EFFECT OF SEED DISTRIBUTION AND POPULATION ON MAIZE (*ZEA MAYS* L.) GRAIN YIELD

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YIELD

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Abstract:

Maize planting is normally accomplished by hand in the developing world where two or more seeds are placed per hill with a heterogeneous plant spacing and density. To understand the interaction between seed distribution and distance between hills on grain yield and nitrogen (N) uptake, experiments were established in 2012 and 2013 at Lake Carl Blackwell (LCB) and Efaw Agronomy Research Stations, near Stillwater, OK. A randomized complete block design was used with three replications and ten treatments; and a factorial treatment structure of 1, 2 and 3 seeds per hill using inter-row spacings of 0.16, 0.32 and 0.48m. Normalized Difference Vegetation Index (NDVI), Intercepted Photosynthetically Active Radiation (IPAR), grain yield and N uptake were measured. Results showed that, on average, NDVI and IPAR increased with number of seeds per hill by 9 and 14%, and decreased with plant spacing by 10 and 11%, respectively. However, they were not good predictors of grain yield. Significant interaction effects ($p<0.01$) for grain yield were observed at Efaw in both years but not at LCB. In 2012, highest grain yield of 11.68 Mg ha^{-1} was achieved at 0.48m spacing with 3 seeds per hill, while lowest grain yield of 6.51 Mg ha^{-1} was obtained at 0.48m spacing with 1 seed per hill. In 2013, highest grain yield of 8.97 Mg ha^{-1} was attained at 0.16m with 1 seed per hill while lowest grain yield of 4.01 Mg ha^{-1} was attained at 0.32m spacing with 1 seed per hill. Treatments, including interaction, in both years and locations did not have any influence on N uptake. However, N uptake was higher at locations with very poor yield. This study showed that planting up to 3 seeds per hill at 0.16m spacing can reduce maize yield by 12 to 15% and that planting 1 seed per hill reduces seeding rate by 66% compared to 3 seeds but no grain N advantage was observed. Considering seed spacing variability at a range used in this study, yield and economic benefits were sufficient to support production of maize at 0.16 m inter-row spacing with 1 seed per hill.

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CHAPTER I

INTRODUCTION

Background

Maize (*Zea mays* L.) is one of the most important crops cultivated throughout the world (FAO, 2009) significantly contributing to global food security (Bekele et al., 2011). Maize is believed to have been domesticated in central Mexico between 6,000 to 10,000 years ago by the indigenous people (Doebley, 2004). The crop spread to other parts of America and later to Europe between the 15^{th} and 16^{th} century through trade. It has slowly been transformed from its early wild grass ancestor to its improved current state (Abdolreza et al., 2006). Today, maize is grown throughout the world primarily for direct human consumption and animal feedstuff among other uses.

The global demand for maize has shown an increasing trend in the past decade. In 2010, maize demand accounted for 40% of the world's major cereals (wheat and rice). Maize is the most important staple food for poor households in the developing world accounting for 73% in Sub Saharan Africa, 46% in South Asia, and 44% in Latin-America. In Developed countries, maize is mainly used as animal feeds accounting for 70% of total usage (Bekele et al., 2011). In addition, there has been a growing interest, especially in the developed countries, to use maize in the bio-fuel industry for making ethanol in an attempt to replace fossil fuel (Persson et al., 2009). The increased demand for maize for ethanol production has increased maize prices globally and that are now near \$0.3 kg^{-1} from about \$0.1 kg^{-1} in the past 10 years.

Current world production averaged over three years (2008-2010) is about 833 million metric tons harvested from about 161 million hectares. From this yield, over 70% is produced in the developed countries from less than 50% of the world total cultivated land under maize (FAO, 2012). Third world maize grain yield are generally less than 2.0 Mg ha^{-1} compared to the yield of over 4.0 Mg ha^{-1} in the developed world. This demonstrates the low maize grain yield, and a need to examine maize farming practices that lead to this low yield in the developing countries.

High maize grain yield in the developed world is characterized by mechanized production systems, high quality seeds, and good agronomic practices. Because the level of mechanization is still low in the developing world, especially Sub Saharan Africa (FAO, 2007), maize planting is normally accomplished by hand. Consequently, two or more seeds are planted per hill resulting in non-equidistant increase in plant population. Planting more than one seed per hill will not only spur competition between plants (Duncan, 1984), but also increase the amount and cost for seeds.

Use of improved seeds is a prerequisite to obtain high crop yield. However, improved seeds (hybrid maize) in Sub Saharan Africa cost nearly ten times more than open pollinated varieties (Van et al., 2011). Besides using home saved seeds, chances of obtaining good yield are further reduced by low or no use of fertilizer (Valerie and

Crawford, 2007). Bekele et al. (2011) noted that the use of germplasm alone will not meet the growing demand for maize unless complemented by improved agronomic practices.

Justification and Objective

Many studies have been conducted on crop spacing, seed distribution and N utilization. However, little attempt has been made to explain the relationship and interaction between these factors and resulting effects on maize grain yield. If maize grain yield can be improved by reducing plant spacing as demonstrated by Widdicombe and Kurt (2002), it is important to determine whether it is possible to manipulate seed distribution to improve N utilization and ultimately, grain yield. Seed singulation with equidistant spacing could reduce competition between plants and the cost of acquiring hybrid seeds by smallholder farmers in third world countries.

The objective of this study was to determine the combined effects of distance between hills, and number of seeds planted per hill on maize grain yield and nitrogen uptake.

CHAPTER II

LITERATURE REVIEW

Plant Spacing

Plant spacing is a practice that determines the spatial distribution of the plants, which affects canopy structure, light interception and radiation use efficiency and consequently, biomass or grain yield (Mattera et al., 2013). Different spatial arrangements produced by changes in row spacing can affect appropriate plant density and therefore, resource competition relationships which are crucial in crop productivity (Worku and Astatkie, 2011; Mattera et al., 2013).

Different studies on plant spacing effects reported varying results. Widdicombe and Kurt (2002) reported a small grain yield increase of 4% when maize population was doubled by narrowing spacing from 0.76 to 0.38m. Shapiro and Wortmann (2006) reported a similar increase (4 %) in yield when spacing was reduced by 25%. De Bruin and Pedersen (2008) reported that decreasing soybean spacing from 0.76 to 0.38m, thus doubling plant population, increased yield by 0.25 Mg ha^{-1}. They concluded that yield and other economic benefits were sufficient to support the production of soy bean in a narrow spacing (0.38m) compared to larger spacing of 0.76m.

Contrary to the above, work done by Dale (2001) showed no significant yield difference in maize planted at 0.76m and 0.38m spacing. Grain yield increases with increasing plant density comes to a plateau at some point, above which increasing plant population is not economical. This is because above the plant population that gives maximum grain yield, the reduction in grain yield due to competition or crowding stress cannot be compensated by the increasing plant stands (Duncan, 1984). The strongest possible effect of plant competition for nutrients, light, moisture and other factors is observed when plants are growing very near to or even in contact with each other.

Grain yield reduction at higher plant densities is due to crowding and its associated effects. At an early vegetative stage, competition has minimal effect on yield reduction. At later vegetative and reproductive stages, competition approaches its peak due to increased demand for nutrients and water (Hashemi et al., 2005). The extent to which plant density affects grain yield depends on the hybrid and other environmental conditions (Duncan, 1984; Fukai and Foale, 1988; Wade and Douglas, 1990).

Plant distributions have a profound effect on grain yield. Wade et al. (1988) noted that the population of plants per square meter (density) and arrangement of individual plants within a square meter determines nutrient use and grain yield of maize. Uneven distribution of plants can reduce grain yield compared to uniform distribution at the same density (Wade et al., 1988). Extreme uneven plant distribution can reduce grain yield up to 30%. (Wade et al., 1990).

Doerge et al. (2002) reported that yield can be increased up to 0.25 $Mgha^{-1}$ for each inch improvement in equidistant plant spacing standard deviation. They added that individual plant yield was at a maximum when plants were within a 0.05 to 0.07 meter of perfect equidistant spacing. However, Liu et al. (2004) noted that plant spacing which results in a perfectly uniform plant distribution has no yield advantage over non-equidistant plant spacing.

Intercepted Photosynthetically Active Radiation

In a plant community, individual plants compete with neighboring plants for resources. Light is one of these resources. Plant population and row width determine light interception and consequently influence photosynthesis and yield (Stewart et al., 2003). Papadopoulos and Pararajasingham (1997) noted that it is possible to manipulate plant spacing to maximize light interception in any crop.

Niinemets (2010) elaborated that light harvesting is of great importance to plants that are growing close to one another. The extent of competition for light or the efficiency for light harvesting depends on how close plants are to each other. Nafziger (2006) noted that within the normal range of crop population, the increase in crop yield from increasing plant population is related to the increase in light interception. He explained that maximizing light interception during grain production is of paramount importance to optimum grain yield.

While investigating light interception and row spacing of yield in soybeans, Board et al. (1992) observed greater light interception in the narrow row culture (0.5m) compared to the wide row culture (1m). They observed that this occurred during vegetative and early reproductive periods of plant growth. Similarly Zhang et al. (2008), in a study of light interception and utilization in relay intercrops of wheat and cotton in China, noted that the best distribution of light is attained in systems with narrow strips and high plant densities. Increasing plant density through narrow row planting of maize could increase light interception and consequently increase grain yield.

Grain Nitrogen (N) Content

Nitrogen (N) is by-far the most limited cereal crop nutrient in the world. Its application does present a number of management challenges, partly, because it is mobile in soil solution (Zhang and Raun, 2006). Many N fertilization studies are generally geared towards finding out the use efficiency of the applied fertilizer sources. This is termed as “N Use Efficiency”. Ignacio and Tony (2011) defined N use efficiency (NUE) as “the grain produced per unit of fertilizer N applied”. It gauges the plants’ ability to take up applied N in fertilizer and assimilation into grain. N use efficiency measures the relative proportion of the amount of fertilizer N in the grain versus the quantity remaining in the soil and lost in the atmosphere or water.

Moll et al. (1982) considered the concept of NUE as two interrelated components; the efficiency with which plants take up the applied N fertilizer and the efficiency with which the absorbed N is assimilated to grain. Processes aimed at improving N use efficiency should consider both uptake and utilization.

Nitrogen use efficiency worldwide for cereals is estimated at approximately 33% (Raun and Johnson, 1999). Low NUE is caused by a number of loss processes such as plant emission, ammonia volatilization, soil denitrification, leaching and surface run off. Garnett et al. (2009) noted that the N fertilizer that is lost poses serious environmental concerns coupled with the monetary value lost. These factors present a case to find better ways of improving NUE. Edmonds et al. (2009) showed that estimated NUE was more than 100% in Sub Saharan Africa, but this was due to the low fertilizer N application rates, and the mining of an already-N-depleted soil.

Nitrogen uptake and use efficiency seems to be closely related to plant spacing. Ignacio and Vyn (2011) reported high N uptake and use efficiency in narrow row with a high plant density. Narrowing maize rows enables plants to occupy spaces between plants; utilizing the applied N fertilizer that would otherwise be lost. Similarly, a study by Barbieri et al. (2008) found that N Uptake increases with narrow row spacing. They realized a 15% increase in N uptake expressed as grain yield with narrow maize rows. They noted, however, that the N uptake and therefore use efficiency decreased with increasing N rate. The low NUE could be because of over application of N fertilizer or improper timing of application. The current study examined grain N concentration as affected by a combination of inter-row spacing and number of seeds per hill.

CHAPTER III

MATERIALS AND METHODS

Experimental Sites

Experiments were conducted for two years in the summer of 2012 and 2013 to evaluate the effect of seed distribution and population on maize grain yield. These were located at Lake Carl Blackwell Research Station and Efaw Agronomy Research Station near Stillwater, OK. Lake Carl Blackwell is situated on a Pulaski fine-sandy loam (coarse/loamy, mixed nonacid, themic Udic Ustifluvent) soil while Efaw Agronomy Research Station is on an Ashport silty clay loam (fine-silty, mixed, superactive, thermic Fluventic Haplustoll) soil.

Experimental Layout and Management

A randomized complete block design was used in all experiments with three replications and 10 treatments. The treatment structure consisted of a complete factorial of 1, 2 and 3 seeds per hill at inter-plant spacing of 0.16, 0.32 and 0.48m. Twin row and mechanical hand planter treatments were included in the treatment structure as the 10th treatment in 2012 and 2013, respectively.

All treatments were planted with the corn hybrid Pioneer P1498HR with row spacing of 0.76m. A poke stick with a metal tip similar to those used in Central and South America was used to open a planting hole. Seeds were placed in the hole and then covered by foot. In 2013, treatment 10 was planted using the hand planter developed at Oklahoma State University (OSU). The OSU hand planter has a reciprocating internal drum that delivers single maize seeds per strike, and has a seed hopper with the capacity to hold 1kg of seed. With the sharp pointed shovel tip of the planter, seeds were delivered to a planting depth of 5cm on tilled ground. Both the poke stick and the OSU hand planter were used to plant the two inner rows for the respective treatments. The stick planter was used to give the desired number of seeds per hill and plant spacing for the respective treatments. Two border rows for all treatments were planted using a John Deere planter. A uniform rate of 180 and 130 kg N ha^{-1} as urea pre-plant was applied to all treatments in 2012 and 2013, respectively (Tables 1 and 2).

Pre-emergence herbicide with atrazine, alachlor and glyphosate as active ingredients and post emergence herbicide with tembotrione and glyphosate as active ingredients were each applied at a rate of 120 L solution per hectare. Pre- emergence herbicide, atrazine, alachlor and glyphosate were mixed at 1.48, 2.24 and 1.57 L as active ingredients per hectare, respectively while post emergence, tembotrione and glyphosate, were mixed at 0.14 and 2.25 L as active ingredients per hectare, respectively. All the experiments were irrigated on days during the growing season when little or no rainfall was anticipated.

Data Collection and Analysis

Experimental plots at both locations were sensed using the active Greenseeker^{TM} at V4, V6 and V8 maize growth stages (Iowa State University, 1993). Photosynthetically active radiation (IPAR) values intercepted by plants were collected using a Line Quantum Sensor at the V6 maize growth stage. At maturity, experimental plots were harvested using a Massey Ferguson 8XP self-propelled combine in 2012. In 2013, plots were harvested and shelled by hand. Sub-samples were collected for each plot and dried in an oven at 65°C for 48 hours. The samples were then ground to pass through a 1mm sieve size. Finely ground samples were then achieved by rolling the samples in bottles with stainless steel rods for 24 hours before analysis for grain N were accomplished using a LECO Truspec CN dry combustion analyzer (Schepers et al., 1989). All the field activities including fertilization dates, sensing dates, planting, and harvest dates are summarized in table 10.

To determine treatment effects on maize grain yield, grain N content, IPAR and NDVI values, the data were analyzed using the PROC GLM procedure of the SAS program (SAS institute, 2003). Treatment means were separated using the Least Significant Difference (LSD) mean separation procedure and the results presented in the following section.

CHAPTER IV

RESULTS

Grain Yield

Efaw

In 2012, emergence difference and plant death resulted to 1-10% fewer plants than the target population (Table 1). There was a strong positive linear relationship between harvest plant population and ears harvested with r^2 of 0.97 (Table 3). A polynomial regression of plant population on grain yield predicting maximum yield is shown in Figure 1. Analysis of variance showed that number of seeds per hill and the interaction between plant spacing and seeds per hill had a significant ($P<0.01$) effect on grain yield (Table 4). The main effect of plant spacing did not significantly affect grain yield. Highest grain yield (11.68Mg ha^{-1}) was harvested at 0.48m spacing with 3 seeds per hill while the lowest yield (6.51Mg ha^{-1}) was obtained at 0.48m spacing with 1 seed per hill. However, the former was not significantly different from yield at 0.32m spacing with 3 seeds per hill (11.26Mg ha^{-1}) and 0.16m spacing with 1 seed per hill (11.06Mg ha^{-1}). Grain yield at 0.16m spacing decreased with number of seeds per hill while those at 0.32 and 0.48m spacing increased with number of seeds per hill.

The interaction between number of seeds per hill and interplant spacing is shown in Figure 2. The treatment structure and means in 2012 are reported in table 5.

In 2013, emergence difference and plant death resulted in a large percent difference, 33-60% fewer plants, than target population (Table 2). However, there was a high linear relationship between harvest population and ears harvested with r^2 of 0.99 (Table 3). A polynomial regression of plant population on grain yield predicting maximum yield is shown in Figure 3. Analysis of variance indicated that maize grain yields were significantly different ($P<0.01$) for the number of seeds per hill, interplant spacing and the interaction (Table 6). The highest maize grain yields (8.97 Mg ha^{-1}) was harvested at 0.16m spacing with one seed per hill while the lowest yield (4.01 Mg ha^{-1}) was obtained at 0.32m spacing with one seed per hill. Figure 4 illustrates the interaction for plant spacing and the number of seeds per hill on maize grain yield. Yield at 0.16m spacing decreased with number of seeds per hill while those at 0.32 and 0.48m spacing increased with number of seeds per hill, a similar trend observed in 2012. However, maximum yield attained with 3 seeds per hill at 0.48m spacing was less than yield with 1 seed per hill at 0.16m spacing. In 2013, highest grain yield (8.97 Mg ha^{-1}) did not differ significantly with treatment 10 (8.76 Mg ha^{-1}) planted with the OSU planter (Table 7).

Lake Carl Blackwell

Due to extremely poor seed emergence and seedling performance, results from 2013 for this location were not included in this report. In 2012, a comparison of harvest population and seeding rate indicated emergence difference and plant death of 28-42%

(Table 1). There was a poor linear relationship between harvest population and ears harvested with r^2 of 0.47 (Table 3). A polynomial regression of harvest plant population on grain yield is shown in figure 5. Analysis of variance indicated that plant spacing, number of seeds per hill and the interaction did not significantly ($P>0.05$) affect grain yield (Table 8). The 0.16m spacing gave highest yield (3.80Mg ha^{-1}) across number of seeds per hill compared to the 0.48m spacing with 2.75Mg ha^{-1} as the lowest yield harvested, representing about 27 % yield decrease. In general, grain yield decreased with increase in plant spacing while no particular pattern was observed with number of seeds per hill. Yield increased from 1 to 2 seeds per hill by 20% but later decreased with 3 seeds per hill by about 9 %. Two seeds per hill had highest yield with 3.36 Mg ha^{-1} compared to 1 seed per hill with 2.57 Mg ha^{-1}. The treatment structure and means are shown in table 9. Figure 6 illustrates the general trend of maize grain yields as affected by seeds per hill and the plant spacing.

Intercepted Photosynthetically Active Radiation

Efaw

In 2012, analysis of variance showed that photosynthetically active radiation (PAR) intercepted by the plants (IPAR) was significantly different for distance between hills ($P<0.01$) but not number of seeds per hill and the interaction (Table 4). Overall, IPAR increased with the number of seeds per hill from 50 to 62% with 1 to 3 seeds per hill, respectively and decreased with plant spacing from 68 to 51 % at the 0.16m to 0.48m spacing, respectively. In 2013, IPAR was significantly different for both number of seeds per hill ($P<0.05$) and distance between hills ($P<0.01$) but not for the interaction (Table 6). As was recorded in 2012, a similar trend followed with an overall increase of 18.8% in IPAR values as seed per hill increased from 1 to 3, meanwhile a small decrease of 1% was observed as plant spacing increased from 0.16m to 0.48m. In 2012, there was no significant linear relationship between IPAR and grain yield, with model r^2 of 0.04, while in 2013, IPAR had poor linear relationship with grain yield with model r^2 of 0.32 (Table 3).

Lake Carl Blackwell

There was a significant effect of distance between hills and the number of seeds per hill on IPAR (Table 8). No significant interaction was observed. A general increase with number of seeds per hill was observed, and an overall decrease with plant spacing. There was an increase from 51 to 64% with 1 to 3 seeds per hill, respectively and a decrease from 65 to 53% at the 0.16m to 0.48m plant spacing, respectively. The increase in IPAR values with number of seeds per hill and its decrease with plant spacing was an indication of bare ground effect from sparse vegetative cover as a result of lower number of seeds per hill and wider spacing. There was a poor linear relationship between IPAR and grain yield with model r^2 of 0.1 (Table 3).

Normalized Difference Vegetation Index

Efaw

In 2012, Normalized Difference Vegetation Index (NDVI) sensor readings were collected and recorded for maize vegetative (V) growth stages V4, V6 and V8. At the V4 growth stage, NDVI was significantly different for number of seeds per hill, plant spacing ($P<0.01$) and the interaction ($P<0.05$). At the V6 maize growth stage, NDVI was significantly different for plant spacing ($P<0.01$) but not number of seeds per hill and the interaction, while at V8, NDVI was significantly different for both plant spacing and number of seeds per hill but not the interaction (Table 4). In 2013, NDVI at V4 and V6 growth stages were significantly different for number of seeds per hill, but not plant spacing. At V8, NDVI was significantly different for number of seeds per hill, plant spacing and the interaction (Table 6). In both years, as would be expected; overall NDVI values increased with maize growth stages. Normalized difference vegetation index was best linearly related to grain yield at V8 maize growth stage with model r^2 of 0.53 and 0.61 in 2012 and 2013, respectively (Table 3).

Lake Carl Blackwell

Plant spacing, number of seeds per hill and the interaction between the two did not significantly ($P>0.05$) affect NDVI values at all three growth stages (V4, V6 and V8). There was a general increase in NDVI values from one maize growth stage to another (Table 8). Values for NDVI increased with number of seeds per hill with the lowest observed with 1 seed and the highest with three seeds at all maize growth stages, and decreased with plant spacing across growth stages. There was no significant linear relationship between NDVI at V8 maize growth stage and grain yield with a very poor model r^2 of 0.05 (Table 3).

Grain Nitrogen (N) Content

Efaw

In 2012, analysis of variance and treatment means showed that grain N content was not significantly different for the number of seeds per hill and interaction between plant spacing and number of seeds per hill ($P>0.05$). The highest grain N content (1.27%) was observed when maize was planted at 0.32m spacing with one seeds per hill. The lowest grain N content (1.14%) was observed at 0.16m spacing with two seeds per hill (Table 4). Grain N content at 0.16m spacing decreased when number of seeds increased from one to two (1.25 to 1.14%), and slightly increased with three seeds per hill (1.17%) while that at 0.32m decreased with number of seeds per hill from 1.27 to 1.21%. Grain N content at 0.48m spacing increased with number of seeds per hill from 1.19 to 1.25%. Like in 2012, grain N content for 2013 was not significantly different for number of seeds per hill, plant spacing and their interaction (Table 6). Highest grain N of 1.22% was achieved at 0.48m spacing with one seed per hill while the lowest N content of 1.04% occurred at 0.16m spacing with two seeds per hill. There was a general decrease in grain N as the number of seeds per hill increased from one to three across plant spacing but grain N content increased generally with plant spacing across number of seeds per hill.

Lake Carl Blackwell

Plant spacing, number of seeds per hill and the interaction between the two did not significantly affect grain N uptake ($P>0.05$). Grain N content slightly decreased with number of seeds per hill from 1.50 to 1.48% while an increase with plant spacing from 1.45 to 1.51% was noted (Table 8). Like at Efaw, a similar trend was noted where grain N content decreased with number of seeds per hill and increased with inter-row spacing.

CHAPTER V

DISCUSSION

Grain Yield

Higher number of seeds per hill resulted to increased plant abortion and decreased ear weight. Considering all years and location, maximum grain yields were attained with plant population ranging from 60,000 to 90,000 plants per hectare. Grain yield decreased with the number of seeds when planted at the 0.16m spacing. At this narrow spacing, increased competition would be expected, and yield should be lower due to the excessive number of plants. However, at the 0.48m spacing, the opposite was observed; as the number of seeds per hill increased from one to three, yield went up. This too would be expected since the wider distances between plant placement would allow for less competitive growth and development of more plants. This trend was observed in both years at Efaw, but not at Lake Carl Blackwell. Figure 2 shows that the same yield level can be achieved when maize is planted at 0.16m and 0.48m spacing with one and three seeds per hill, respectively. Figure 4 illustrates that the maximum grain yield attained at 0.48m spacing was less than the initial yield at 0.16m with one seed per hill. At Lake Carl Blackwell, grain yield was not significantly affected by plant spacing, number of seeds per hill and the interaction between the two. Considering all three plant spacing, there was no overall decrease or increase in grain yield as the number of seeds increased from one to three. At the 0.16m spacing, a non significant increase in grain yield from one to three seeds per hill was observed. In 2013, as was hypothesized, yield levels between the highest treatment with 1 seed per hill at 0.16m spacing and that planted using the hand planter developed at OSU were not significantly different.

Intercepted Photosynthetically Active Radiation

Intercepted photosynthetically active radiation (IPAR) increased with number of seeds per hill and decreased with increased inter plant spacing in both years and locations. At lower plant spacing, there are more plants with a thicker canopy to intercept light. Increased number of seeds per hill, provide for a more dense plant canopy with comparatively more soil cover. Indeed greater light interception would be observed in these scenarios. In a similar study, Zhang et al. (2008) noted that light capture can be improved by better plant spacing. They concluded that narrow plant spacing with higher stand density increased light interception. However, more light capture would not necessarily result in increased grain yield. Keating and Carberry (1993) elaborated that plants could take spatial advantage due to increased soil cover and capture more light. This would not offset competition at a later stage of plant development, in effect, lowering grain yield. Sharratt and McWilliams (2005) found that crop spacing and canopy structure influenced light interception. They concluded that increase in IPAR at close spacing and/or dense plant stand means equal or more water and nutrients are used. According to them, competition for other resources at the thicker plant canopy is inevitable. These support the result from the current study that closer plant spacing and increased number of seeds per hill increases light interception. However, light interception explained only 30% or less variability in maize grain yield, while a greater portion was explained by other variables.

Normalized Difference Vegetation Index

Readings for NDVI were significantly different for plant spacing and the number of seeds per hill. Essentially, NDVI increased with number of seeds per hill and decreased with plant spacing in all years and locations. As plant spacing increased, plant stand and ground cover decreased. The bare soil surface in between plant stands reduced the NDVI values. Also, increasing number of seeds per hill provided a thicker plant canopy; NDVI values would be expected to increase with this increased plant canopy. A similar study by Lukina et al. (2000) found that NDVI decreased with an increase in plant spacing. They explained that decreased NDVI with plant spacing is a result of increased bare soil surface which has higher reflectance in the visible than near infrared region of the spectrum. Trout et al. (2008) found a strong linear relationship between canopy cover and NDVI with a correlation coefficient r^2=0.95. Higher crop canopy covers indicate higher biomass and therefore increased NDVI values. The two studies above agree with this result that closer plant spacing and increased number of seeds per hill increases NDVI values. The regression analysis showed a fairly strong linear relationship with NDVI explaining up to 60% of the variability in grain yield.

Grain Nitrogen (N) Content

The interaction between plant spacing and number of seeds per hill did not significantly affect grain N uptake. Grain N content was high at Lake Carl Blackwell compared to Efaw location. There was an inverse relationship between grain N content and yield. As yield increased, grain N content decreased and vice versa, implying that high grain protein was achieved with low grain yield. Grain N content decreased with number of seeds per hill. This could be because of increased competition between the increasing number of seeds per hill for the same N quantity in the soil. Grain N content also increased with plant spacing. Nitrogen uptake was lowest at narrow inter-row spacing (0.16m) compared to wider inter-row spacing (0.48m). This finding is however contrary to studies by Barbieri et al. (2008); Ignacio and Vyn (2011) both found that narrowing plant spacing, thus increasing the number of plants per square meter, resulted in increased N uptake.

CHAPTER VI

CONCLUSION

Competition between plants growing close to one another is inevitable (Duncan, 1984; Fukai and Foale, 1988; Wade and Douglas, 1990; and Hashemi et al., 2005). Increasing the number of seeds per hill in the present study increased competition between plants and lowered grain yield. Significant differences in grain yield were observed among treatments. Maize grain yields obtained using the OSU hand planter was not significantly different from the highest yield obtained in 2013. However, there was no advantage in grain nitrogen concentration by varying inter-row plant spacing and/or number of seeds per hill within a range used in this study. High grain nitrogen concentration were recorded in years and/or locations with very low grain yield. Normalized Difference Vegetation Index and IPAR increased with number of seeds per hill by 9 and 14%, and decreased with plant spacing by 10 and 11%, respectively but were not good predictors of grain yield. Overall, this study confirmed that maximum maize grain yield was observed with one seed per hill and that grain yield decreased by 12 to 15% if more than 1 seed is placed in the same hill. Maize planting at narrow inter-row spacing (0.16m) with one seed per hill reduces seeding rate by 66% comapred to planting three seeds per hill at same spacing . This result in economic benefits through reduction in the quantity and cost for seeds. The combined effect of seed spacing variability and number of seeds per hill at a range used in this study showed that yield and economic benefits were sufficient to support production of maize under narrow inter-row spacing (0.16m) with one seed per hill.

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Table 1: Treatment structure with pre-plant N rate, seeding rate and harvest plant population at Efaw and Lake Carl Blackwell, OK, 2012.

Treatment	**Seeds hill^{-1}**	**Plant spacing (m)**	**Pre-plant N (kg ha^{-1})** ¥	**Seeding rate (plants ha^{-1})** £	**Plant Population (plants ha^{-1})¶ Efaw**		**Plant Population (plants ha^{-1})¶ LCB**	
					Measured	**% decrease**	**Measured**	**% decrease**
1	1	0.16	180	82,236	74,354	10	59,514	28
2	2	0.16	180	164,473	156,673	5	107,556	35
3	3	0.16	180	246,710	229,093	7	169,579	31
4	1	0.32	180	41,118	39,437	4	29,040	29
5	2	0.32	180	82,236	81,245	1	59,514	28
6	3	0.32	180	123,355	121,896	1	85,327	31
7	1	0.48	180	27,412	27,215	1	19,719	28
8	2	0.48	180	54,824	51,627	6	39,437	28
9	3	0.48	180	82,236	74,930	9	59,156	28
10	TR	TR	180	82,236	76,364	7	47,324	42

Seeding rate £---estimated plant population, Plant population¶—actual number of plants at harvest, pre-plant N¥---Urea (46-0-0) fertilizer applied. TR.—Twin row treatment

Table 2: Treatment structure with pre-plant N rate, seeding rate and harvest plant population at Efaw, OK, 2013.

Treatment	Seeds hill^{-1}	Plant spacing (m)	Pre-plant N (kg ha^{-1}) ¥	Seeding rate (seeds ha^{-1}) £	Population (plants ha-1)¶	
					Measured	% decrease
1	1	0.16	130	82236	54884	33
2	2	0.16	130	164473	68426	58
3	3	0.16	130	246710	80050	68
4	1	0.32	130	41118	27442	33
5	2	0.32	130	82236	53686	35
6	3	0.32	130	123355	40744	67
7	1	0.48	130	27412	18694	32
8	2	0.48	130	54824	22649	59
9	3	0.48	130	82236	44459	46
10	Mech.	Mech.	130	82236	51649	37

Seeding rate £---estimated plant population, Plant population¶—actual number of plants at harvest, pre-plant N¥---Urea (46-0-0) fertilizer applied. Mech.—Mechanical hand planter treatment.

Table 3: Linear regression results including coefficient of variation, r^2, slope and slope significance for the relationship between grain yield with NDVI and IPAR, and between plant population at harvest and number of ears harvested at LCB and Efaw locations, 2012 and 2013.

Year	Dependent Variable	Independent Variable	C.V (%)	Slope	Slope Significance	Model r^2
			Efaw			
2012	Grain yield	V8 NDVI	16.5	15.60	<.0001***	0.53
2012	Grain yield	IPAR	23.6	0.01	0.3201ns	0.04
2013	Grain yield	V8 NDVI	16.0	16.00	<.0001***	0.61
2013	Grain yield	IPAR	29.3	6.10	0.0011***	0.32
2012	Plant population	No. of ears	7.1	0.74	<.0001***	0.97
2013	Plant population	No. of ears	4.1	0.94	<.0001***	0.99
			LCB			
2012	Grain yield	IPAR	42.0	4.14	0.1196ns	0.10
2012	Grain yield	V8 NDVI	44.0	3.10	0.2835ns	0.05
2012	Plant population	No. of ears	39.5	0.40	<.0001***	0.47

C.V- coefficient of variation, r^2-regression coefficient, *** -significant at 0.01 level of probability and ns-not significant.

Table 4: Analysis of Variance for NDVI values, intercepted photosynthetically active radiation (IPAR), grain yield (Mg ha $^{-1}$) and N Content (%) at Efaw, 2012.

Sources of Variation		NDVI V4	NDVI V6	NDVI V8	IPAR	Grain Yield (Mg ha $^{-1}$)	N Content (%)
					Mean Square		
Seeds per hill		0.0738^{***}	0.0151^{ns}	0.0600^{***}	0.0334^{ns}	11.46^{***}	0.0025^{ns}
Plant spacing		0.1225^{***}	0.0613^{***}	0.0756^{***}	0.0828^{***}	6.39^{ns}	0.0075^{ns}
Seeds per hill x Spacing		0.0034^{**}	0.0054^{ns}	0.0035^{ns}	0.0031^{ns}	12.58^{***}	0.0071^{ns}
Seeds per hill.	Spacing				Treatment Means		
1	0.16	0.4200	0.5633	0.7567	0.6133	11.06	1.25
1	0.32	0.3100	0.6167	0.6000	0.4700	6.8	1.27
1	0.48	0.2600	0.4800	0.5100	0.4233	6.51	1.19
2	0.16	0.5700	0.6933	0.8100	0.6967	9.97	1.14
2	0.32	0.4100	0.6400	0.7533	0.4933	10.58	1.26
2	0.48	0.3333	0.4800	0.6400	0.5633	7.42	1.22
3	0.16	0.6667	0.7167	0.8467	0.7300	9.6	1.17
3	0.32	0.4900	0.6367	0.7833	0.5833	11.26	1.21
3	0.48	0.3733	0.5500	0.7133	0.5500	11.68	1.25
SED		0.02	0.05	0.03	0.09	1.27	0.06
C.V (%)		7	11	5.7	19	16.4	6.2

***, ** significant at 0.01 and 0.05 levels of probability respectively; ns not significant; SED – Standard Error of the difference between two equally replicated means; C.V. – Coefficient of Variation

Table 5: Treatment Structure and means for NDVI values, intercepted photosynthetically active radiation (IPAR), grain yield (Mg ha^{-1}) and N Content (%) at Efaw, 2012

Treatment	Seeds per hill	Plant Spacing	V4NDVI	V6NDVI	V8NDVI	IPAR	Grain Yield (Mg ha^{-1})	N Content (%)
1	1	0.16	0.4188	0.5626	0.7591	0.6162	11.06^{A}	1.25^{BA}
2	2	0.16	0.569	0.692	0.8129	0.6952	9.97^{BA}	1.14^{B}
3	3	0.16	0.6663	0.716	0.8454	0.7308	9.60^{BA}	1.17^{BA}
4	1	0.32	0.3121	0.6189	0.5996	0.4699	6.80^{C}	1.27^{A}
5	2	0.32	0.4109	0.6396	0.7543	0.4968	10.58^{A}	1.26^{BA}
6	3	0.32	0.4913	0.6347	0.7838	0.5829	11.26^{A}	1.21^{BA}
7	1	0.48	0.2605	0.4789	0.5118	0.422	6.51^{C}	1.19^{BA}
8	2	0.48	0.3358	0.4768	0.6399	0.5636	7.42^{BC}	1.22^{BA}
9	3	0.48	0.3764	0.5518	0.7111	0.549	11.68^{A}	1.25^{BA}
10	TR	0.32	0.3801	0.4843	0.7126	0.5412	10.17^{A}	1.24^{BA}
SED			0.02	0.05	0.03	0.09	1.27	0.06
C.V (%)			7	11	5.7	19	16.4	6.2

TR – Twin row; SED – Standard Error of the difference between two equally replicated means; and C.V. – Coefficient of Variation; Means with same letter indicate LSD (α=0.05) are not significantly different.

Table 6: Analysis of Variance for NDVI values, intercepted photosynthetically active radiation (IPAR), grain yield (Mg ha^{-1}) and N Content (%) at Efaw, 2013

Source of Variation		NDVI V4	NDVI V6	NDVI V8	IPAR	Grain Yield (Mg ha^{-1})	N Content (%)
		Mean Square					
Seeds per hill		0.0239^{***}	0.0189^{***}	0.0309^{***}	0.0537^{**}	9.66^{***}	0.0142^{ns}
Plant spacing		0.0004^{ns}	0.0002^{ns}	0.0584^{***}	0.1442^{***}	18.12^{***}	0.0048^{ns}
Seeds per hill x Spacing		0.0011^{**}	0.0022^{***}	0.0012^{***}	0.0021^{***}	5.61^{***}	0.0109^{ns}
Seeds per hill	Spacing	Treatment Means					
1	0.16	0.4135	0.5098	0.7057	0.5211	8.97	1.11
1	0.32	0.4179	0.5649	0.5764	0.3328	4.01	1.20
1	0.48	0.4238	0.5276	0.5163	0.3088	4.25	1.22
2	0.16	0.5062	0.6025	0.7932	0.629	7.81	1.03
2	0.32	0.4914	0.5952	0.6647	0.404	6.51	1.15
2	0.48	0.4685	0.5692	0.6474	0.3614	5.55	1.12
3	0.16	0.5493	0.6456	0.802	0.7039	7.43	1.17
3	0.32	0.5196	0.6234	0.7288	0.5603	7.17	1.09
3	0.48	0.5636	0.6643	0.6667	0.4582	7.02	1.09
SED		0.01	0.01	0.01	0.1	0.52	0.06
C.V (%)		3.6	2.5	1.6	26.2	9.1	6.6

** and *** are significant at 0.05 and 0.01 probability level; ns not significant; SED – Standard Error of the difference between two equally replicated means; C.V. – Coefficient of Variation

Table 7: Treatment Structure and means for NDVI values, intercepted photosynthetically active radiation (IPAR), grain yield (Mg ha^{-1}) and N Content (%) at Efaw, 2013

Treatment	Seeds per hill	Plant Spacing	V4NDVI	V6NDVI	V8NDVI	IPAR	Grain Yield (Mg ha^{-1})	Grain N Content (%)
1	1	0.16	0.4135	0.5098	0.7057	0.5211	8.97^{A}	1.11^{BAC}
2	2	0.16	0.5062	0.6025	0.7932	0.629	7.81^{BC}	1.04^{C}
3	3	0.16	0.5493	0.6456	0.802	0.7039	7.43^{DC}	1.17^{BA}
4	1	0.32	0.4179	0.5649	0.5764	0.3328	4.01^{F}	1.20^{A}
5	2	0.32	0.4914	0.5952	0.6647	0.404	6.51^{DE}	1.15^{BAC}
6	3	0.32	0.5196	0.6234	0.7288	0.5603	7.17^{DC}	1.09^{BAC}
7	1	0.48	0.4238	0.5276	0.5163	0.3088	4.25^{F}	1.22^{A}
8	2	0.48	0.4685	0.5692	0.6474	0.3614	5.55^{E}	1.12^{BAC}
9	3	0.48	0.5636	0.6643	0.6667	0.4582	7.02^{DC}	1.10^{BAC}
10	Mech.	0.16	0.464	0.5647	0.705	0.3971	8.76^{A}	1.06^{BC}
SED			0.01	0.01	0.01	0.1	0.52	0.06
C.V (%)			3.6	2.5	1.6	26.2	9.1	6.6

Mech. – Mechanical planter; SED – Standard Error of the difference between two equally replicated means; and C.V. – Coefficient of Variation; Means with same letter indicate LSD (α=0.05) are not significantly different.

Table 8: Analysis of Variance for NDVI values, intercepted photosynthetically active radiation (IPAR), grain yield (Mg ha^{-1}) and N Content (%) at LCB, 2012

Sources of Variation	NDVI V4	NDVI V6	NDVI V8	IPAR	Grain Yield (Mg ha^{-1})	N Content (%)
				Mean Square		
Seeds per hill	0.0082^{ns}	0.0200^{ns}	0.0188^{ns}	0.0365^{**}	1.63^{ns}	0.0042^{ns}
Plant spacing	0.0001^{ns}	0.0030^{ns}	0.0226^{ns}	0.0347^{**}	3.32^{ns}	0.0135^{ns}
Seeds per hill x Plant spacing	0.0040^{ns}	0.0102^{ns}	0.0312^{ns}	0.0025^{ns}	1.88^{ns}	0.0062^{ns}
Seeds per hill				Treatment Means		
1	0.244	0.277	0.3806	0.5137	2.57	1.50
2	0.2689	0.3207	0.456	0.5953	3.36	1.50
3	0.304	0.3712	0.4631	0.6392	3.03	1.48
Plant Spacing						
0.16	0.2712	0.3189	0.4905	0.6522	3.8	1.45
0.32	0.2703	0.3072	0.4112	0.5635	2.49	1.51
0.48	0.2753	0.3428	0.3979	0.5325	2.75	1.51
SED	0.05	0.06	0.04	0.07	1.1	0.09
C.V (%)	20.2	24.2	34.6	15.1	44	7.6

** Significant at 0.05 probability level; and ns not significant; SED – Standard Error of the difference between two equally replicated means; C.V. – Coefficient of Variation

Table 9: Treatment Structure and means for NDVI values, intercepted photosynthetically active radiation (IPAR), grain yield (Mg ha $^{-1}$) and N Content (%) at LCB, 2012

Treatment	Seeds per hill	Plant Spacing	V4NDVI	V6NDVI	V8NDVI	IPAR	Grain Yield (Mg ha $^{-1}$)	Grain N (%)
1	1	0.16	0.2448	0.254	0.3543	0.5789	2.83^{A}	1.46^{A}
2	2	0.16	0.2917	0.3614	0.6168	0.6813	3.88^{A}	1.5^{A}
3	3	0.16	0.2774	0.341	0.5005	0.6964	4.65^{A}	1.37^{A}
4	1	0.32	0.2743	0.321	0.4617	0.5123	2.55^{A}	1.54^{A}
5	2	0.32	0.2462	0.2758	0.3236	0.5381	1.98^{A}	1.52^{A}
6	3	0.32	0.2908	0.3245	0.4484	0.6401	2.91^{A}	1.54^{A}
7	1	0.48	0.2129	0.2555	0.3257	0.4499	2.32^{A}	1.49^{A}
8	2	0.48	0.2689	0.325	0.4275	0.5665	3.76^{A}	1.48^{A}
9	3	0.48	0.3441	0.4474	0.4404	0.5811	2.04^{A}	1.54^{A}
10	TR	0.32	0.2581	0.3039	0.4775	0.6246	3.63^{A}	1.46^{A}
SED			0.05	0.06	0.12	0.07	1.1	0.09
C.V (%)			20.2	24.2	34.6	15.1	44	7.6

TR – Twin row; SED – Standard Error of the difference between two equally replicated means; and C.V. – Coefficient of Variation; Means with same letter indicate LSD (α=0.05) are not significantly different.

Table 10: Field activities with hybrid used and planting dates, pre-plant N fertilizer dates, harvest dates, and sensing dates at Efaw and Lake Carl Blackwell (LCB), OK. 2012 and 2013.

	Year 2012		**Year 2013**
Field Activity	**Efaw**	**LCB**	**Efaw**
Planting date	9-Apr-12	10-Apr-12	25-Apr-13
Hybrid	Pioneer P1498HR	Pioneer P0876HR	Pioneer P1498HR
Pre-plant N Fertilization date[¥]	2-Apr-13	29-Mar-12	18-Mar-13
Harvest date	6-Aug-12	8-Aug-12	29-Aug-13
Sensing date for NDVI at V4	7-May-12	7-May-12	28-May-13
Sensing date for NDVI at V6	16-May-12	16-May-12	3-Jun-13
Sensing date for NDVI at V8	23-May-12	23-May-12	11-Jun-13
Sensing date for NDVI at V10	30-May-12	29-May-12	20-Jun-13

[¥] Pre-plant N fertilizer--urea (46-0-0) applied at uniform rate to all treatments.
V (4, 6, 8, and 10) are maize growth stages.

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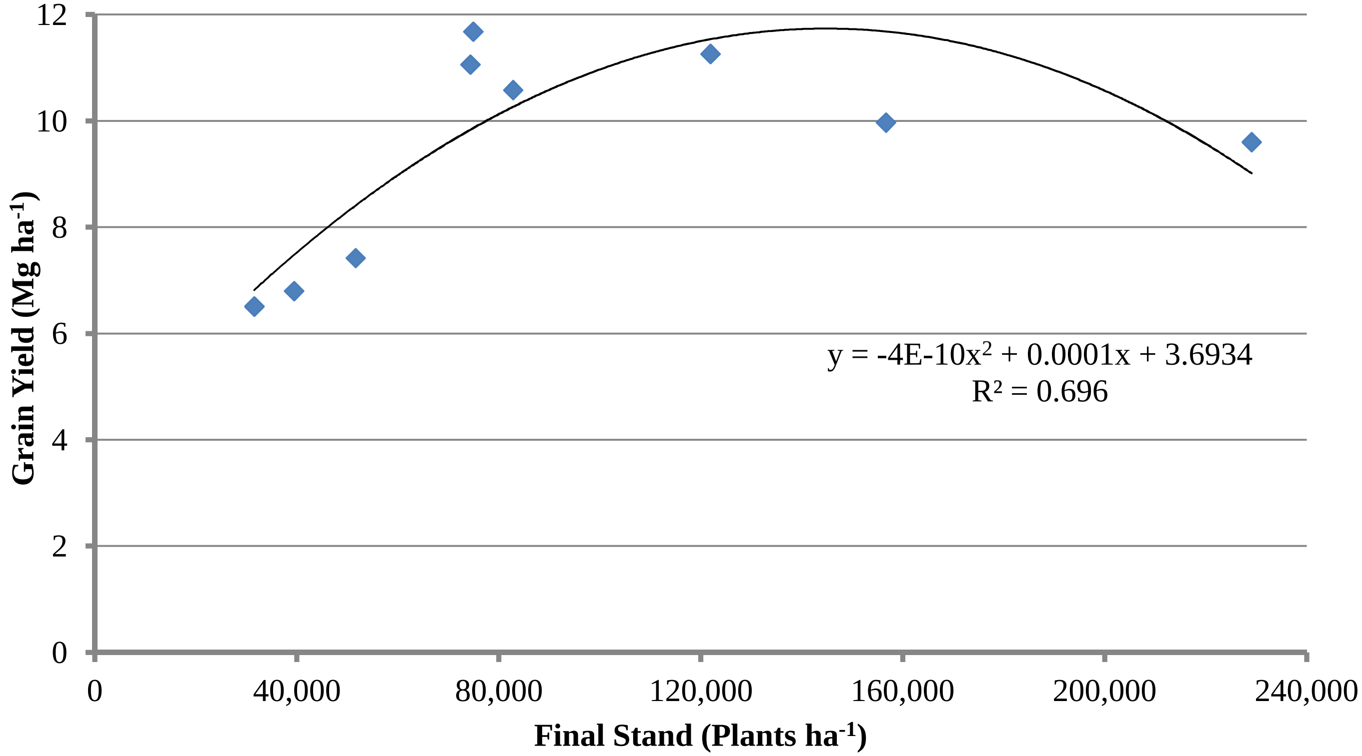


Figure 1: Polynomial regression predicting maximum maize grain yield using final plant population at Efaw, 2012.

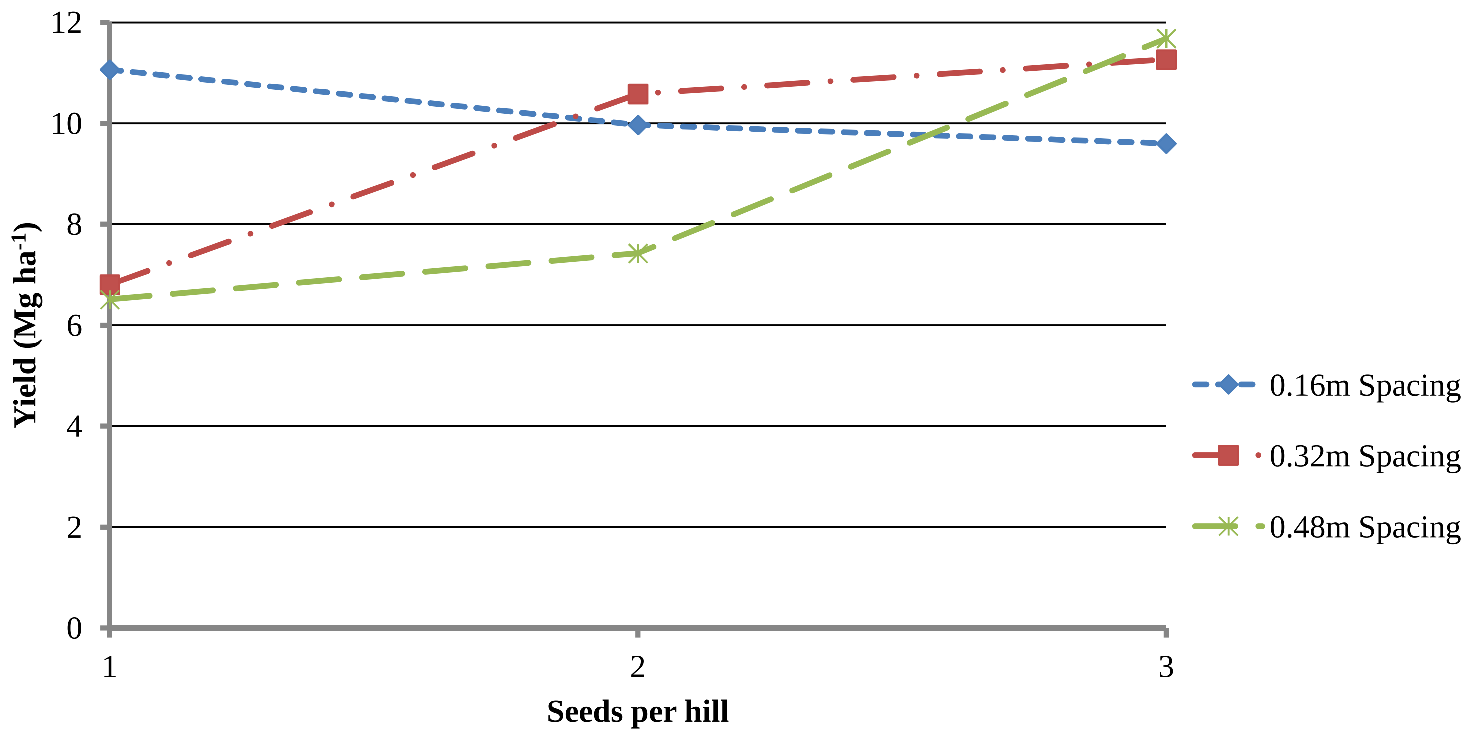


Figure 2: The interaction effects of plant spacing (0.16m, 0.32m & 0.48m) and number of seeds per hill (1, 2 &3) on grain yields (Mg ha^{-1}) averaged across replication at Efaw, 2012.

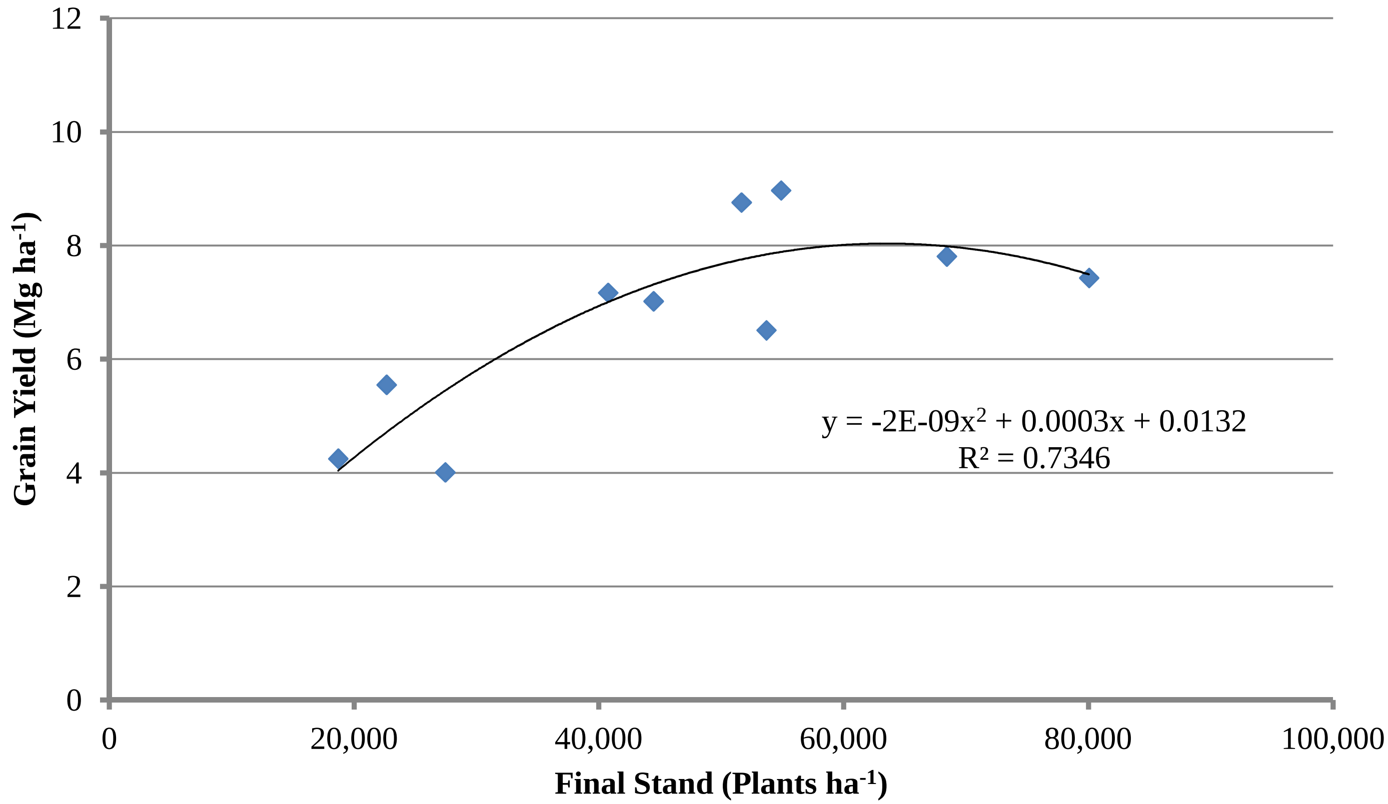


Figure 3: Polynomial regression predicting maximum maize grain yield using final plant population at Efaw, 2013.

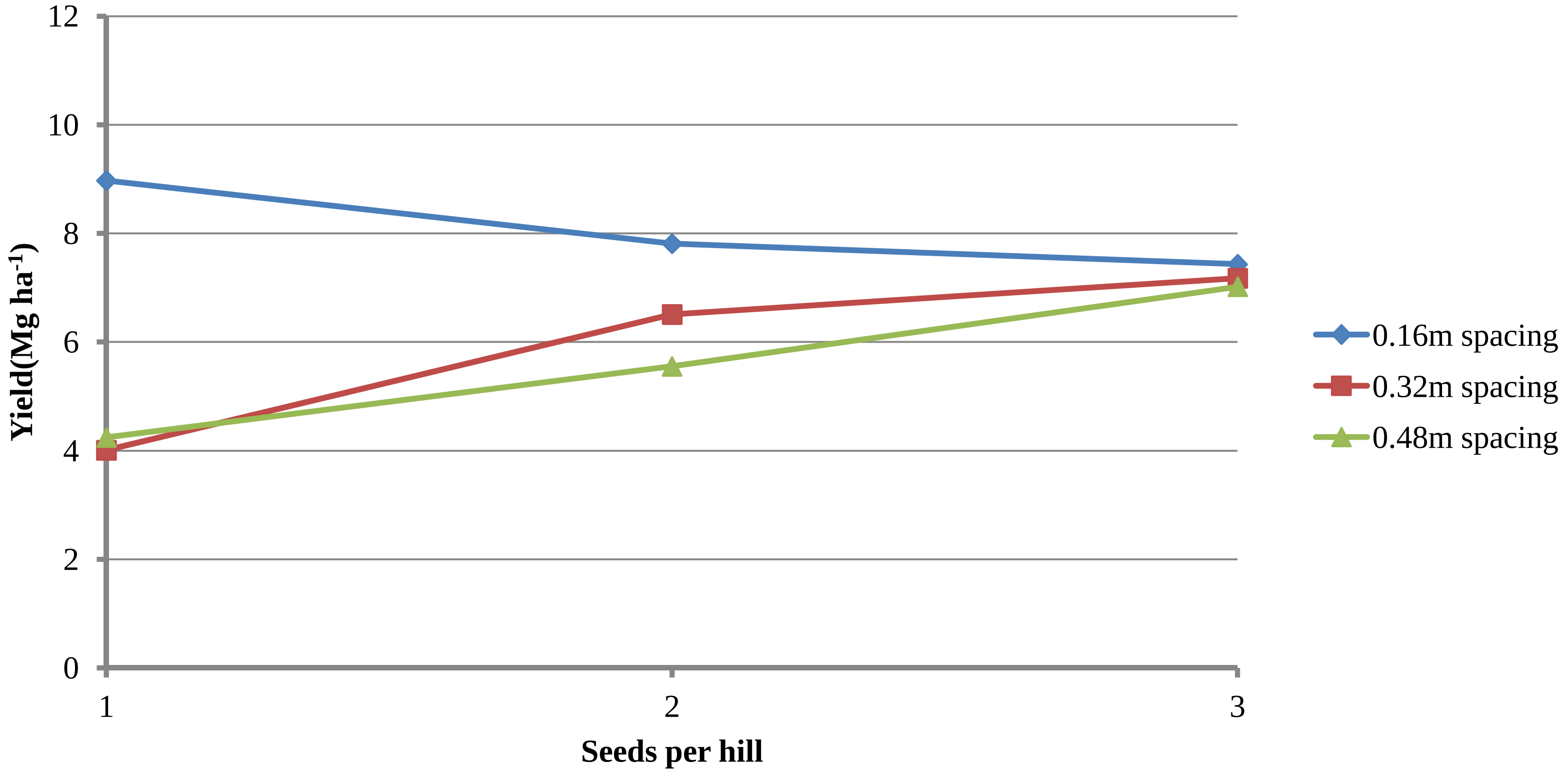


Figure 4: The interaction effects of plant spacing (0.16m, 0.32m & 0.48m) and number of seeds per hill (1, 2 &3) on grain yields (Mg ha^{-1}) averaged across replication at Efaw, 2013.

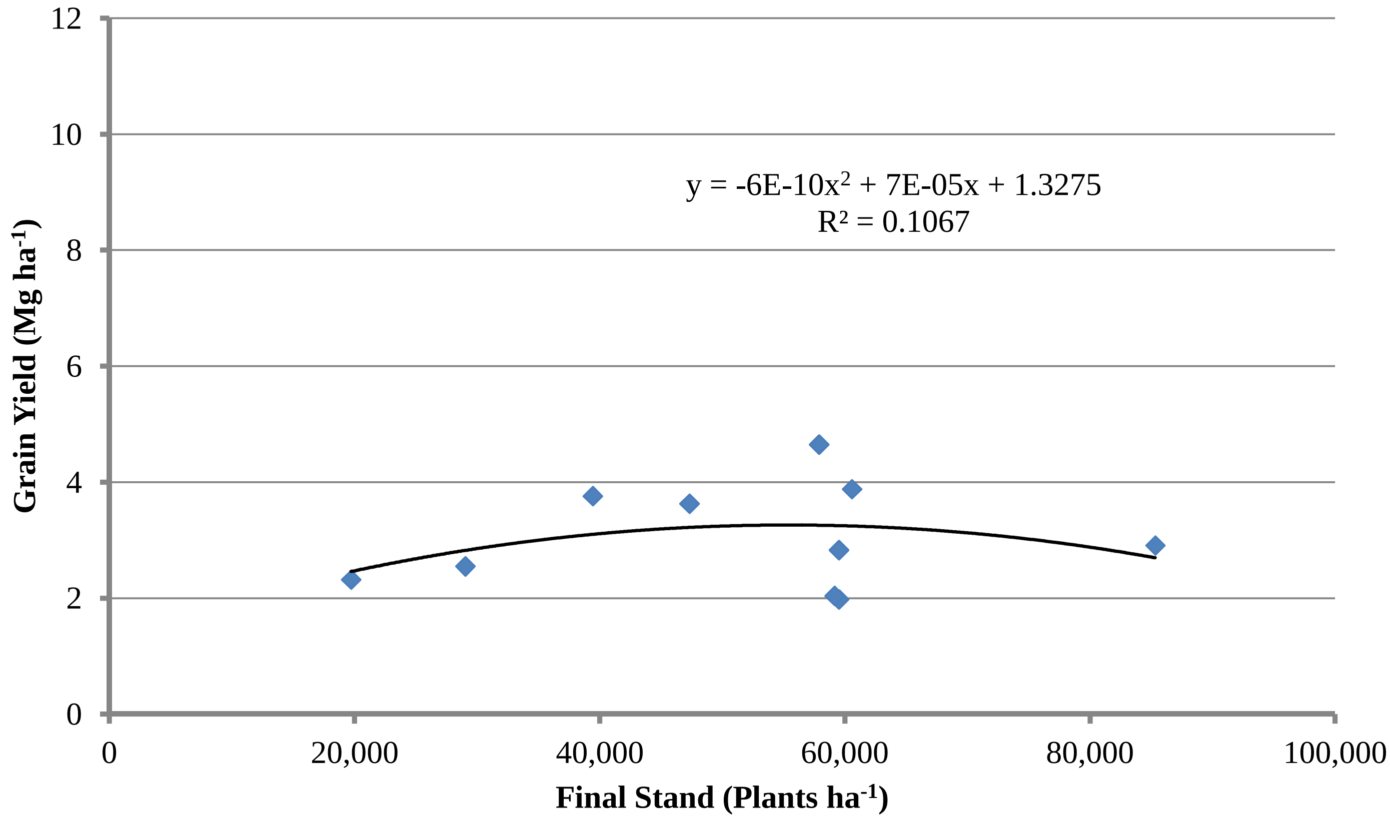


Figure 5: Polynomial regression predicting maximum maize grain yield using final plant population at LCB, 2012.

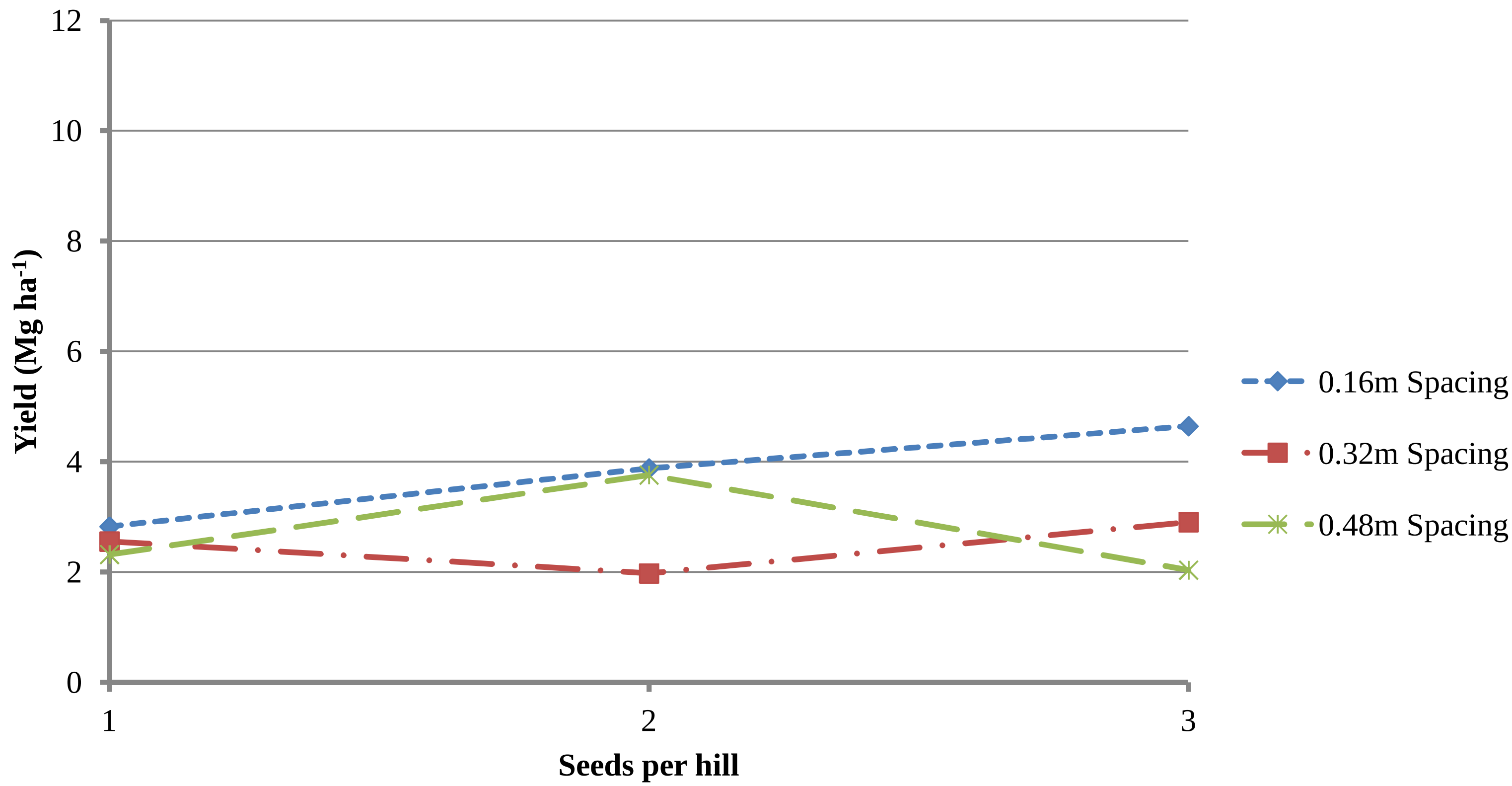
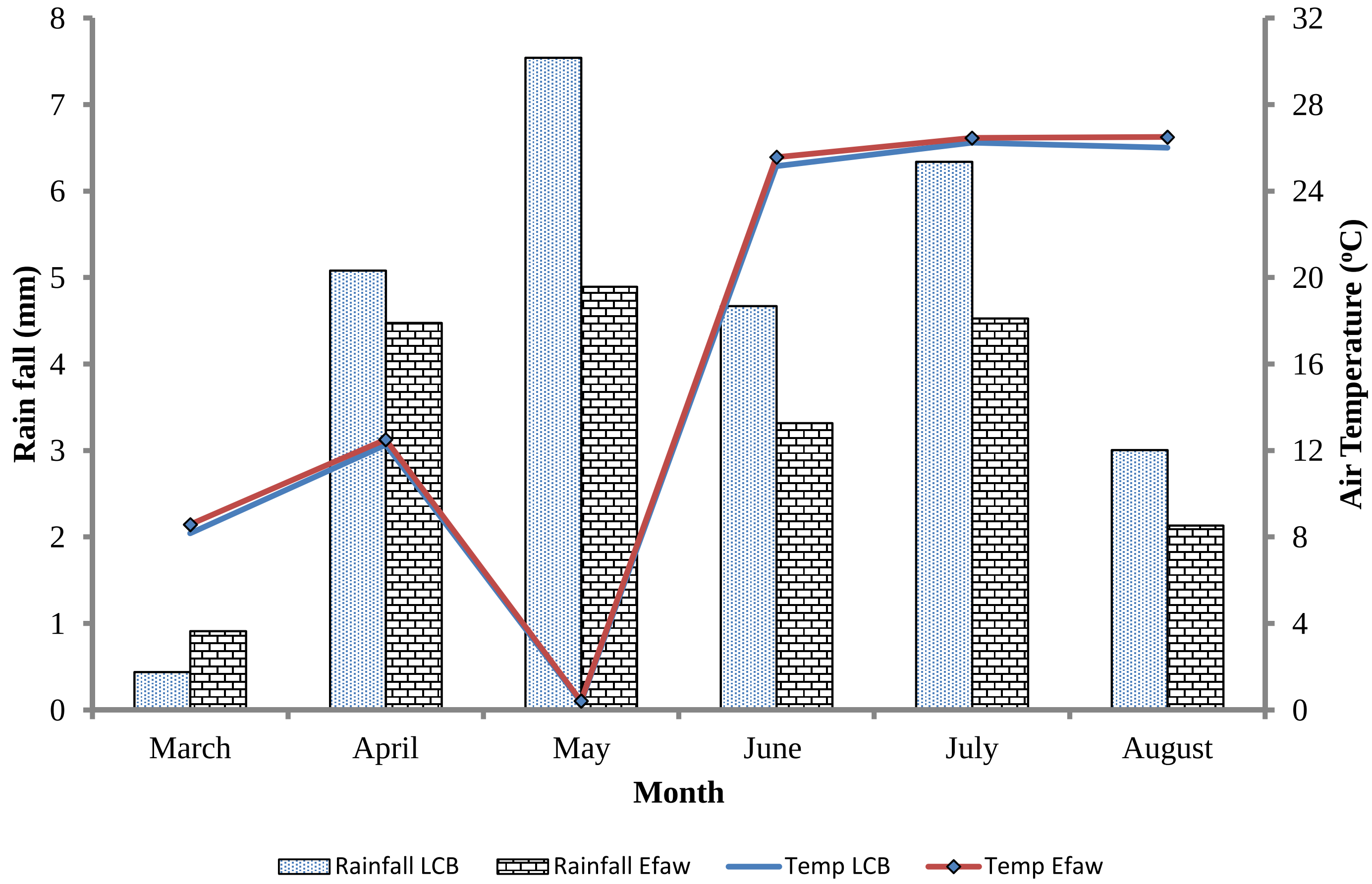


Figure 6: Grain yield (Mg ha^{-1}) averaged across replications as influenced by plant spacing (0.16m, 0.32m & 0.48m) and the number of seeds per hill (1, 2 &3) at Lake Carl Blackwell (LCB) location, 2012.

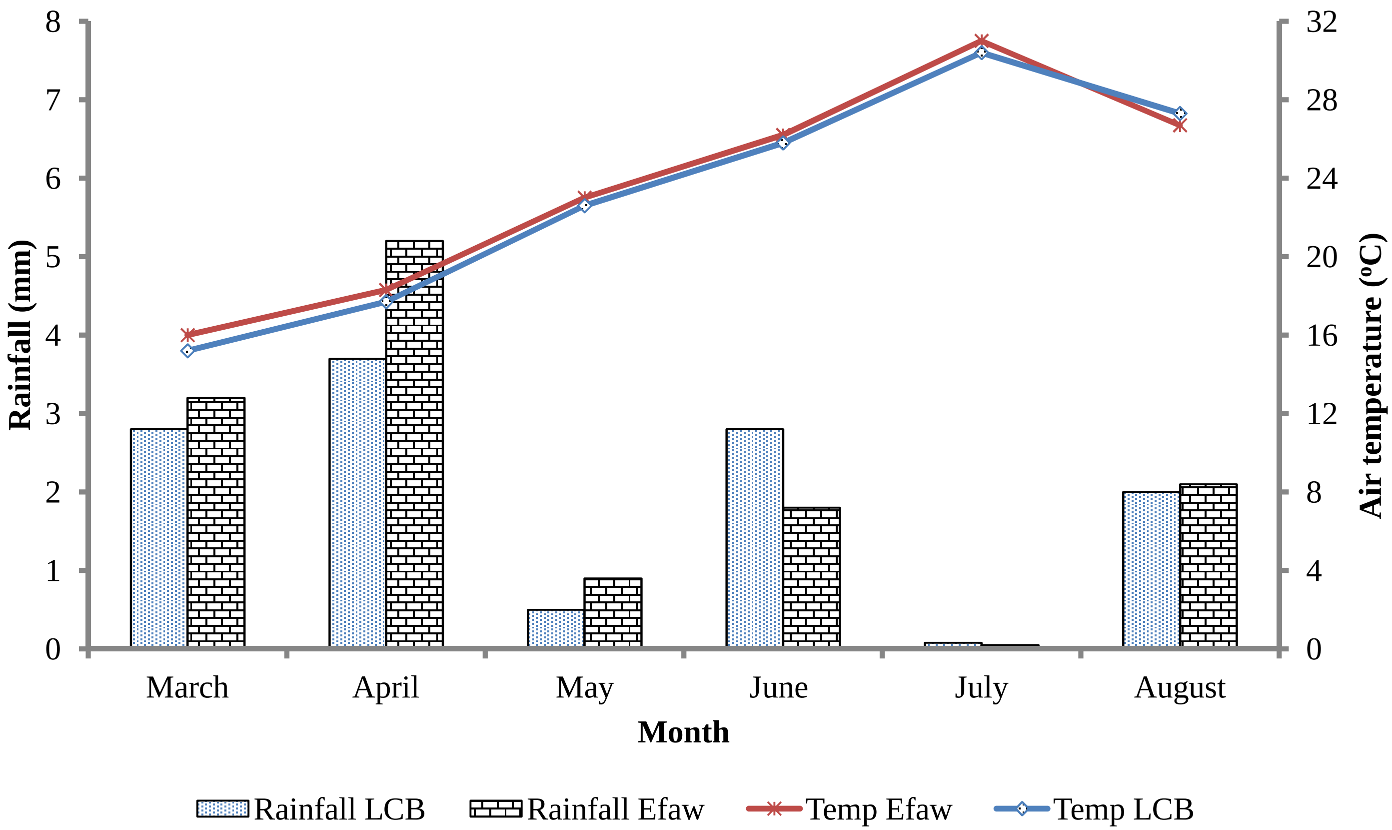
APPENDICES

Appendix 1: Treatment application with the mechanical hand planter at Efaw, 2013

Appendix 2: Treatment application with a poke stick at Efaw and LCB; 2012 and 2013.



Appendix 3: Average monthly air temperatures and rainfall at Lake Carl Blackwell and Efaw (Stillwater), Oklahoma 2013 (Mesonet database)



Appendix 4: Average monthly air temperatures and rainfall at Lake Carl Blackwell and Efaw, Oklahoma (Stillwater), 2012 (Mesonet database)

VITA

Peter Omara

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