen deficiency symptom in plants with low fertilizer treatment in ESP planting geometry, 2014 (grain sorghum)

4.1.1.3 Root Observation

The board on the side of the box was removed after plant harvest. Though full growth of the roots were restricted due to the size of the growing boxes, plants in the clump and ESP planting geometry showed different rooting patterns. Observations over the course of the experiment indicates that plants in clump produced roots that extended angularly (Figure 4.2), while roots in the plants grown with the ESP planting geometry extended straight downward (Figure 4.3). More vigorous root systems were observed in boxes with high numbers of tillers. No visual difference was not noticed between full and half fertilizer treatment. Another research at West Texas A&M University also showed similar rooting patterns in plants grown with clump and ESP planting geometry (Schneider, 2009).

Figure 4.2 Rooting pattern of grain sorghum plants grown in a clump planting geometry, Canyon, Texas, 2014 (Grain Sorghum)

Figure 4.3 Rooting pattern of grain sorghum plants grown in an ESP planting geometry, Canyon, Texas, 2014 (Grain Sorghum)

4.1.2 2015 (Grain Sorghum)

4.1.2.1 Yield parameters

Planting geometry significantly affected ($P \leq 0.05$) grain yield while fertilizer levels did not affect grain yield (Table 4.6). Plants in clumps produced 1.75 times more grain yield (105 g box^{-1}) than plants in ESPs (64 g box^{-1}) (Table 4.7). Both planting geometry and fertilizer level had a highly significant ($P \leq 0.001$) effect on stover yield (Table 4.6). Clump plants produced significantly lower stover yield (140 g box^{-1}) than ESP plants (187 g box^{-1}), while increasing fertilizer levels: level1, level2, level 3 increased stover yield (127 g box^{-1}), (172 g box^{-1}), (192 g box^{-1}) respectively (Table 4.7).

ESP plants plants produced significantly ($P \leq 0.05$) more tillers per plant (3.28 tillers $plant^{-1}$) than clump plants (0.17 tillers $plant^{-1}$) (Table 4.7). More tillers per plant and lower grain yield in ESP planting geometry significantly decreased ($P \leq 0.05$) harvest index (Table 4.6). ESP plants had lower harvest index (0.26) than clump plants (0.43) (Table 4.7). Both planting geometry and fertilizer levels had a significant effect ($P \leq 0.05$) on tillers with a panicle per plant (Table 4.6). ESP plants had more tillers with a panicle (2.27 tillers $plant^{-1}$) compared to clump plants (0.17 tillers $plant^{-1}$) (Table 4.7), however little or no grain in the panicle of ESP plants could not increase grain yield. It indicates that clump plants produce fewer tillers but there is a high probability of these tillers having a productive head, while ESP plants produce more tillers, then may not produce a panicle or one with little or no grain. ESP level 3 produced 3.17 tillers $plant^{-1}$ while clump level 3 did not produce any tillers (Table 4.8). This indicates widely and evenly spaced plants produced excess photosynthate under high fertility.

Planting geometry had a highly significant ($P \leq 0.001$) effect on total nitrogen uptake in aboveground biomass (Table 4.6). Significantly higher grain yield in clump planting geometry resulted in higher nitrogen uptake (4.14 g box^{-1}) compared to ESP plants (3.84 g box^{-1}) (Table 4.7). Though nitrogen uptake amount in aboveground biomass values for level 1, level 2, and level 3 were 2.17 g box^{-1}, 4.34 g box^{-1}, 5.48 g box^{-1} respectively, they were not statistically different. Planting geometry did not have a significant effect ($P \leq 0.05$) on total aboveground P uptake but fertilizer level did have a highly significant effect ($P \leq 0.001$) on aboveground P uptake (Table 4.6). Level 3 and 2 had significantly higher P uptake (0.63 g box^{-1}) and (0.58 g box^{-1}) in aboveground biomass compared to level 1 (0.35 g box^{-1}) (Table 4.7).

Clump plants produced more grain yield than ESP plants. In the 2014 greenhouse study both planting geometry had similar yield. However, in 2015 ESP plant produced more tillers during the vegetative growth phase but, many of the produced tillers did not bear any head resulting in significant reduction in grain yield in ESP plants. Medium fertilizer level produced significantly higher grain yield ($P \leq 0.1$). It indicates medium as the suitable fertilizer rate. Though plants did not show any sign of fertilizer burn at the higher rates and also showed no response to high N and P supply.

ESP plants produced more tillers and reduced harvest index than clump plants as described in the 2014 greenhouse study. ESP plants produced more stover yield than clumps by producing more tillers. High fertilizer rate also stimulated more tiller production during the vegetative growth phase. In contrast to N uptake in aboveground biomass in the 2014 greenhouse study, plants in clump absorbed more N from applied fertilizer. Grain has a higher percentage of N concentration than any other plant parts. Clump plants produced more grain and translocated more N from applied fertilizer resulting in more N uptake in aboveground biomass. Though higher fertilizer level resulted in more N uptake in aboveground biomass, values were not statistically different, indicating high variation in N uptake. Excess of plant available phosphorus may have resulted no difference in P uptake in clump and ESP plants.

Table 4.6: Summary table of P>F values for grain weight, stover weight, harvest index, tillers per plant, tillers with panicle per plant, fertilizer N and P uptake in aboveground biomass

Parameter	Fertilizer	Geometry	Fertilizer X Geometry
Grain weight	0.5079	0.0004	0.0807
Stover weight	<.0001	<.0001	0.1078
Harvest index	0.0949	<0.0001	0.1428
Tillers per plant	0.2014	<0.0001	0.0742
Tillers w/ panicle per plant	0.0005	<0.0001	0.0001
N uptake in aboveground biomass	0.1354	<.0001	0.0655
P uptake in aboveground biomass	0.0371	0.0008	0.3184

Table 4.7: Effect of fertilizer level and planting geometry on grain weight, stover weight, harvest index, tillers per plant, tillers with panicle per plant, fertilizer N and P uptake in aboveground biomass

Treatment	Dry grain wt. (g box^{-1})	Dry stover wt. (g box^{-1})	Harvest index (ratio)	Tillers (tillers plant^{-1})	Tillers w/ panicle (tillers plant^{-1})	N uptake (aboveground biomass) (g box^{-1})	P uptake (aboveground biomass) (g box^{-1})
Fertilizer §							
Level 1	78	127c	0.38	1.37	0.67b	2.17	0.35b
Level 2	90	172b	0.34	1.63	1.42a	4.34	0.58a
Level 3	86	192a	0.31	2.17	1.58a	5.48	0.63a
Geometry							
Clump	105a	140b	0.43a	0.17b	0.17b	4.14a	0.58
ESP	64b	187a	0.26b	3.28a	2.27a	3.84b	0.47

Numbers within a column followed by the different letters are statistically significant at P≤0.05

§ Fertilizer levels [Level 1(3 g N, 0.44 g P) box^{-1}, Level 2 (6 g N, 0.88 g P) box^{-1} and Level 3 (9 g N, 1.32 g P) box^{-1}]

Table 4.8: Effect of interaction between planting geometries and fertilizer levels on dry grain weight and tillers with panicle

Geometry	Fertilizer	Dry grain wt. (g box^{-1}) ψ	Tillers w/ panicle (tillers plant^{-1})ℜ
ESP	Level 1	71b	1.08c
	Level 2	59b	2.58b
	Level 3	61b	3.17a
Clump	Level 1	85b	0.25d
	Level 2	120a	0.25d
	Level 3	109a	0.00e

ℜ Numbers within a column followed by the different letters are statistically significant at P≤0.05

ψ Numbers within a column followed by the different letters are statistically significant at P≤0.10

Planting geometry ($P \leq 0.05$) and fertilizer level ($P \leq 0.001$) significantly affected dry root weight (Table 4.9). Clump plants had lower root weight (72 g box^{-1}) compared to ESP plants (113 g box^{-1}) (Table 4.10). Root weight increased with increasing fertilizer levels; 74 g box^{-1} for level 1, 96 g box^{-1} for level 2, and 108 g box^{-1} for level 3 respectively. Planting geometry significantly affected ($P \leq 0.001$) root shoot ratio (Table 4.9). Plants in ESP treatment had higher (0.44) root to shoot ratio compared to clump plants (0.30) (Table 4.10).

Both planting geometry and fertilizer level had a significant effect ($P \leq 0.05$) on fertilizer NUE and PUE (Table 4.9). Plants in clump showed higher NUE and PUE (20 kg kg^{-1}N) (138 kg kg^{-1}P) than plants in ESP (13 kg kg^{-1}N) (92 kg kg^{-1}P) respectively (Table 4.10). Increased level of fertilizer significantly reduced NUE and PUE (Table 4.10). Both NUE and PUE were highest (26 kg kg^{-1}N) (178 kg kg^{-1}P) at fertilizer level 1 and lowest (10 kg kg^{-1}N) (65 kg kg^{-1}P) at fertilizer level 3.

Increased fertilizer level increased the tillers per plant. ESP plants had more root weight, which may have resulted in more tillers produced in the plants. Sorghum plants with more tillers produced more extensive root system and extracted more water (Broad and Hammer, 2004). Plants in ESP had higher root-shoot ratio, indicating ESP plants produced a better developed root system maybe because water stress caused greater exploration of growing medium. Clump plant showed higher N and P use efficiency. An abundant supply of nutrients in the root zone resulted in higher NUE and PUE in clump plants. Moreover, use efficiency is directly proportional to the grain yield. Plants in clump planting geometry had significantly higher grain yield and high harvest index, which resulted in higher NUE and PUE. Higher NUE and PUE at low fertilizer levels indicates plant efficiently use applied nutrients when they are supplied with lower rate.

Table 4.9 Summary table of P>F values for growing season water use, root weight, root-shoot ratio, N use efficiency, and P use efficiency

Parameter	Fertilizer	Geometry	Fertilizer X Geometry
Growing season water use	<0.0001	0.0181	0.5326
Root weight	<0.0001	0.0012	0.3553
Root-shoot ratio	0.3745	<0.0001	0.1018
N use efficiency	0.0007	<0.0001	0.2537
P use efficiency	0.0007	<0.0001	0.2540

Table 4.10 Effect of fertilizer level and planting geometry on growing season water use, root weight, root-shoot ratio, N use efficiency, and P use efficiency

Treatment	Growing season wate use (lit)	Dry root wt. (g box^{-1})	Root-shoot ratio	N use efficiency † (kg kg^{-1}N)	P use efficiency †† (kg kg^{-1}P)
Fertilizer					
Level 1	80b	74c	0.35	26a	178a
Level 2	95a	96a	0.37	15b	102b
Level 3	99a	108a	0.39	10c	65c
Geometry					
Clump	90b	72b	0.30b	20a	138a
ESP	93a	113a	0.44a	13b	92b

Numbers within a column followed by the different letters are statistically significant at P≤0.05
† Nitrogen use efficiency = Dry grain yield (kg)/fertilizer N applied (kg)
†† Phosphorus use efficiency = Dry grain yield (kg)/fertilizer P applied (kg)

4.1.2.2 Plant Stress Symptoms

Plants grown in clumps showed lesser water stress in all fertilizer levels than plants grown in ESP. Higher water stress in ESP plants may have resulted due to higher amount of water used by tillers in produced. used High fertilizer treatment showed earlier sign of water stress than medium and low fertilizer treatment. High and medium fertilizer showed more frequent water stress signs than low fertilizer treatment.

4.1.2.3 Root Observation

Roots were observed against the Plexiglas wall 16 DAP both in clump and ESP treatments. Plants roots in the clump planting geometry showed spreading and an angular root growing pattern from the beginning, while plants in the ESP showed roots growing straight downward. However, only the roots developed against the wall could be observed, regular observation showed roots grown in the ESP planting geometry extended to the bottom earlier than roots of plants grown in the clump planting geometry. Plant roots at 65 days after planting in clump planting geometry were spread across the box depth while, roots of the plants in ESP planting geometry were more concentrated at the top of the box. Growing medium in the clump planting geometry was wetter than the growing medium in the ESP in all treatments. More roots were observed in the box with more tillers. Though fertilizer treatment did not show any visual difference between the roots of the plants among high, medium, and low fertilizer treatments during plant growth stages, root observation after root extraction showed some differences. Roots in the high and medium fertilizer treatment was denser and more robust than low fertilizer treatment roots in both planting geometries.

Figure 4.4 Root growth pattern and growing medium moisture status in ESP (left) and clump (right) treatment boxes, Canyon, Texas, 2015.

Figure 4.5 Plants in clump (left) and equally spaced planting (right) geometry, Canyon, Texas, 2015

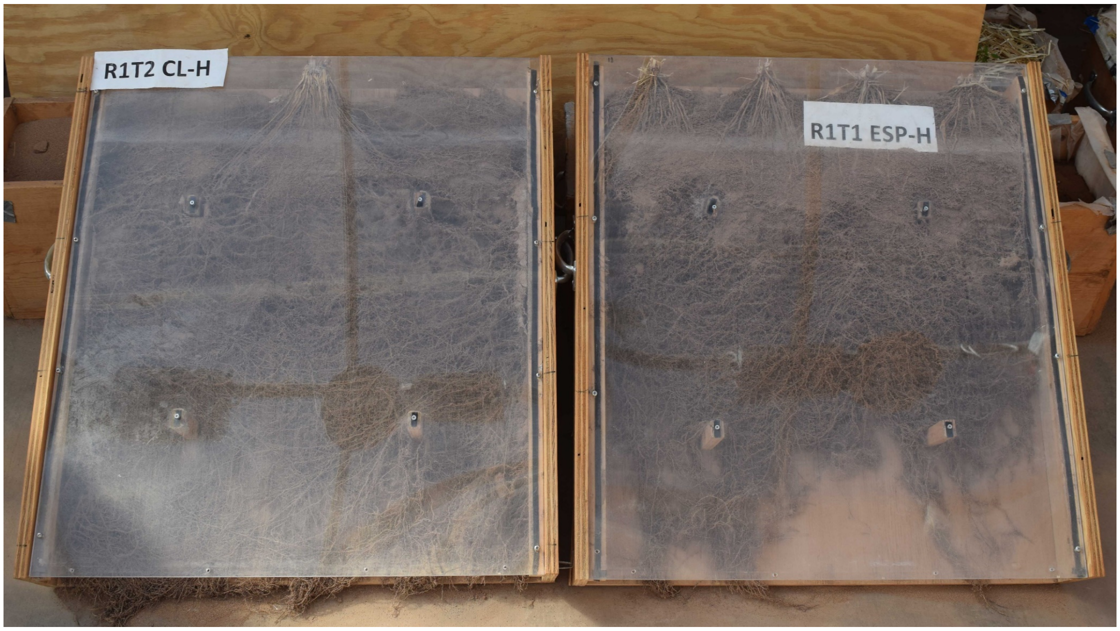

Figure 4.6 Roots of sorghum plants grown in clump (left) and ESP (right) planting geometry at high fertilizer treatment

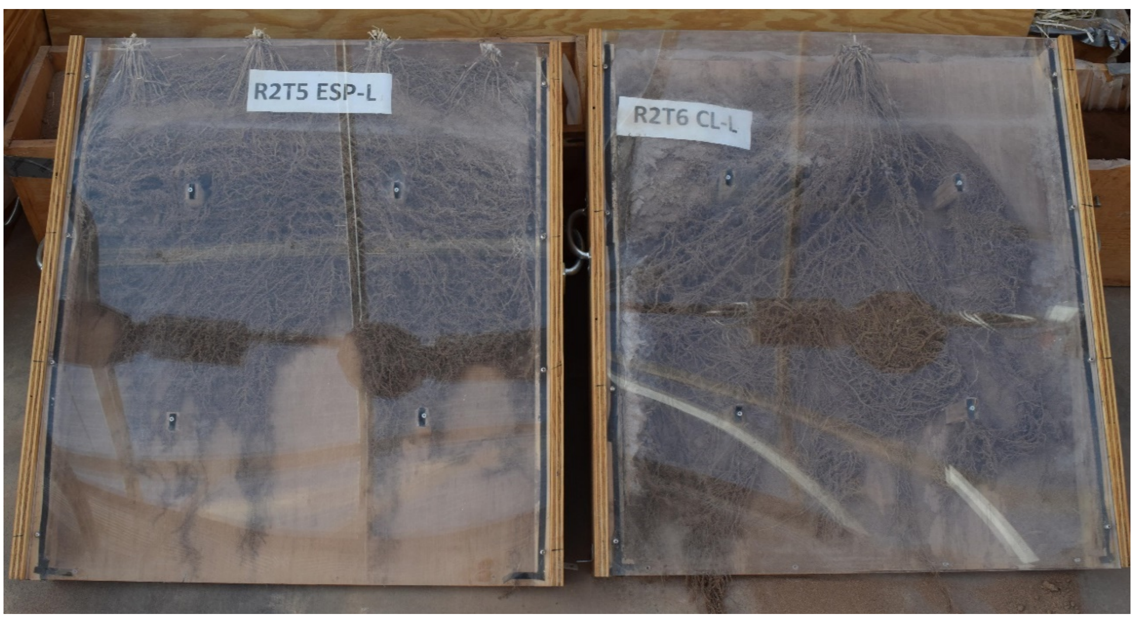

Figure 4.7 Roots of sorghum plants grown in clump (right) and ESP (left) planting geometry at low fertilizer treatment.

4.2 Field Studies

4.2.1 2014 (Grain Sorghum)

Planting geometry and fertilizer treatment had no significant effect ($P \leq 0.05$) on grain yield or harvest index but had a significant effect ($P \leq 0.05$) on stover yield (Table 4.11). Stover yield was higher in ESP plots (5463 kg ha^{-1}) than clump plots (4743 kg ha^{-1}) (Table 4.12). Plants in ESP produced significantly more tillers than plants in clumps (Table 4.13). ESP plants produced more tillers (1.85 $plant^{-1}$) than those in clumps (0.16 $plant^{-1}$) (Table 4.14), which increased total stover yield. N and P uptake in aboveground biomass were significantly affected ($P \leq 0.05$) by planting geometry but N and P uptake were not affected by fertilizer levels (Table 4.11). N and P uptake in ESP plants (164 kg ha^{-1}) (21 kg ha^{-1}) were higher than clump plants (130 kg ha^{-1}) (17 kg ha^{-1}) (Table 4.12).

Lack of plant available soil moisture during anthesis causes significant reduction in grain yield in grain sorghum (Bandaru et al., 2006). Plants at the active vegetative growth stage did not receive enough precipitation. Less than half of the tillers produced a panicle in ESP plants. Panicles on the tillers were small and had only a few grains, which resulted in low grain yield. Later, the crop received precipitation (144 mm) in September when main stalk heads were at soft dough stage. Late season precipitation stimulated the production of more tillers but they barely produced any head. Thus, total biomass production was increased significantly, but grain yields were increased little or none. Clump plants had a greater percentages of tillers with a panicle, which resulted in greater harvest index than ESP plants. Fertilized treatment resulted in more N uptake due to more tillers produced. Newly produced tillers are rich in crude protein resulting in more N and P uptake in aboveground biomass. Myers (1978a) reported grain sorghum grown in high

N treatment plots showed reduced grain yield, which may have seen due to excessive vegetative growth resulting in less available water for grain filling stage. Planting grain sorghum in clumps helps to minimize tiller production (Krishnareddy et al., 2010). Bandaru et al. (2006): Kapanigowda et al., (2010) reported higher harvest index in clump plants under dryland conditions.

Table 4.11: Summary table of P>F values for grain weight, stover weight, harvest index, and N and P uptake in aboveground biomass

Parameter	Fertilizer	Geometry	Fertilizer X Geometry
Grain weight	0.9535	0.6672	0.3144
Stover weight	0.1311	0.0010	0.6543
Harvest Index	0.5831	0.0915	0.3075
N uptake in aboveground biomass	0.0633	0.0064	0.7482
P uptake in aboveground biomass	0.9231	0.0455	0.1818

Table 4.12: Effect of fertilizer level and planting geometry on grain weight, stover weight, harvest index, and N and P uptake in aboveground biomass

Treatment	Dry grain wt. (kg ha^{-1})	Dry stover wt. (kg ha^{-1})	Harvest index (ratio)	N uptake (aboveground biomass) (kg ha^{-1})	P uptake (aboveground biomass) (kg ha^{-1})
Fertilizer §					
Unfertilized	1852	5463	0.26	138	19
Fertilized	1874	6066	0.24	157	19
Geometry					
Clump	1943	4743b	0.29	130b	17b
ESP	1783	5463a	0.21	164a	21a

Numbers within a column followed by the different letters are statistically significant at $P \leq 0.05$

§ Fertilizer levels: Fertilized (68 kg N ha^{-1} and 10 kg P ha^{-1}), Unfertilized: no fertilizer added

Table 4.13 Summary table of P>F values for tillers per plant, tillers with panicle per plant, and percent tillers with panicle

Parameter	Fertilizer	Geometry	Fertilizer X Geometry
Tillers per plant	0.2474	<0.0001	0.4003
Tillers with panicle per plant	0.7187	0.0047	0.4911
% tillers with panicle	0.9309	0.3043	0.3360

Table 4.14 Effect of fertilizer level and planting geometry on tillers per plant, tillers with panicle per plant, and percent tillers with panicle

Treatment	Tiller (tillers $plant^{-1}$)	Tillers w/ panicle (tillers $plant^{-1}$)	% tillers w/ panicle
Fertilizer			
Unfertilized	0.91	0.45	47
Fertilized	1.10	0.39	46
Geometry			
Clump	0.16b	0.09b	55
ESP	1.85a	0.74a	39

Numbers within a column followed by the different letters are statistically significant at P≤0.05

Planting geometry significantly affected NUE and PUE (Table 4.15). Clump plants had higher NUE and PUE (32 kg kg^{-1} N) (215 kg kg^{-1} P) than ESP planting geometry (23 kg kg^{-1} N) (160 kg kg^{-1} P) (Table 4.16). Clump plants showed higher N and P use efficiency. Fertilizer was applied in a thick band under clumped plants which may have supplied enough N and P in the plant root zone and resulted in better plant response to applied fertilizer.

Table 4.15 Summary table of P>F values for N use efficiency, and P use efficiency

Parameter	Geometry
N use efficiency	0.0420
P use efficiency	0.0342

Table 4.16 Effect of fertilizer level and planting geometry in N use efficiency and P use efficiency

Treatment	N use efficiency† (kg kg^{-1} N)	P use efficiency†† (kg kg^{-1} P)
Geometry		
Clump	32a	215a
ESP	23b	160b

Numbers within a column followed by the different letters are statistically significant at P≤0.05
† Nitrogen use efficiency = Dry grain yield (kg)/fertilizer N applied (kg)
†† Phosphorus use efficiency = Dry grain yield (kg)/fertilizer P applied (kg)

4.2.2 2015 (Grain Sorghum)

Planting geometry and fertilizer levels did not have a significant effect ($P \leq 0.05$) on grain yield (Table 4.17). However, planting geometry significantly ($P \leq 0.05$) affected stover yield (Table 4.17). ESP plants produced more biomass (5297 kg ha^{-1}) than clump plants (4437 kg ha^{-1}) (Table 4.18). Both planting geometry and fertilizer level significantly ($P \leq 0.05$) affected harvest index (Table 4.17). Plants in clumps had higher harvest index (0.44) compared to plants in ESP (0.40). Similarly, unfertilized plots had higher harvest index (0.43) than fertilized (0.40) (Table 4.18). Planting geometry, fertilizer levels, and their interaction had significant effects ($P \leq 0.05$) on number of tillers produced during the vegetative growth stage (Table 4.20). Plants in the ESP-fertilized treatment produced the highest number tillers (1.93 $plant^{-1}$) and clump unfertilized treatment produced the lowest number of tillers (0.13 $plant^{-1}$) (Table 4.22). Later, many of these adventitious tillers died and many of them did not produce a head. At harvesting stage, plants in ESP geometry had significantly more ($P \leq 0.05$) tillers (1.18 tillers $plant^{-1}$) than the clump treatment (0.30 tillers $plant^{-1}$) and those in the fertilized treatment had significantly more ($P \leq 0.001$) tillers (1.00 tillers $plant^{-1}$) than those in the unfertilized treatment (0.48 tillers $plant^{-1}$) (Table 4.21). Plants used some of available water to produce tillers and this resulted in insufficient water to produce productive heads during grain filling stage.

Fertilizer levels and interaction between planting geometry and fertilizer levels had a significant ($P \leq 0.05$) effect on aboveground N uptake (Table 4.17). However, planting geometry and fertilizer level did not have a significant effect on aboveground P uptake. Fertilized plants had significantly higher N uptake (97 kg ha^{-1}) compared to unfertilized plants (92 kg ha^{-1}) (Table 4.18). Fertilized plants produced more tillers per plants and used more N from soil. Clump fertilized treatment had significantly ($P \leq 0.05$) higher nitrogen uptake (92 kg ha^{-1}) compared to other treatments (Table 4.19). High nitrogen concentration in grain and stover may have resulted in more uptake in clump-fertilized treatment.

Grain and stover yield were not affected by fertilizer levels. Both planting geometries yield similar amounts of grain. High amount of precipitation and N supply (as described in 2014 field study) during the vegetative growth stage resulted in more tillers in ESP planting geometry. Consequently, many tillers died and many that survived did not produce grain due to unavailability of soil water during the grain filling stage, resulting in similar yields for clump and ESP planting geometry. More tillers in ESP resulted in lower harvest index than clump plants as described in 2014 field study. Fertilized treatment resulted in more N uptake due to more tillers produced. Phosphorus uptake remained unaffected by fertilizer levels and planting geometry which may be due to abundant plant available phosphorus.

Table 4.17 Summary table of P>F values for grain weight, stover weight, harvest index, and N and P uptake in aboveground biomass

Parameter	Fertilizer	Geometry	Fertilizer X Geometry
Grain weight	0.2690	0.7720	0.9873
Stover weight	0.1836	0.0017	0.9718
Harvest index	0.0336	0.0126	0.9224
N uptake in aboveground biomass	0.0319	0.3053	0.0032
P uptake in aboveground biomass	0.2031	0.6582	0.6582

Table 4.18 Effect of fertilizer level and planting geometry on grain weight, stover weight, harvest index, and N and P uptake in aboveground biomass

Treatment	Dry grain wt. (kg ha^{-1})	Dry stover wt. (kg ha^{-1})	Harvest index (ratio)	N uptake (aboveground biomass) (kg ha^{-1})	P uptake (aboveground biomass) (kg ha^{-1})
Fertilizer §					
Unfertilized	3590	4726	0.43a	92b	14
Fertilized	3348	5008	0.40b	97a	14
Geometry					
Clump	3439	4437b	0.44a	94	14
ESP	3500	5297a	0.40b	96	14

Numbers within a column followed by the different letters are statistically significant at P≤0.05

§ Fertilizer levels: Fertilized (68 kg N ha^{-1} and 10 kg P ha^{-1}), Unfertilized: no fertilizer added

Table 4.19 Effect of interaction between planting geometries and fertilizer levels on N uptake in aboveground biomass

Geometry	Fertilizer	N uptake in aboveground biomass (kg ha^{-1})
ESP	Unfertilized	97a
	Fertilized	94a
Clump	Unfertilized	87b
	Fertilized	100a

Numbers within a column followed by the different letters are statistically significant at P≤0.05

Table 4.20 Summary table of P>F values for tillers per plant 66 DAP, tillers per plant at harvest, tillers with panicle at harvest and percent tillers with panicle

Parameter	Fertilizer	Geometry	Fertilizer X Geometry
Tillers per plant 66 DAP	0.0047	<0.0001	0.0369
Tillers per plant at harvest	0.0015	0.0008	0.2825
Tillers w/ panicle per plant at harvest	0.0027	0.0026	0.0910
% tillers w/ panicle at harvest	0.2499	0.0179	0.0910

Table 4.21 Effect of fertilizer level and planting geometry on tillers per plant 66 days after planting (DAP), tillers per plant at harvest, tillers with panicle at harvest and percent tillers with panicle

Treatment	Tillers 66 DAP (tillers $plant^{-1}$)	Tillers at harvest (tillers $plant^{-1}$)	Tillers w/ panicle at harvest (tillers $plant^{-1}$)	% tillers w/ panicle
Fertilizer				
Unfertilized	0.56b	0.48b	0.27b	83
Fertilized	1.13a	1.00a	0.80a	73
Geometry				
Clump	0.23b	0.30b	0.27b	88a
ESP	1.46a	1.18a	0.80a	67b

Numbers within a column followed by the different letters are statistically significant at $P \leq 0.05$

Table 4.22 Effect of planting geometries and fertilizer level interaction on tillers per plant 66 DAP

Geometry	Fertilizer	Tillers 66 DAP (tillers $plant^{-1}$)
ESP	Unfertilized	0.99b
	Fertilized	1.93a
Clump	Unfertilized	0.13c
	Fertilized	0.33c

Numbers within a column followed by the different letters are statistically significant at $P \leq 0.05$

Estimated Transpiration/ evapotranspiration ratio (the portion of ET that is used as T) was significantly affected ($P \leq 0.05$) by planting geometry (Table 4.23). ESP planting geometry had higher T/ET (0.60) than in clump (0.54) (Table 4.24). Fertilizer treatment showed no significant difference in T/ET.

The ESP plants produced a more complete crop canopy than the clump plants, so there was more shading of the soil surface. That is believed to have reduced water evaporation from the soil surface (Stewart and Peterson, 2015). Tillers in ESP plants created even more canopy cover resulted in significantly higher T/ET ratio than in clump plants.

Table 4.23 Summary table of P>F for estimated T/ET

Parameter	Fertilizer	Geometry	Fertilizer X Geometry
T/ET	0.8055	0.0347	0.8576

Table 4.24 Effect of fertilizer level and planting geometry on estimated T/ET

Treatment	Estimated T/ET (ratio)
Fertilizer	
Unfertilized	0.57
Fertilized	0.56
Geometry	
Clump	0.54b
ESP	0.60a

Numbers within a column followed by the different letters are statistically significant at P≤0.05

Planting geometry did not significantly affect (P≤0.05) fertilizer NUE and PUE (Table 4.25). Clump and ESP planting geometry had similar grain yield and enough supply of N and P resulted no difference in N and P use efficiencies.

Table 4.25 Summary table of P>F values of N use efficiency and P use efficiency

Parameter	Geometry
N use efficiency	0.9202
P use efficiency	0.8588

Table 4.26 Effect of fertilizer level and planting geometry on N use efficiency and P use efficiency

Treatment	N use efficiency † ($kg\ kg^{-1}N$)	P use efficiency †† ($kg\ kg^{-1}P$)
Geometry		
Clump	49	334
ESP	50	340

Numbers within a column followed by the different letters are statistically significant at P≤0.05
† Nitrogen use efficiency = Dry grain yield (kg)/fertilizer N applied (kg)
†† Phosphorus use efficiency = Dry grain yield (kg grain)/fertilizer P applied (kg)

4.2.3 2015 (Corn)

Planting geometry did not have a significant effect on grain yield and harvest index but stover yield was significantly affected (P≤0.05) by planting geometry (Table

4.31). ESP plants produced significantly more stover yield (6961 kg ha^{-1}) compared to clump plants (6104 kg ha^{-1}) (Table 4.32). Planting geometry did not have any effect on aboveground N and P uptake, and T/ET ratio.

Plants were grown without fertilizer application. Plants in ESP produced very few tillers; hence, no data for tillers were obtained. Higher stover yield in ESP plants resulted from more vegetative growth due to better response to plant available water. Lack of plant available water during the grain filling stage resulted in no difference in grain yield in clump and ESP treatments. Similar grain yield and harvest index resulted in no difference in N and P uptake in aboveground biomass. Estimated T/ET ration was not affected by planting geometry. However, short height of sorghum plants and more tillers created a more complete canopy cover than corn plants, which resulted in higher T/ET ratio in sorghum plots.

Table 4.27 Summary table of P>F values of grain weight, biomass weight, harvest index, N and P uptake in aboveground biomass, and estimated T/ET

Parameter	Geometry
Grain weight	0.1716
Stover weight	0.0267
Harvest Index	0.0609
N uptake in aboveground biomass	0.7888
P uptake in aboveground biomass	0.3081
Estimated T/ET	0.0577

Table 4.28 Effect of planting geometry in dry grain weight, dry biomass weight, harvest index, N and P uptake in aboveground biomass, and estimated T/ET

Treatment	Grain weight (kg ha^{-1})	Stover weight (kg ha^{-1})	Harvest index (ratio)	N uptake (kg ha^{-1})	P uptake (kg ha^{-1})	Estimated T/ET
Geometry						
Clump	2957	6104b	0.49	70	12	0.45
ESP	3157	6961a	0.46	71	13	0.50

Numbers within a column followed by the different letters are statistically significant, P≤0.05

CHAPTER V
SUMMARY AND CONCLUSIONS

In the 2014 greenhouse study, clump planting geometry did not have a significant effect on grain yield, P uptake in aboveground biomass, nitrogen use efficiency (NUE), phosphorus use efficiency (PUE), root weight, or root shoot ratio. Dry stover weight, tillers per plant, and N uptake in the aboveground biomass were significantly higher in ESP plants than in clumps. However, harvest index in clump plants was significantly higher compared to ESP plants. It indicates ESP plants used more assimilates to produce tillers. Fertilizer levels had a significant effect on NUE and PUE. Plants in the low fertilizer level had significantly higher NUE and PUE than higher fertilizer level. Though N uptake in aboveground biomass was significantly higher in ESP plants, NUE was not affected by geometry.

In the 2015 greenhouse study, clump planting geometry had significantly higher grain yield, harvest index, N uptake in aboveground biomass, NUE, and PUE than in ESPs. Clump plants produced significantly fewer tillers per plant and tillers with panicle per plant than ESP. Also, clump plants had significantly lower stover weight, and root shoot ratio. Fertilizer levels had a significant effect on stover yield, tillers with panicle per plant, root weights, NUE, and PUE. Higher fertilizer level increased dry stover yield, tillers with panicles per plant, P uptake in aboveground biomass and dry root weight. However, plants in low level of fertilization had significantly higher NUE and PUE than high fertilizer levels.

Fertilizer level did not have a significant effect on grain yield in either year. Clump plants had more grain yield, more aboveground N uptake, NUE and PUE. It indicates clump plants more effectively allocated assimilates to grain yield by reducing tiller production.

Plants in clumps during the hottest time of the day were less stressed than the plants in the ESPs. ESP plants showed earlier leaf yellowing than clump plants in the low fertilizer treatment. Clump growing medium was moister than ESP treatment boxes irrespective of fertilizer levels. Roots in clump plants developed angularly and then downward while roots in ESP plants developed straight down. Higher tiller numbers were associated with more robust rooting systems.

In the 2014 field study, planting geometry did not significantly affect grain yield, and harvest index. ESP plants had significantly higher stover yield, N and P uptake in aboveground biomass and significantly more tillers per plant and tillers with panicle per plant than clumps. However, clumps had significantly higher NUE and PUE compared to ESP plots. Plants did not receive abundant precipitation in the early stage of growth followed by high precipitation during late vegetative growth stage. This resulted in the production of more tillers without a productive head. N uptake in aboveground biomass was significantly higher in ESP plants. Plants produced more tillers from the added nitrogen but grain yield remained unaffected

In the 2015 field study, planting geometry did not have a significant effect on grain yield, N and P uptake in aboveground biomass, NUE, and PUE. Plants in ESP had significantly higher stover yield, and estimated T/ET ratio. Plants in ESP also had a significantly more tillers per plant and tillers with panicle per plant than clumps. Clump plants only had significantly higher harvest index than ESP. Added fertilizer resulted in significantly higher N uptake than unfertilized plots. Fertilizer also significantly increased tillers per plant and tillers with panicle per plant and consequently reduced harvest index in fertilized plots. Plants received above average precipitation in the early vegetative growth. Enough soil moisture and applied fertilizer level stimulated tiller growth in both ESP and clump treatments but low precipitation in the following month did not support the growth of tillers to produce a panicle. Visual observation showed plants in fertilized treatments were stressed and showed the signs of maturity earlier than non-fertilizer treatments. Enough soil water and fertility resulted more photosynthate and produced more tillers but, unpredictable precipitation resulted in no added crop yield from tillers. Tillers have the potential to produce grain when moisture and nutrients are not limited, but in dryland, unpredictable precipitation may not always favor crop production. Clumped-fertilized plants showed highest N uptake than any other treatments, possibly due to better uptake of applied nutrients and ability to translocate assimilates to grain without producing more tillers.

Corn grown in the clump and ESP planting geometry in 2015 did not have a significant difference in grain yield, harvest index, N and P uptake and estimated T/ET. However, stover yield was significantly higher in ESP plants than clumps.

The ratio of transpiration and evapotranspiration (T/ET) was estimated for corn and sorghum plots for the study of 2015. T/ET ratio was significantly higher in ESP plots than clump plots in grain sorghum. Evenly distributed plants developed more tillers and crop canopy that acted as cover on the soil surface, which ultimately reduced evaporation from the soil surface. Decreased crop canopy in the clump configuration allowed more radiation to hit the ground, resulting in more evaporation from the soil surface. Thus, use of mulch to cover the soil surface in the clump planting geometry could have significant effects on increasing T/ET ratio and grain yield. Further research may help to establish the relationship of mulching, T/ET ratio and grain yield in dryland grain sorghum and corn. Hence, future potential studies are (1) to evaluate different rates of fertilizer (2) to evaluate different methods of placement under clump and ESP plants, and (3) to evaluate root growth at different fertilizer rates in the field.

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APPENDIX

A Table 1. Mean values of dry grain weight, dry stover weight, and harvest index, greenhouse 2014 (sorghum)

Geo‡	Fert¶	Dry grain weight (g box^{-1})	Dry stover weight (g box^{-1})	Harvest index (ratio)
ESP	Level 1	126	126	0.50
ESP	Level 2	119	125	0.49
CL	Level 1	130	94	0.58
CL	Level 2	106	77	0.57

‡: Planting geometry (CL: CL, ESP: Equal Spaced Planting)
¶: fertilizer level [Level 1(4.32 g N and 0.63 P)/box, level 2 (8.64 g N and 1.25 g P)/box]

A Table 2. Mean values of dry root weight, root-shoot ratio, tillers per plant, NUE, and PUE, greenhouse 2014 (sorghum)

Geo	Fert	Dry root wt. (g box^{-1})	Root-shoot ratio	Tillers (tillers plant^{-1})	NUE † (kg kg^{-1}N)	PUE †† (kg kg^{-1}P)
ESP	Level 1	47	0.19	1.25	29	200
ESP	Level 2	48	0.20	0.83	14	95
CL	Level 1	43	0.19	0	30	207
CL	Level 2	51	0.28	0	12	85

† NUE: Nitrogen use efficiency = Dry grain weight (kg)/Fertilizer N applied (Kg)
††PUE: Phosphorus use efficiency= Dry grain weight (kg)/Fertilizer P applied (Kg)

A Table 3. Mean values of percent N and P concentration in grain, percent N and P concentration in stover and percent N and P concentration in root, greenhouse 2014 (sorghum)

Geo	Fert	% N con. Grain	% P con. Grain	% N con. Stover	% P con. Stover	% N con. Root	% P con. Root
ESP	Level 1	2.14	0.35	0.86	0.09	0.72	0.16
ESP	Level 2	2.30	0.31	1.51	0.15	1.29	0.13
CL	Level 1	2.17	0.31	0.99	0.11	0.85	0.12
CL	Level 2	2.34	0.35	1.56	0.18	1.17	0.14

A Table 4. Mean values of N and P uptake in grain, N and P uptake in stover and percent fertilizer N and P uptake, greenhouse 2014 (sorghum)

Geo	Fert	N uptake in grain (g)	N uptake in stover (g)	P uptake in grain (g)	P uptake in stover (g)	% Fert N uptake§	% Fert P uptake
ESP	Level 1	2.70	1.08	0.44	0.12	87	89
ESP	Level 2	2.74	1.92	0.36	0.19	54	45
CL	Level 1	2.83	0.93	0.41	0.10	87	81
CL	Level 2	2.43	1.22	0.37	0.14	43	41

§ % fertilizer uptake = (N or P uptake in grain +N or P uptake in stover)/fertilizer N or P applied

A Table 5. Mean values of dry grain weight, dry stover weight, harvest index, root weight and root shoot ratio, greenhouse 2015 (sorghum)

Geo	Fert ϕ	Dry grain weight (g box^{-1})	Dry stover weight (g box^{-1})	Harvest index (ratio)	Dry root weight (g box^{-1})	Root-shoot † ratio
ESP	Level 1	71	142	0.33	83	0.39
ESP	Level 2	59	194	0.23	121	0.48
ESP	Level 3	62	225	0.21	128	0.45
CL	Level 1	85	112	0.43	59	0.30
CL	Level 2	120	150	0.45	70	0.26
CL	Level 3	110	159	0.41	88	0.33

ϕ Fertilizer levels [Level 1(3 g N, 0.44 g P)/box, Level 2 (6 g N, 0.88 g P) /box and Level 3 (9 g N, 1.32 g P) /box]

†Root shoot ratio = Dry root weight/ Dry aboveground biomass weight

A Table 6. Mean values of tillers per plant, tillers with panicle per plant, NUE and PUE, greenhouse 2015 (sorghum)

Geo	Fert	Tillers $plant^{-1}$	Tillers with panicle $plant^{-1}$	NUE (Kg kg^{-1}N)	PUE (Kg kg^{-1}P)
ESP	Level 1	2.50	1.08	24	162
ESP	Level 2	3.00	2.58	10	67
ESP	Level 3	4.33	3.17	7	47
CL	Level 1	0.25	0.25	28	194
CL	Level 2	0.25	0.25	20	137
CL	Level 3	0	0	12	83

A Table 7. Mean values of percent N and P concentration in grain, percent N and P concentration in stover and percent N and P concentration in root, greenhouse 2015

Geo	Fert	% N con. Grain	% P con. Grain	% N con. Stover	% P con. Stover	% N con. Root	% P con. Root
ESP	Level 1	1.71	0.29	0.62	0.08	0.68	0.05
ESP	Level 2	2.17	0.40	1.32	0.11	0.94	0.07
ESP	Level 3	2.47	0.35	1.81	0.13	1.47	0.07
CL	Level 1	1.66	0.27	0.75	0.08	0.77	0.04
CL	Level 2	2.32	0.33	1.36	0.12	0.91	0.05
CL	Level 3	2.43	0.34	1.71	0.15	1.14	0.06

A Table 8. Mean values of N and P uptake in grain, N and P uptake in stover and percent fertilizer N and P uptake in aboveground biomass, greenhouse 2015

Geo	Fert	N uptake in grain (g)	N uptake in stover (g)	P uptake in grain (g)	P uptake in stover (g)	% Fert N uptake	% Fert P uptake
ESP	Level 1	1.21	0.88	0.20	0.14	70	79
ESP	Level 2	1.27	2.58	0.24	0.26	64	57
ESP	Level 3	1.51	4.07	0.21	0.36	62	43
CL	Level 1	1.39	0.85	0.22	0.13	75	80
CL	Level 2	2.79	2.02	0.39	0.27	80	76
CL	Level 3	2.67	2.70	0.38	0.33	60	54

A Table 9. Mean values of dry grain weight, dry stover weight, dry biomass weight, and harvest index, field study 2014 (sorghum)

Geo	Fert §	Dry grain weight (kg ha^{-1})	Dry stover weight (kg ha^{-1})	Harvest index (ratio)
ESP	Unfertilized	1967	6404	0.24
ESP	Fertilized	1600	7170	0.18
CL	Unfertilized	1738	4523	0.28
CL	Fertilized	2148	4964	0.30

§ Fertilizer level (Fertilized: 68 kg N ha^{-1} and 10 kg P ha^{-1}; unfertilized: no fertilizer added)

A Table 10. Mean values of tillers per plant, tillers with panicle per plant, percent tillers with panicle per plant, NUE and PUE field study 2014 (sorghum)

Geo	Fertilizer	Tillers $plant^{-1}$	Tillers w/ panicle $plant^{-1}$	% tillers w/ panicle $plant^{-1}$	NUE (kg kg^{-1}N)	PUE (kg kg^{-1}P)
ESP	Unfertilized	1.69	0.83	47	24	160
ESP	Fertilized	2.00	0.66	32	-ψ	-
CL	Unfertilized	0.14	0.06	47	32	215
CL	Fertilized	0.19	0.12	60	-	-

ψ NUE and PUE were not estimated for unfertilized plots

A Table 11. Percent N and P concentration in grain, and percent N and P concentration in stover, field study, 2014 (sorghum)

Geo	Fertilizer	% N conc. grain	%P conc. grain	% N conc. stover	% P conc. stover
ESP	Unfertilized	2.43	0.33	1.69	0.25
ESP	Fertilized	2.56	0.36	1.83	0.20
CL	Unfertilized	2.42	0.30	1.72	0.23
CL	Fertilized	2.45	0.30	1.78	0.24

A Table 12. Mean values of grain weight, stover weight, and harvest index, field study 2015 (sorghum)

Geo	Fertilizer	Dry grain weight (kg ha^{-1})	Stover weight (kg ha^{-1})	Harvest index (ratio)
ESP	Unfertilized	3623	5160	0.41
ESP	Fertilized	3378	5434	0.38
CL	Unfertilized	3559	4292	0.45
CL	Fertilized	3320	4582	0.42

† Fertilizer level (Fertilized: 68 kg N ha^{-1} and 10 kg P ha^{-1}; unfertilized: no fertilizer added)

A Table 13. Mean values of tillers per plant at 66 DAP, number of tillers per plant at harvest, and percent tillers with panicle, field study 2015 (sorghum)

Geo	Fertilizer	66 DAP (tillers $plant^{-1}$)	At harvest (tillers $plant^{-1}$)	At harvest (tillers w/ panicle $plant^{-1}$)
ESP	Unfertilized	0.98	0.82	0.42
ESP	Fertilized	1.92	1.55	1.20
CL	Unfertilized	0.14	0.14	0.12
CL	Fertilized	0.33	0.46	0.41

A Table 14. Mean values NUE, PUE, and estimated T/ET, field study 2015 (sorghum)

Geo	Fertilizer	NUE (kg kg^{-1}N)	PUE (kg kg^{-1}P)	Estimated T/ET
ESP	Unfertilized	- ψ	-	0.60
ESP	Fertilized	50	340	0.60
CL	Unfertilized	-	-	0.54
CL	Fertilized	49	334	0.53

ψ NUE and PUE were not estimated for unfertilized plots

A Table 15. Mean values of percent N and P concentration in grain and percent N and P concentration in stover, field study 2015 (sorghum)

Geo	Fertilizer	% N con. grain	% P con. grain	% N con. stover	% P con. stover
ESP	Unfertilized	1.78	0.31	0.65	0.04
ESP	Fertilized	1.88	0.33	0.58	0.06
CL	Unfertilized	1.69	0.32	0.62	0.05
CL	Fertilized	1.99	0.36	0.74	0.06

A Table 16. Mean values of dry grain weight, dry stover weight, harvest index, and estimated T/ET, field study 2015 (corn)

Geo	Dry grain wt. (kg ha^{-1})	Dry stover wt. (kg ha^{-1})	Harvest index (ratio)	Estimated T/ET
ESP	3157	6961	0.45	0.50
CL	2957	6104	0.49	0.45

A Table 17. Mean values of percent N and P concentration in grain, percent N and P concentration in stover, field study 2015 (corn)

Geo	% N con. grain	% P con. grain	% N con. stover	% P con. stover
ESP	1.59	0.31	0.56	0.07
CL	1.61	0.30	0.67	0.09