PRECISION PLANTING OF MAIZE (*Zea mays* L.)

By

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ABSTRACT: Precision seed placement and the resulting leaf orientation have the potential to influence some of the parameters that controls productivity. The objectives of this work were to evaluate the impact of seed placement and leaf orientation on cumulative intercepted photosynthetic active radiation (CIPAR), radiation use efficiency (RUE), grain yield, and plant-to-plant yield inequality of maize (*Zea mays* L.). Precision placement of maize used to orient leaf azimuths predominantly across and with the row was compared to conventionally planted seeds with random leaf orientation. Seed placements and leaf orientations were evaluated across plant populations (37050, 49400, 61750, 74100, and 98800 plants ha^{-1}), hybrids with differing canopy architecture (planophile and erectophile), and row configuration (single and twin rows). In 2012, by-plant yield and plant distance were measured and used to evaluate plant-to-plant yield inequality. In Chapter I, results show that CIPAR was higher for seed placements that resulted on across row leaf orientation rather than random. Yield responded positively to improved light interception and under irrigated conditions, precision planting of maize increased yield by 9 to 14% compared to conventionally planted seeds. In Chapter II, estimated CIPAR for leaf orientations were ranked as across-row > random > with-row, but greater RUE was observed for with-row rather than across-row or random leaf orientations. Additionally, across-row and with-row increased yield by 541 and 568 kg ha^{-1} compared to random leaf orientation. In Chapter III, Lorenz curves and Gini coefficient (G) demonstrated that by-plant yield inequality tended to reduce with precision planting. Lower by-plant yield inequality as indicated by small G coefficient was associated with lower coefficient of variation (CV), lower range, L-skewed, and leptokurtic distributions. Plant-to-plant yield variation expressed by the CV of by-plant yield indicated that seed placement and leaf orientation had little influence on yield variation but plant-to-plant yield variation was positively correlated with plant distance variation (plant distance CV). This work found that precision planting tended to reduce plant-to-plant yield inequality, increase light interception, and promote changes in radiation use efficiency which can result in yield improvement compared to conventionally planted seeds with random leaf orientation.

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SEED PLACEMENT AND LEAF ORIENTATION EFFECT ON LIGHT INTERCEPTION AND GRAIN YIELD OF MAIZE (*Zea mays* L.)

ABSTRACT

Precision planting of maize has the potential to affect some of the parameters that influence final grain yield. The purpose of this research was to improve maize light interception by using seed placement at planting to manipulate leaf azimuth across the row. Seed placement and the resultant leaf orientation were evaluated across three levels of plant population (PP) using two hybrids with different canopy architectures. For seed placements that resulted in leaf orientation across the row, seeds were planted (i) upright with caryopsis pointed down, parallel to the row (upright); and (ii) laying flat, embryo up, perpendicular to the row (flat) that were compared to conventionally planted seeds with random leaf orientation. Increased PP resulted in greater light interception but yield tended to decrease as PP increased. The planophile hybrid produced consistently greater yields than the erectophile hybrid, ranging from 283 to 903 kg ha^{-1}. Overall, mean grain yield for upright and flat seed placement and across row leaf orientation increased yield by 351 and 463 kg ha^{-1} compared to random seed placement. Greater CIPAR was found for oriented seeds and across row leaf orientation rather than random seed placement and leaf orientation. At physiological maturity, upright, flat, and random seed placements 555, 525, and 521 MJ m^{-2} of PAR, respectively. Maize yield responded positively to improved light interception and better radiation use efficiency. Under irrigated conditions, precision planting of maize increased yield by 9 to 14% compared to conventionally planted seeds.

INTRODUCTION

Management Practices and Productivity

Corn grain yields in the U.S. have increased from 1 Mg ha^{-1} (1930) to over 7 Mg ha^{-1} in 1990 (Troyer, 1990). Based on data obtained from the United States Department of Agriculture (USDA, 2011) corn grain yields in the U.S. have increased 24% since 1990 and average 9 Mg ha^{-1} today. Many strategies have been used to promote this yield increase including genetic improvements, the use of fertilizers in particular nitrogen, weeds, pest and disease control, tillage practices, crop rotation, reduced row spacing, and higher plant population. Many of these cultural practices evolved as a response to agricultural research to ensure global food security and promoted a considerable increase in yield levels. Additional yield increases are expected in the near future due to the demand for food. The question is, how much more can yields be increased, or are yield levels reaching a plateau? Yield competitions have demonstrated that genetic yield potential is seldom achieved, exposing the existence of yield gaps and an opportunity for additional yield increases even in optimized production systems. Reduction of yield gaps is one of the challenges facing crop production in the future, especially as resources become more limited. Resources such as water, nutrients, and solar radiation are required to be efficiently managed to assure the system's sustainability.

Solar radiation establishes the ultimate limit for crop production since all the energy used by crops throughout the growing season is obtained from solar radiation (Ray and Sinclair , 1998). Cultural practices such as increased plant population and reduced row spacing have taken advantage of higher light interception to increase yield. Increased light interception has a positive effect on productivity, often described as a linear function when the crop does not experience biotic and/or abiotic stress. Stinson and Moss (1960) suggested that light can be a limiting factor in corn production when nutrients and soil moisture are adequate. Decreased row spacing and increased plant population may not take full advantage of available radiation especially in production environments with a shorter growing season (Westgate, 1997). Additional exploitation of solar radiation will probably not come from further increases in plant population or reduction of row spacing, but from innovative approaches such as seed placement and its effects on leaf azimuth orientation that can optimize the use of resources without major changes in cultural practices.

Plant Population

According to Duvick (1992) and Cardwell (1982), 60% of the yield improvement in maize can be credited to genetic advances while the remaining 40% is the result of improved management practices. Increasing plant densities and decreasing row spacing are well known strategies to improve light interception and maize grain yield. Tollennar and Bruulsema (1988) found grain yield and absorbed solar radiation increased with plant population up to 100000 plants ha^{-1}. Karlen et al., (1985) found dry matter yield increases of 4 Mg ha^{-1} by elevating plant density from 6.7 to 13.5 plants m^{-2}.

Hunter (1980) classified the plant response to increasing population in three categories: (1) absence of inter-plant competition, yield per plant is maximized; (2) plants compete for resources, yield increases with plant population, but gain for each individual plant is marginal; and (3) plant population in excess of the required is needed to intercept the critical amount of photosynthetically active radiation (PAR). The main effect of high plant density is the increase in leaf area index (LAI). The increase in LAI has a direct impact on light interception and dry matter accumulation; as a result, yield is directly related to leaf area (Gardner et al., 1985). Olson and Sander (1988) found that by increasing plant population, LAI was enhanced whereas Hunter (1980) found that increased leaf area per plant of short-season maize resulted in grain yield increase.

Moreover, Alessi and Power (1974) demonstrated that depending on hybrid and season, LAI can be enhanced up to 4.9 by planting early maturing maize hybrids at densities of 74,000 plants ha^{-1}. Work by Maddonni et al. (2001) demonstrated that plant population significantly affected leaf size and individual leaf area as well as plant height and plant leaf area. Additionally, they reported leaf azimuth changes as plant population was increased. This is important because at elevated LAI, leaves of one plant will overlap and cause shading in the leaves of the neighboring plant, promoting competition for available radiation which can decrease the photosynthetic capacity of the canopy. Ear number and yield per plant can be reduced with mutual shading of plants (Prine and Schroder, 1964).

Canopy Architecture

Leaf architecture of modern corn hybrids can optimize light interception and increase grain yield by providing a means for the plants to intercept more light (Stewart et al., 2003). Optimization of light interception occurs due a better light distribution through the canopy known as light attenuation that is numerically represented by the extinction coefficient (*k*). Light attenuation is affected by the amount of radiation, foliage density, and leaf arrangement and used to describe how radiation penetrates the crop canopy by integrating LAI and the light penetration. This means that leaf angle, and azimuth will influence light attenuation. Pendleton and Hammond (1969) stated that relative photosynthetic potential of maize leaves was two times greater in the upper portion of the canopy than the middle portion and five times greater than the bottom part of the canopy. In addition, Boyd and Murray (1982) suggested that light transmittance through the crop canopy is affected by leaf architecture and can hinder weed development.

According to the leaf inclination, crop canopies can be classified into three main types, including erectophile, plagiophile, and planophile canopy architectures. de Wit (1965) defined erectophile as predominantly vertical leaf angles (>60°) and planophile when leaf angle is predominantly horizontal (<35°). In theory, if the canopy is considered planophile most of the light interception will occur at the uppermost part of the canopy. Individual leaves can become light saturated faster; less light will reach lower parts of the canopy affecting canopy photosynthetic efficiency and yield (Hay and Porter, 2006). Alternatively, erectophile canopies allow for better light penetration and improve the whole canopy photosynthetic efficiency. The problem with erectophile canopies is that critical LAI is required to increase, meaning that more leaves are necessary to intercept a given amount of light compared to planophile canopies. Gardner

(1985) showed that as leaf inclination increases from horizontal, leaf photosynthetic rate decreases while critical LAI increases, resulting in higher total photosynthesis.

Seed placement and Leaf Orientation

The principle of seed placement was first mentioned by Peters and Woolley (1959), who suggested that kernels planted upright with flat side facing the adjacent row seemed to be a promising mean for saving soil moisture as a result of more efficient soil shading. They observed a relation between initial seed position and leaf azimuth of maize, and suggested that more solar radiation could be intercepted with leaves from oriented kernels. In addition, they indicated that more efficient soil shading could reduce soil moisture evaporation losses and improve weed control. Later, research done by Fortin and Pierce (1996) showed that random seed placement results in random ear leaf orientation, thus it is reasonable to assume that controlled seed placement should result in controlled leaf azimuth.

Other aspects of initial seed position were presented by Patten and Van Doren (1970) who found earlier and more complete emergence with more seedling growth when maize was planted with the proximal end of the seed down. Giardin and Tollenaar (1994) observed the systematic nature of leaf azimuths and credited these changes in the canopy to intra-specific interference that provided a more uniform light distribution. Moreover, germination rate and success of eight weed species were found to be highly dependent on seed position in controlled environment germination (Bosy and Aarssen, 1995). Recently, Torres et al. (2011) found that leaf azimuth and emergence were significantly affected by seed position at planting and hybrid. They suggested that if seeds are systematically planted in the same manner, emergence can be more uniform and leaves methodically oriented resulting in more homogeneous crop stands.

Preliminary results from plots planted in 1958 using two row spacing's (0.76 and 1.01 m) demonstrated a yield advantage from precision seed placement at planting. Conventionally planted plots were out-yielded by seed-oriented plots (Peters and Woolley, 1959). Toler et al. (1999) used precision seed placement to manipulate plant canopy and obtain across row, with row, and random leaf orientations. Across row leaf orientation intercepted more light (10 and 25%) and produced higher grain yield (10 and 21%) than random and with row leaf orientations.

The yield increase observed in these experiments was attributed to the higher light interception and quicker canopy closure, as well as, reduced inter- and intra-plant competition. The effect of increased light interception gives the crop a competitive advantage in relation to weeds, because available light for weeds will be reduced. More efficient use of light has provided a means for constant yield increases that were usually achieved due to improved management practices and breeding. Environmental concerns associated with the use of pesticides and fertilizers in agriculture, and the challenge to feed a growing population motivates the development of innovative management practices. This research was initiated to support the development of precision planting of maize and to evaluate if seed placement of maize can be used as a management practice to promote grain yield increase by improving the crop ability to intercept light.

HYPHOTHESIS AND OBJECTIVES

The objectives of this experiment were to evaluate seed placement of maize at planting and its resultant leaf orientation effects on light interception, grain yield, radiation use efficiency, and grain nitrogen content. Controlled seed positions were compared to conventionally planted seeds with random seed placement (control) across three plant population densities and using two hybrids with dissimilar canopy architectures.

We hypothesize that precision planting of maize can be used to manipulate canopy geometry and enhance the total amount of PAR intercepted through the growing season. The hypothesis is that oriented maize leaves can intercept more light than randomly distributed maize leaves due to a reduction on reciprocal shading of one plant to the next. Because grain yield is proportional to the amount of PAR accumulated during the growing season, precision planting of maize may result in yield increase.

MATERIALS AND METHODS

Site Description and Experimental Design

Field trials were established at two sites in 2010, 2011, and 2012 to evaluate the influence of seed placement and leaf orientation on light interception, radiation use efficiency, total grain nitrogen, and grain yield. Experiments were conducted at Lake Carl Blackwell (LCB) near Stillwater-OK, on a Port silt loam-fine-silty, mixed, thermic Cumulic Haplustoll. The other experimental site was located at Efaw in Stillwater-OK, on a Norge loam, fine-silty, mixed thermic Udic Paleustoll.

The experimental design used was a randomized complete block with three replications. Treatment structure consisted of a factorial combination of seed placement, and plant population (PP) using a planophile hybrid and using an erectophile hybrid in an incomplete factorial. Seed placements were chosen to manipulate maize leaves perpendicularly or across in relation to the row. According to Torres et al. (2011) seed placements described as upright with caryopsis pointed down, parallel to the row (upright); laying flat, embryo up, perpendicular to the row (flat) will generate predominantly more leaves oriented between 60° and 90°. Conventionally planted seeds with random seed placement that resulted in random leaf orientation was used as the control.

Experiments located at EFAW were planted on 29 April 2010, 4 April 2011, and 19 April 2012 at plant populations of 37000, 49400, and 61700 plants ha^{-1}. Trials were planted at LCB on 25 May 2010, 4 May 2011, and 10 April 2012 at plant populations of 49400, 74100 and 98800 plants ha^{-1}. Maize hybrids planted at both sites were P0902HR and P1173HR in 2010 and 2011, and hybrids PO876HR and P1395XR in 2012. Hybrids P0902HR and PO876HR have planophile canopy architecture and require on average 749 and 705 thermal units (TU, °C d) from emergence to silking and 1366 and 1433 °C d to physiological maturity, respectively. Hybrids P1173HR and P1395XR have erectophile leaf architecture and require on average 727 and 777 °C d to silking and approximately 1516 °C d to physiological maturity for both hybrids.

The method for planting the seed-oriented treatments consisted of blocking the central seed boxes on a four-row planter to open furrows and at the same time raising the press wheels so furrows would remain open. Subsequently, seeds were carefully hand-planted in the furrows to ensure proper placement. A template that marked the exact distances between plants to reach a given PP was used to sow seed oriented plots. Plots with random seed placement were conventionally planted using a four-row planter. Individual plots measured 6.09 m long by 3.50 m wide and row spacing was 0.76 m.

All plots received pre-plant nitrogen rates of 180 kg N ha^{-1} and a top dress application around V8 growth stage of 60 kg N ha^{-1} as urea ammonium nitrate (UAN, 28%). Phosphorus and potassium were applied according to soil test recommendations determined each year. In 2011 and 2012 at EFAW, a drip irrigation system was used to provide water at critical periods of crop development to ensure crop production. However, no irrigation was used at EFAW in 2010 and drought stress was encountered.

At LCB, a lateral pivot was used in 2010 and 2011, but in 2012 a drip irrigation system was installed since the amount of water in the irrigation reservoir was not adequate to allow irrigation using the lateral pivot.

Measurements, Calculations, and Analysis

Dependent variables included grain yield, grain nitrogen concentration and fraction of intercepted PAR. Light interception data were collected as photosynthetic photon flux density (PPFD, µmol s^{-1} m^{-2}) during the crop development between V4 and R1 growth stages. Three light measurements were taken per plot, under clear sky, around solar-noon. The quantum sensor was placed diagonally under the crop canopy at the soil level, across the space between the center rows. A line quantum-sensor LI-191SA connected to a LI-1400 data-logger (both from LI-COR, Lincoln, NE) was used to gather incident PAR above and under the canopy. Measurements were then expressed as a fraction of intercepted photosynthetically active radiation by the canopy (fPAR) calculated as the ratio of incident PAR under the canopy at the soil level and incident PAR above the canopy.

Since crop development and growth rate are dependent on temperature in the absence of stress (Hay and Porter, 2006), fPAR measurements were evaluated as a function of TU accumulated from emergence until each measurement date. Thermal units integrate temperature above a base temperature and below a maximum over time. For maize, base temperature is 10°C and maximum temperature is 30°C (Coelho and Dale, 1980). Asymptotic equations were fitted to the relation between fPAR and TUs using the software TableCurve 2D version 5.01 (SYSTAT Software Inc. 2002).

Coefficients from fitted equations were used to predict daily intercepted PAR (IPAR) for seed placement, PP, and hybrid. Daily solar radiation data for every site and year was obtained from the Mesonet weather stations located near each experimental site (http://www.mesonet.org/, verified 25 Sept. 2012). Daily solar radiation was transformed to daily incident PAR (400-700 nm) by assuming that 45% of total solar radiation is actually PAR (Meek et al., 1984). The product of IPAR and incident PAR for each day of the growing season was accumulated from emergence to silking and to physiological maturity to determine cumulative IPAR (CIPAR, MJ m^{-2}) (Ritchie et al., 1993). Radiation use efficiency (RUE, g MJ^{-1}) was determined as the ratio of grain yield and CIPAR at silking and at physiological maturity.

Statistical analysis was first performed to evaluate main and interaction effects of seed placement and PP. Afterward, analysis of main and interaction effects of seed placement and hybrid was performed. Analysis of variance (ANOVA) and means by site and year were performed using the GLM procedure from SAS software v.9.2 (SAS Inst., Cary, NC). Orthogonal and single degree of freedom contrasts were used to make specific comparisons between treatments while trend analysis was performed to understand the effect of increasing PP. In addition, regression analysis and correlation coefficients were generated using PROC REG and PROC CORR procedures in SAS (SAS Inst., Cary, NC) to investigate the relationship between grain yield, CIPAR, RUE at silking and physiological maturity.

RESULTS AND DISCUSSION

In general, interactions by year were not consistent; although, there was a significant year by PP interaction effect for grain yield at EFAW. Due to differences in environmental conditions experienced at each trial, analysis was performed by location and year. Plots at LCB were severely damaged by wild life in 2011, as such the experiment was harvested to evaluate total grain N but grain yield data were lost.

Grain Yield

Orientation of maize seeds resulted in higher yields compared to random seed placement, except at EFAW in 2010 when the random produced 223 and 261 kg ha^{-1} higher yield than the upright and flat orientated seeds, respectively (Table 1). Excluding the experiment at EFAW in 2010, the average yield gain due to upright and flat seed placement was 9 and 14 % compared to the random, respectively. These results agree to the findings reported by Peters and Woolley (1959) and Toler et al. (1999) who found yield advantage of oriented seeds compared to random. In addition, Toler et al. (1999) showed a 10% grain yield increase for across row leaf orientation which resulted from upright seed placement in relation to random leaf orientation (random seed placement). The year of 2010 at EFAW was the only site-year that did not receive any irrigation, thus light interception became less important as compared to water demands. According to these findings it is reasonable to conclude that under unfavorable environmental conditions seed placement may not be an important factor to maize productivity.

Analysis of variance for EFAW indicated that seed placement and leaf orientation did not affect yield in 2010, but in 2011 the upright and flat seed planting produced 6 and 14% higher yields compared to random seed placement (Table 1). In 2012, upright and flat seed placement resulted in a 5 and 12% yield increase when compared to conventionally planted seeds. Orthogonal contrasts indicated no differences between upright and random seed placements in any year at EFAW; however, the flat seed placement was significantly higher than random in 2011.

Table 1 shows that at LCB, upright seed placement was 7% higher than random while flat seed placement produced 19% greater yield than random in 2010. Contrasts showed that only the flat seed placement was actually significantly higher than random; no difference was found between upright and random seed placements in 2010 at LCB. Alternatively, the upright treatment was significantly different from the random in 2012 while no difference between flat and random treatments was observed. The yield of the upright seed placement was the highest observed in 2012, representing a difference of 1195 kg ha^{-1} greater than the random seed placement (Table 1). Further, a positive difference of 662 kg ha^{-1} in favor of flat seed placement was observed when compared to the random. Even though, there was 9% yield difference between flat and random, single degree of freedom contrast revealed that this difference was not statistically significant.

A significant yield response to increasing PP was observed in 2010, but no effect was observed in 2011 and 2012 due to increased PP at EFAW. Yield increased linearly in 2010, while in 2011 yield decreased in linear fashion as PP increased. In 2012, neither linear nor quadratic trends were observed; highest yield was found at the lower PP (4751 kg ha^{-1}) and lowest yield found at the medium PP (4170 kg ha^{-1}) (Table 1). Plant population effect on yield observed in 2010 was different from the trends found in 2011 and 2012, which justify the year by treatment interaction found at EFAW. No irrigation was used at EFAW in 2010 and drought severely affected yield and response to PP. In 2011 and 2012, PP of 37050 plants ha^{-1} was sufficient to achieve maximum yield compared to medium and high PP.

At LCB, ANOVA showed a significant effect of PP on yield in 2010 while single degree of freedom contrasts indicated that linear and nonlinear trends were significant (Table 1). Plant population of 49400 and 74100 plants ha^{-1} had similar productivity that was greater than with 98800 plants ha^{-1}. This suggests plant competition likely occurred at PP of 98800 plants ha^{-1}, exceeding the optimum PP required to reach the critical amount of light as suggested by Hunter (1980). Karlen and Camp (1985) also reported that reproductive development and grain yield can be negatively influenced by plant populations in excess of optimum levels. In contrast, a significant linear trend for grain yield as a function of PP was observed in 2012 and the highest yield was 7240 kg ha^{-1} produced with PP of 98800 plants ha^{-1} (Table 1).

No interaction effect of seed placement and PP on yield was detected with ANOVA contradicting the findings of Toler et al. (1999) who found a significant seed placement by PP interaction. However, contrasts showed some inconsistency in the yield response of seed placement treatments across levels of PP at EFAW in 2010 and 2011 as well as at LCB in 2010 (Table 1). In 2011 at EFAW, the yield of random seed placement was higher at low PP and decreased as PP increased while the yield of upright seed position was lower at low PP and increased with PP. In 2010 at LCB, interaction contrast revealed a linear trend for upright versus random and flat versus random. These results indicate that PP will likely influence maize yield response to seed placement and leaf orientation.

Pooled over hybrids, no effect of seed placement and leaf orientation on yield was detected by ANOVA at EFAW (Table 2). However, contrasts indicated that upright was 351 kg ha^{-1} greater than random in 2011. In addition, the flat seed position had 301 kg ha^{-1} higher yields than random but this difference was not statistically different. The yield of the random treatment was 88 and 189 kg ha^{-1} greater than upright and flat treatments respectively in 2010 at EFAW, while in 2012, upright and random seed placements produced similar yields that were higher than the yield produced by the flat seed placement (Table 2).

Seed oriented treatments improved yield compared to random seed placement at LCB. Upright and flat seed placements out-yielded conventionally planted seeds in 2010 by 1373 and 1310 kg ha^{-1}, which represents an increase over the random by 27 and 26% respectively (Table 2). In 2012, upright seed placement produced 7179 kg ha^{-1} that was significantly higher than 6065 kg ha^{-1} produced by the random, whereas flat seed placement yielded 6210 kg ha^{-1} and was not different from random placement.

Results in Table 2 indicate that hybrid performance was significantly different in 2011 and 2012 at EFAW and at LCB in 2012. The hybrid with planophile leaf architecture generally out-yielded the hybrid with erectophile canopy architecture. At EFAW, the planophile hybrid produced 283, 313, and 776 kg ha^{-1} more yield than the erectophile hybrid in 2010, 2011, and 2012, respectively, whereas at LCB, the planophile out-yielded erectophile hybrid by 389 in 2010 and by 903 kg ha^{-1} in 2012 (Table 2).

The effect of seed placement and PP on grain nitrogen concentration was usually small, except at LCB in 2010 and 2012 that showed a significant effect of PP on grain nitrogen concentration (Table 3). Contrasts indicated a linear trend for grain nitrogen concentration but similar to ANOVA this effect was not consistent with the results from 2011 and 2012 at EFAW. Grain nitrogen concentration was affected by hybrid only in 2010 at LCB; the effect of seed placement and the interaction with hybrid were not significant (Table 4).

Light Interception

Figure 1 depicts fPAR measurements as a function of TU as affected by PP at LCB and EFAW. Increased PP promoted higher light interception; even though, the improvement in fPAR was often not enough to detect significant differences. Higher light interception as a result of increased PP was expected since LAI is enhanced as plant population increases. Gardner et al. (1985) suggested that light interception was directly influenced by greater LAI. As TUs accumulated during the growing season fPAR increased until a critical fPAR was reached. This critical level of fPAR was usually observed between approximately 600 and 700 °C d accumulated after emergence, but dependedon the location (Figure 1).

Measurements showed that upright and flat treatments intercepted more fPAR compared to random seed placement (Figure 2a). Differences among treatments were observed between 500 and 800 °C d, but no treatment effect was found at earlier vegetative stages and during reproductive stages at LCB. At EFAW, the effect of seed placement and leaf orientation on fPAR was observed at late vegetative growth stage in which seed oriented treatments tented to improve light interception compared to random seed treatments (Figure 2b).

When pooled over hybrids, fPAR showed similar results to what was found when seed placement and leaf orientation were evaluated across plant populations at LCB, but not at EFAW. Small differences in fPAR measurements were observed at early vegetative stages, but from approximately V8 to tassel vegetative stage differences between measurements became more evident at LCB (Figure 3a). Differences in light interception measurements between planophile and erectophile hybrids were small and not significant (Figure 4).

Cumulative Intercepted Light

Using asymptotic regression functions obtained from the fPAR and TU regression it was possible to predict how much light was intercepted at each day of the growing season since emergence. Daily IPAR was multiplied by incident PAR and accumulated until silking and physiological maturity. An example of IPAR accumulation as a function of TU for the upright, flat and random seed placements at LCB in 2010 is shown in Figure 5. Cumulative IPAR was higher for the upright and flat treatments compared to the random. It was interesting to observe that seed placement and leaf orientation treatments became more distinct as plants developed and began to compete with each other.

Table 5 shows CIPAR and RUE at silking and physiological maturity for seed placement, PP, and hybrid, and seed placement over hybrids at EFAW and LCB from 2010 to 2012. Generally, CIPAR increased linearly as PP increased at silking and physiological maturity at both sites. Conversely, highest CIPAR was observed for the PP of 49400 plants ha^{-1}, following a quadratic trend in 2010 and 2011 at EFAW. Average CIPAR at physiological maturity was 491, 508, and 523 MJ m^{-2} for 37050, 49400, and 61750 plants ha^{-1} at EFAW, respectively, while at LCB mean CIPAR was 561, 598, and 612 MJ m^{-2} for PP of 49400, 74100, and 98800 plants ha^{-1}, respectively (Table 5).

There were no differences between seed placement and leaf orientation treatments up to silk stage at EFAW, but at maturity oriented seed treatments had between 4 to 7% higher CIPAR compared to random seed placement (Table 5). Cumulative IPAR at LCB tended to be higher for seed oriented treatments. For example, upright and flat seed positions had approximately 15% greater CIPAR than the random treatment at silking and about 4% higher at physiological maturity (Table 5). Overall all sites and years, up to physiological maturity, upright seed placement intercepted on average 553 MJ m^{-2} of PAR; flat intercepted 549 MJ m^{-2} of PAR; and random seed position intercepted 525 MJ m^{-2} of PAR. Due to adverse environmental conditions encountered during the maize development, the crop rarely reached the theoretical 95% of light interception which likely restrained grain productivity. Admittedly, relatively small differences in CIPAR were found during reproductive growth stages; however, Andrade (2001) has noted that even minute increments in light interception resulted in grain yield increases.

When pooled over hybrids; mean CIPAR of the random treatment had higher CIPAR at silking (197 MJ m^{-2}), but not at physiological maturity (489 MJ m^{-2}) at EFAW

(Table 5). At LCB, oriented seeds had higher CIPAR at silk stage (284 and 282 MJ m^{-2} for upright and flat treatments, respectively). At maturity estimated CIPAR of random was 29 MJ m^{-2} greater than flat seed placement, but 58 MJ m^{-2} lower than upright seed placement (Table 5). Regarding CIPAR of planophile and erectophile hybrids, small differences were noted at silking whereas at physiological maturity greater CIPAR was found for the erectophile hybrid. However, the erectophile hybrid TU requirement to achieve physiological maturity was higher than that required for the planophile hybrid to reach maturity, reflecting on the amount light accumulated up to maturity.

Radiation Use Efficiency

Radiation use efficiency was generally inversely related to PP; low PP usually resulted in higher RUE which was consistent across sites (Table 5). At EFAW, average RUE ranged from 1.82 to 1.64 g MJ^{-1} of CIPAR at silking whereas at LCB, mean RUE for 49400, 74100, and 98800 plant ha^{-1} was 3.19, 3.06 and 2.40 g MJ^{-1}, respectively. Westgate et al. (1997) reported maize RUE values ranging from 2.24 to 2.89, 2.09 to 3.02, and 2.16 to 2.89 g MJ^{-1} for PP of 4.9, 7.4, and 9.9 plants m^{-2}, respectively. In their study, three maize hybrids over two years of study were investigated using 0.76 and 0.38 m row spacing. Moreover, a noteworthy decline in RUE at high PP was also observed by Andrade et al. (1993).

The reason for better RUE can be attributed to the fact that yield tended to decrease with increased plant population. However, the lower PP intercepted less light at silking and maturity than medium and high PP causing the RUE values to increase. Highest RUE was observed for flat at silking (1.86 g MJ^{-1}) and physiological maturity

(0.68 g MJ^{-1}) at EFAW. Although, at LCB random seed placement and leaf orientation used radiation more efficiently at silking, while at maturity, it was the least efficient. When pooled over hybrids, precision planting tended to improve RUE in relation to the random. Moreover, the planophile hybrid had consistently better RUE compared to the erectophile hybrid at both locations which likely occurred because of higher yield of planophile hybrids.

Grain Yield, CIPAR, and RUE Relation

Overall, there was a positive and significant correlation between yield and CIPAR at physiological maturity (Table 6). The correlation between yield and CIPAR for the hybrid effect was weak and not significant at both phenological stages (r=0.26 and r=0.23, silking and maturity, respectively). Grain yield and CIPAR were highly correlated at silking (r=0.75, $P<0.01$) and physiological maturity (r=0.91, $P<0.01$) for the seed placement main effect (Table 6).

Yield response to CIPAR can be represented by a linear function for seed placement and leaf orientation ($r^2=0.82$, $P<0.01$), PP ($r^2=0.66$, $P<0.01$), and seed placement within hybrid ($r^2=0.56$, $P<0.01$) especially at maturity (Figure 6a and 6b). Although, regression analysis of yield as a function of CIPAR at physiological maturity revealed that a second order polynomial was highly related to yield (data not shown). Maximum yield for the upright treatment was predicted 7495 kg ha^{-1} with 726 MJ m^{-2} of CIPAR, while the flat seed placement function predicted 7078 kg ha^{-1} with 658 MJ m^{-2} of CIPAR, slightly lower maximum yield than the upright function predicted. The random treatment function predicted maximum yield of 6282 kg ha^{-1} with 661 MJ m^{-2} of CIPAR.

The presence of barren plants in the maize population may explain the decline on predicted yield as CIPAR increases beyond the amount required for maximum productivity. This can occur because PAR is intercepted but barren plants have no contribution to final grain yield. Edwards et al. (2005) presented a model that also predicted a decline in maize yield for CIPAR greater than 600 MJ m^{-2}. However, they emphasized that barren and lodged plants were not observed in the experiments; hence there was no reason to assume that maize yield would decline as CIPAR increased over 600 MJ m^{-2} (Edwards et al., 2005).

CONCLUSIONS

In the recent past, it was difficult to imagine that oriented seeds could be mechanically planted, but current advances in precision planting may change the way maize seeds are planted around the world. This work was initiated to support the development of precision planting and to show that seed placement and its effects on leaf orientation can be beneficial to maize production. Moreover, this study identified an opportunity for improvement of maize crop light interception and grain yield through the use of precision planting. A positive relation between intercepted light and yield was found and explained the yield differences encountered in this study. Under adverse environmental conditions such as drought, improved light interception may not be important. Under irrigated conditions, precision seed placement and across leaf orientation increased yield by promoting higher light interception especially as interplant competition begins to limit light availability. The crop barely reached the idealized 95% of light interception for optimum productivity and for this reason, any increment in light interception owed to management practices caused grain yield to increase. In conclusion, leaf azimuth orientation through seed placement at planting improved light interception of maize and resulted in grain yield increases from 9 to 14% compared to seeds planted with random placement and leaf orientation.

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Table 1. Analysis of variance and orthogonal contrasts for main effects of plant population (PP) and seed placement (SP) on grain yield at EFAW and Lake Carl Blackwell, OK, 2010-2012.

Plant	Seed	EFAW			LCB	
Population†	Placement‡	2010	2011	2012	2010	2012
		Grain Yield, kg ha^{-1}				
Low		2000	3340	4751	6344	6395
Medium		2280	3137	4170	6567	6954
High		2543	3036	4416	4146	7240
	Upright	2213	3158	4418	5610	7439
	Flat	2175	3390	4702	6226	6906
	Random	2436	2966	4216	5221	6244
Source of Variation	DF	Significance level (Pr > F)				
PP	2	**	NS	NS	***	NS
SP	2	NS	**	NS	**	*
Block	2	NS	NS	NS	***	NS
PP x SP	4	NS	NS	NS	NS	NS
Contrasts						
Main Effects						
PP Linear Trend	1	**	*	NS	***	*
PP Quadratic Trend	1	NS	NS	NS	***	NS
Upright versus Random	1	NS	NS	NS	NS	**
Flat versus Random	1	NS	**	NS	***	NS
Interaction Effects						
Up versus Random (Linear)	1	NS	**	NS	**	NS
Up versus Random (Quad.)	1	NS	NS	NS	NS	NS
Flat versus Random (Linear)	1	NS	NS	NS	**	NS
Flat versus Random (Quad.)	1	*	NS	NS	NS	NS
SED		314	224	532	544	717
CV (%)		17	9	15	12	13

*, **, *** significant at 0.10, 0.05, and 0.01 probability levels, respectively; NS, not significant.

† Low plant population at EFAW and LCB was 37050 and 49400 plants ha^{-1}, respectively; Medium plant population at EFAW and LCB was 49400 and 74100 plants ha^{-1}, respectively; High plant population at EFAW and LCB was 61050 and 98800 plants ha^{-1}, respectively.

‡ Seed placement used to achieve predominantly across row leaf orientation were; Upright-seeds planted upright with caryopsis pointed down, kernel parallel to the row; and Flat-seeds planted laying flat, with embryo up, kernel perpendicular to the row. Conventionally planted seeds with Random seed placement were used to achieve random leaf orientation.

§ SED, standard error of the difference between two equally replicated means.

Table 2. Analysis of variance and orthogonal contrasts for main effects of hybrid and seed placement (SP) pooled over hybrid on grain yield at EFAW and Lake Carl Blackwell (LCB), OK, 2010-2012.

Hybrid†	Seed Placement‡	EFAW			LCB	
		2010	2011	2012	2010	2012
		Grain Yield, kg ha^{-1}				
Planophile		2347	3115	4212	6151	6936
Erectophile		2064	2802	3436	5762	6033
	Upright	2109	3093	3911	6435	7179
	Flat	2210	3042	3640	6372	6210
	Random	2298	2741	3921	5062	6065
Source of Variation	DF	Significance level (Pr > F)				
Hybrid	1	NS	*	*	NS	**
SP (Hybrid)	2	NS	NS	NS	NS	*
Rep	2	NS	NS	NS	**	*
Hybrid x SP (Hybrid)	2	NS	NS	NS	NS	NS
Contrasts						
Main Effects						
Planophile versus Erectophile	1	NS	*	**	NS	**
Upright versus Random	1	NS	*	NS	*	**
Flat versus Random	1	NS	NS	NS	*	NS
Interaction Effects						
Upright versus Random (Hybrid)	1	NS	NS	NS	NS	NS
Flat versus Random (Hybrid)	1	NS	NS	NS	NS	NS
SED§		318	250	510	746	563
CV (%)		18	10	16	16	11

*, **, *** significant at 0.10, 0.05, and 0.01 probability levels, respectively; NS, not significant.

† Planophile, leaf angle is predominantly horizontal; Erectophile predominantly vertical leaf angles.

‡ Seed placement used to achieve predominantly across row leaf orientation were; Upright-seeds planted upright with caryopsis pointed down, kernel parallel to the row; and Flat-seeds planted laying flat, with embryo up, kernel perpendicular to the row. Conventionally planted seeds with Random seed placement were used to achieve random leaf orientation.

§ SED, standard error of the difference between two equally replicated means.

Table 3. Analysis of variance and main effect means of plant population (PP), seed placement (SP), and hybrids for total nitrogen (N) in the grain at EFAW and Lake Carl Blackwell (LCB), OK, 2010-2012.

Plant Population†	Seed Placement‡	EFAW 2010	EFAW 2011	EFAW 2012	LCB 2010	LCB 2011	LCB 2012
		Total N, mg kg^{-1}					
Low		132	148	158	136	162	149
Medium		129	144	160	129	166	140
High		128	141	157	129	165	138
	Upright	128	144	153	131	166	139
	Flat	130	143	163	132	165	143
	Random	132	146	159	131	163	146
Source of Variation	DF	Significance Level (Pr > F)					
PP	2	NS	NS	NS	**	NS	**
SP	2	NS	NS	NS	NS	NS	NS
Block	2	NS	**	NS	***	NS	NS
PP x SP	4	NS	NS	NS	NS	NS	NS
SED§		5	7	5	5	9	5
CV (%)		5	6	6	5	7	6

*, **, *** significant at 0.10, 0.05, and 0.01 probability levels, respectively; NS, not significant.

† Low plant population at EFAW and LCB was 37050 and 49400 plants ha^{-1}, respectively; Medium plant population at EFAW and LCB was 49400 and 74100 plants ha^{-1}, respectively; High plant population at EFAW and LCB was 61050 and 98800 plants ha^{-1}, respectively.

‡ Seed placement used to achieve predominantly across row leaf orientation were: Upright-seeds planted upright with caryopsis pointed down, kernel parallel to the row; and Flat-seeds planted laying flat, with embryo up, kernel perpendicular to the row. Conventionally planted seeds with Random seed placement were used to achieve random leaf orientation.

§ SED, standard error of the difference between two equally replicated means.

Table 4. Analysis of variance and main effect means of hybrids and seed placement (SP) pooled over hybrid for total nitrogen (N) in the grain at EFAW and Lake Carl Blackwell (LCB), OK, 2010-2012.

	Seed	EFAW			LCB		
Hybrid†	Placement‡	2010	2011	2012	2010	2011	2012
		Total N, mg kg^{-1}					
Planophile		126	145	159	129	167	142
Erectophile		121	147	159	114	160	147
	Upright	121	145	156	122	166	145
	Flat	124	148	162	123	160	142
	Random	125	145	158	120	165	147
Source of Variation	DF	Significance Level (Pr > F)					
Hybrid	1	NS	NS	NS	***	NS	NS
SP (Hybrid)	2	NS	NS	*	NS	NS	NS
Rep	2	NS	NS	NS	NS	**	NS
Hybrid x SP (Hybrid)	2	NS	NS	NS	NS	NS	NS
SED§		5	8	3	5	8	7
C.V. (%)		5	7	4	5	6	6

*, **, *** significant at 0.10, 0.05, and 0.01 probability levels, respectively; NS, not significant.

† Planophile, leaf angle is predominantly horizontal; Erectophile predominantly vertical leaf angles.

‡ Seed placement used to achieve predominantly across row leaf orientation were; Upright-seeds planted upright with caryopsis pointed down, kernel parallel to the row; and Flat-seeds planted laying flat, with embryo up, kernel perpendicular to the row. Conventionally planted seeds with Random seed placement were used to achieve random leaf orientation.

§ SED, standard error of the difference between two equally replicated means.

Table 5. Cumulative intercepted photosynthetically active radiation (CIPAR) and radiation use efficiency (RUE) at silking and physiological maturity for the effects of seed placement (SP), plant population (PP), hybrid, and seed placement pooled over hybrids [SP (Hybrid)] at EFAW and Lake Carl Blackwell (LCB), OK, in 2010-2012.

Site	Effect	Level	CIPAR at Silking			CIPAR at Physiological Maturity			RUE at Silking			RUE at Physiological Maturity		
			2010	2011	2012	2010	2011	2012	2010	2011	2012	2010	2011	2012
			MJ m^{-2}						g MJ^{-1}					
EFAW	PP†	Low	197	216	164	465	490	518	1.01	1.55	2.90	0.43	0.68	0.92
		Medium	212	232	176	482	510	534	1.07	1.35	2.37	0.47	0.62	0.78
		High	208	224	189	491	515	564	1.22	1.35	2.34	0.52	0.59	0.78
	SP‡	Upright	185	196	177	471	490	555	1.19	1.60	2.50	0.47	0.64	0.80
		Flat	184	197	175	460	481	541	1.18	1.72	2.69	0.47	0.70	0.87
		Random	186	199	179	440	461	517	1.31	1.49	2.35	0.55	0.64	0.82
	Hybrid‡	Planophile	187	198	180	471	488	557	1.25	1.58	2.33	0.50	0.64	0.76
		Erectophile	174	180	208	524	542	586	1.18	1.55	1.65	0.39	0.52	0.59
	SP (Hybrid)	Upright	187	197	178	475	494	560	1.13	1.54	2.20	0.44	0.62	0.70
		Flat	168	177	158	454	470	537	1.32	1.75	2.30	0.49	0.66	0.68
		Random	196	209	186	456	478	532	1.17	1.31	2.11	0.50	0.57	0.74
LCB	PP	Low	187	308	214	520	504	658	3.38		2.99	1.22		0.97
		Medium	207	354	236	545	555	688	3.18		2.95	1.21		1.01
		High	217	368	250	559	570	706	1.91		2.90	0.74		1.03
	SP	Upright	212	370	254	541	561	695	2.64		2.91	1.04		1.07
		Flat	220	371	256	549	564	697	2.83		2.70	1.13		0.99
		Random	187	330	215	527	535	669	2.80		2.90	0.99		0.93
	Hybrid	Planophile	173	287	204	449	456	575	3.55		3.40	1.37		1.21
		Erectophile	158	228	267	527	519	595	3.64		2.26	1.09		1.01
	SP (Hybrid)	Upright	224	367	260	551	559	699	2.87		2.76	1.17		1.03
		Flat	227	355	265	479	480	587	2.81		2.34	1.33		1.06
		Random	193	315	222	508	494	634	2.62		2.73	1.00		0.96

† Low, medium and high plant population densities at EFAW were 37050, 49400, and 61750 plants ha^{-1} and at LCB plant densities were 49400, 74100, and 98800 plants ha^{-1}.

‡ Seed placement used to achieve predominantly across row leaf orientation were; Upright- seeds planted upright with caryopsis pointed down, kernel parallel to the row; and Flat- seeds planted laying flat, with embryo up, kernel perpendicular to the row. Conventionally planted seeds with Random seed placement were used to achieve random leaf orientation.

§ Planophile, leaf angle is predominantly horizontal; Erectophile predominantly vertical leaf angles.

Table 6. Correlation coefficients between grain yield, cumulative intercepted photosynthetically active radiation (CIPAR) and radiation use efficiency (RUE) at silking and physiological maturity for plant population (PP), seed placement (SP), hybrid, and seed placement pooled over hybrids [SP (Hybrid)] using combined data from EFAW and Lake Carl Blackwell, OK, 2010-2012.

Main Effect	Variable	CIPAR at Silking	CIPAR at Maturity	RUE at Silking	RUE at Maturity
PP	Yield	0.17NS	0.82 ***	0.94 ***	0.94***
	CIPAR at Silking		0.18 NS	-0.16 NS	-0.05NS
	CIPAR at Maturity			0.66 ***	0.58**
	RUE at Silking				0.97***
SP	Yield	0.75***	0.91 ***	0.93 ***	0.95***
	CIPAR at Silking		0.36 NS	0.45 *	0.58**
	CIPAR at Maturity			0.79 ***	0.73***
	RUE at Silking				0.95***
Hybrid	Yield	0.26NS	0.23 NS	0.91 ***	0.96***
	CIPAR at Silking		0.05 NS	-0.14 NS	0.09NS
	CIPAR at Maturity			-0.01 NS	-0.03NS
	RUE at Silking				0.95***
SP (Hybrid)	Yield	0.77***	0.75 ***	0.93 ***	0.94***
	CIPAR at Silking		0.21 NS	0.49 *	0.68***
	CIPAR at Maturity			0.68 ***	0.50**
	RUE at Silking				0.91***

*, **, *** significant at 0.10, 0.05, and 0.01 probability levels, respectively; NS, not significant.

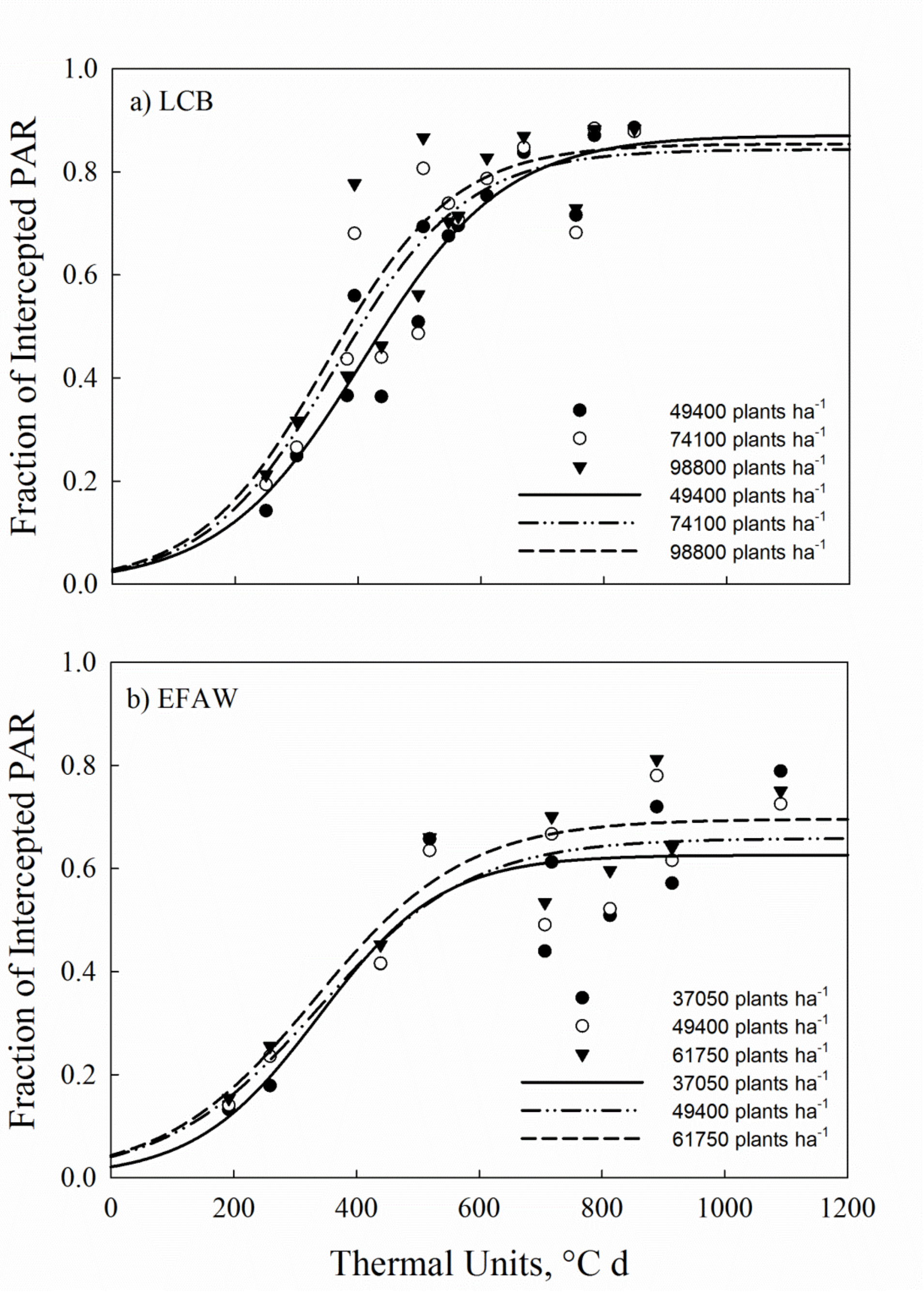

Figure 1. Fraction of intercepted photosynthetically active radiation (fPAR) as a function of thermal units for plant population at a) Lake Carl Blackwell (LCB) and b) EFAW, OK, 2010-2012.

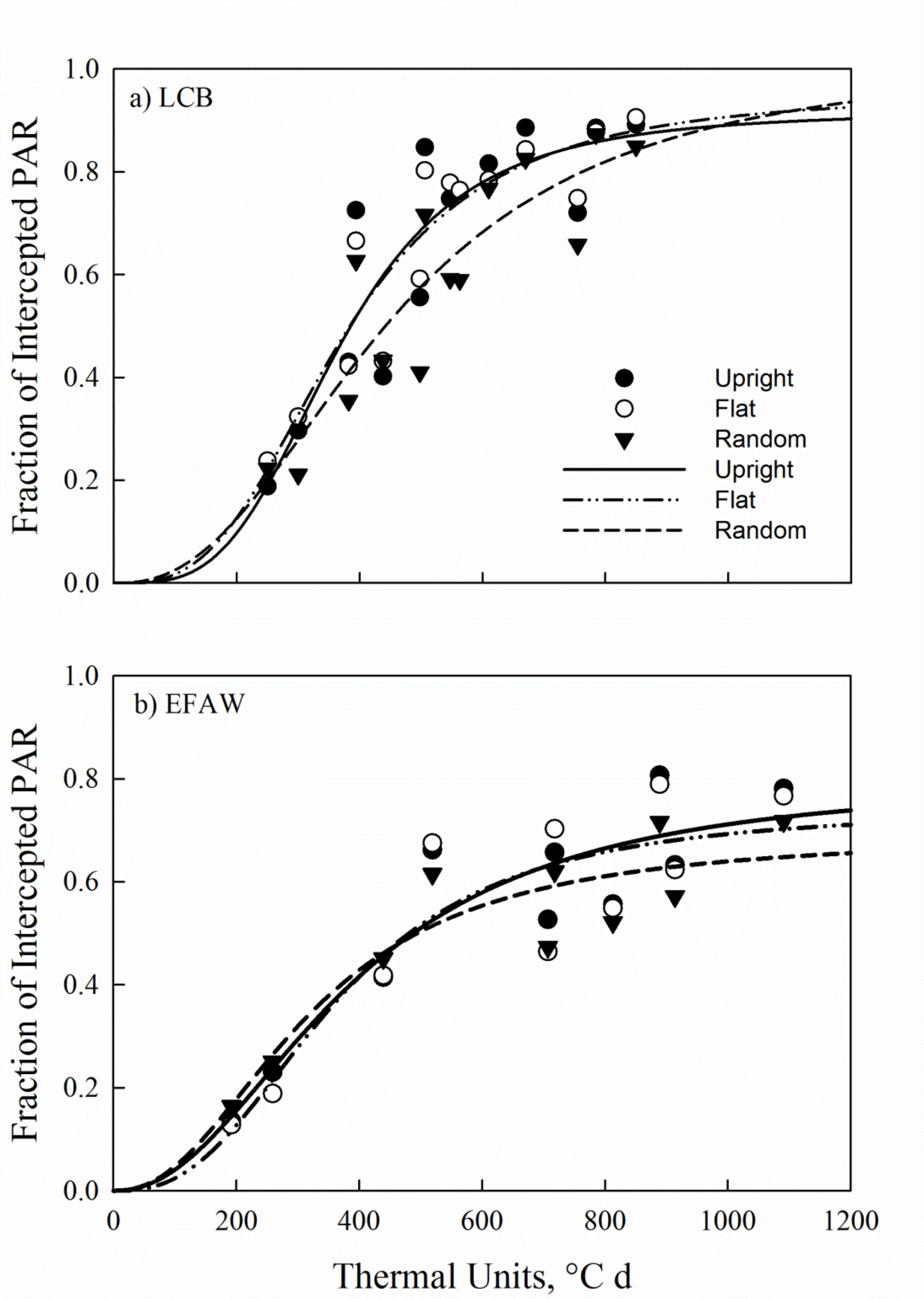

Figure 2. Fraction of intercepted photosynthetically active radiation (fPAR) as a function of thermal units for seed placement pooled over plant population at a) Lake Carl Blackwell (LCB) and b) EFAW, OK, 2010-2012.

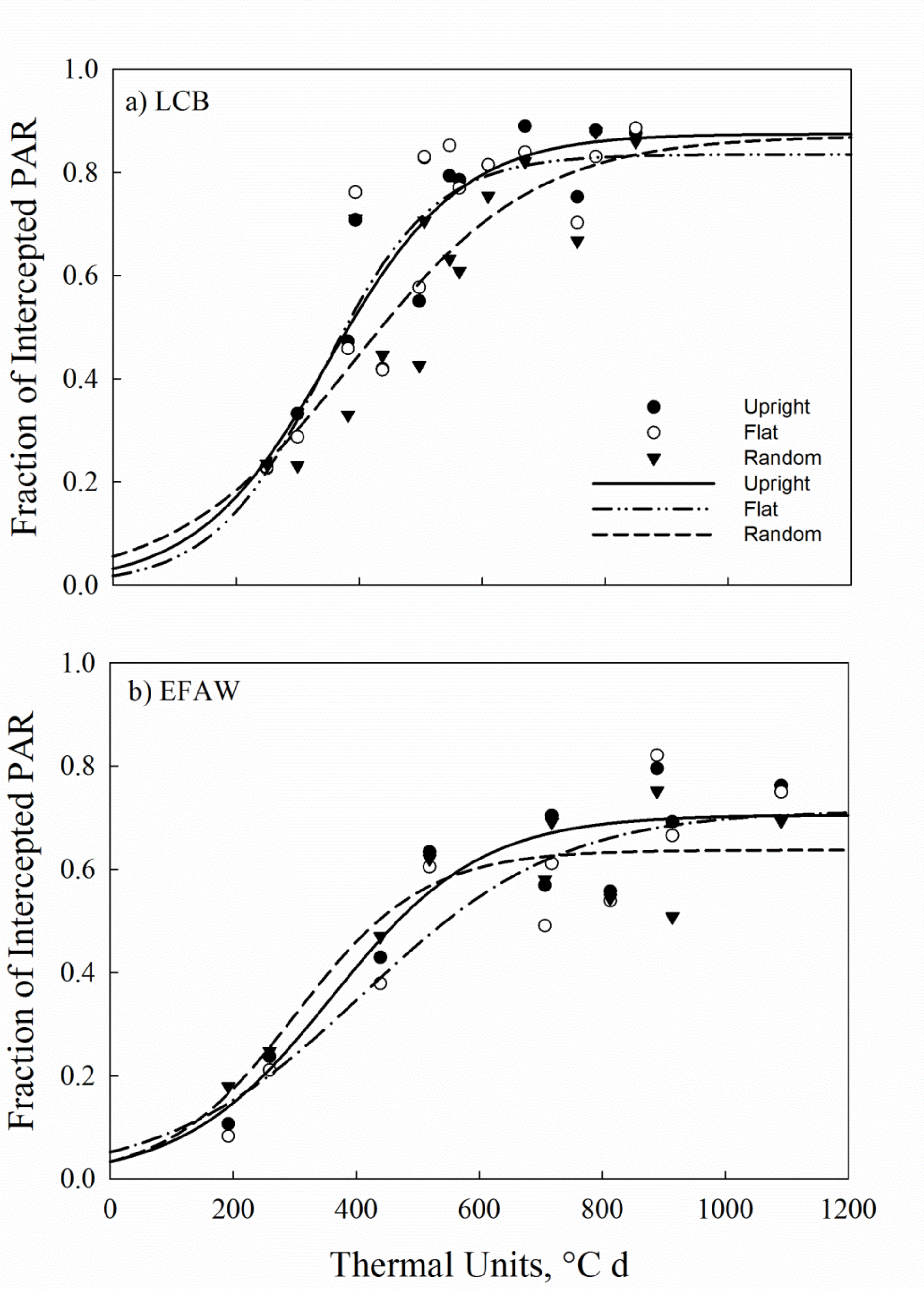

Figure 3. Fraction of photosynthetically active radiation (fPAR) as a function of thermal units for seed placement pooled over hybrid at a) Lake Carl Blackwell (LCB) and b) EFAW, OK, 2010-2012.

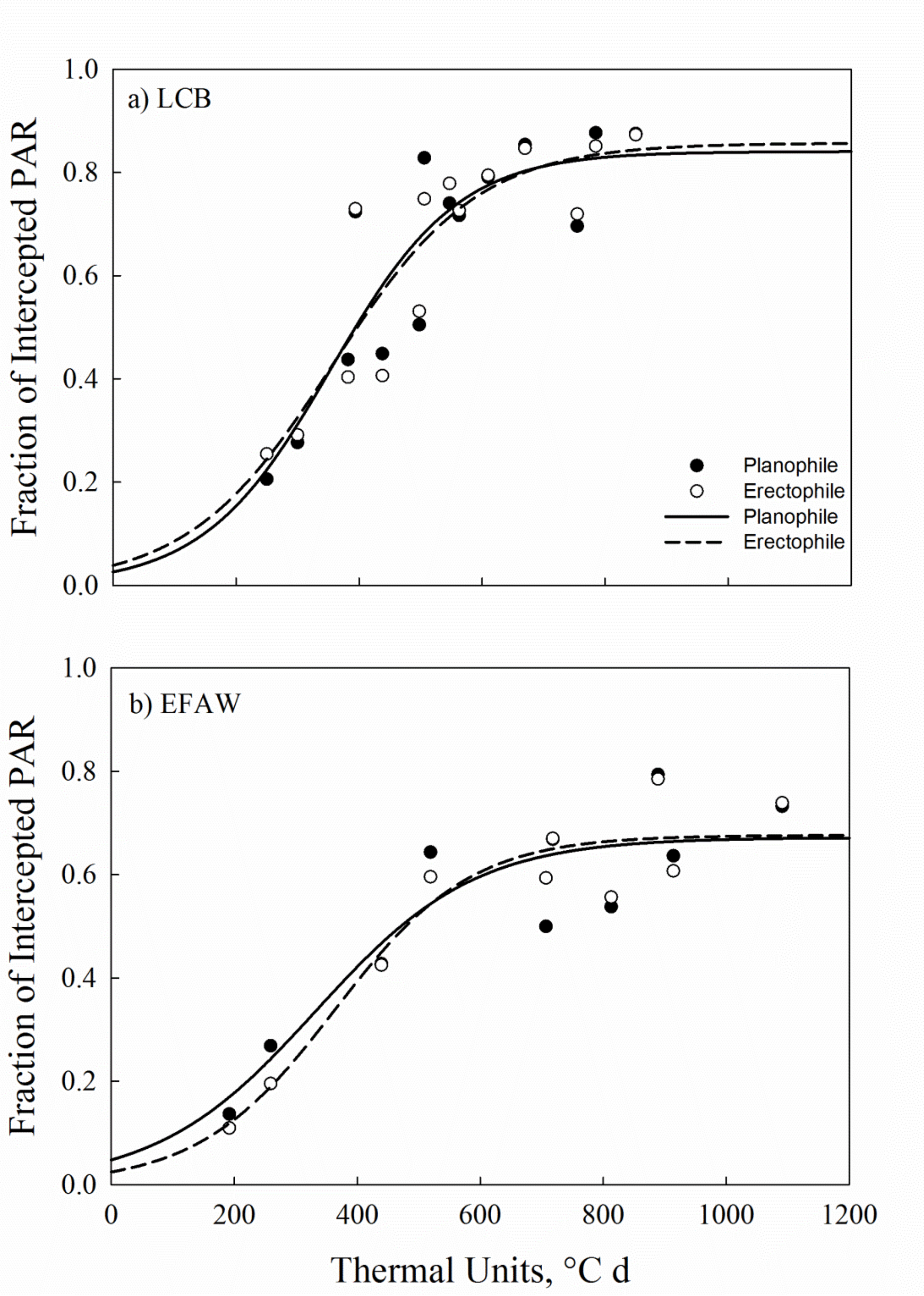

Figure 4. Fraction of intercepted photosynthetically active radiation (fPAR) as a function of thermal units for maize hybrids at a) Lake Carl Blackwell (LCB) and b) EFAW, OK, 2010-2012.

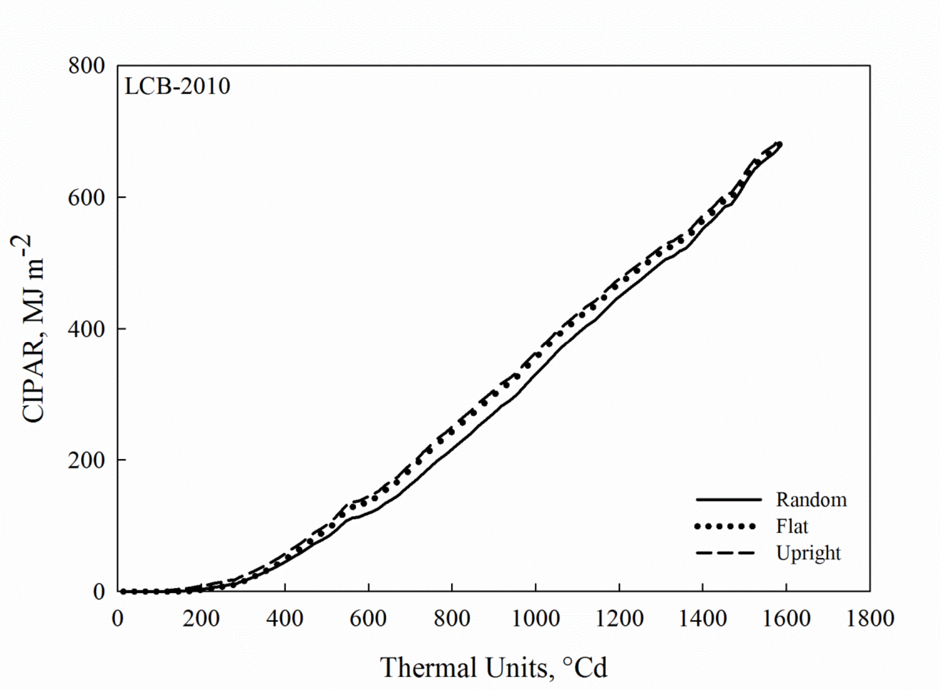

Figure 5. Cumulative intercepted photosynthetically active radiation (CIPAR) as a function of thermal units for seed placement at Lake Carl Blackwell, OK, 2012. Flat and upright seed placements result in across row leaf orientation; random seed placement result in random seed orientation

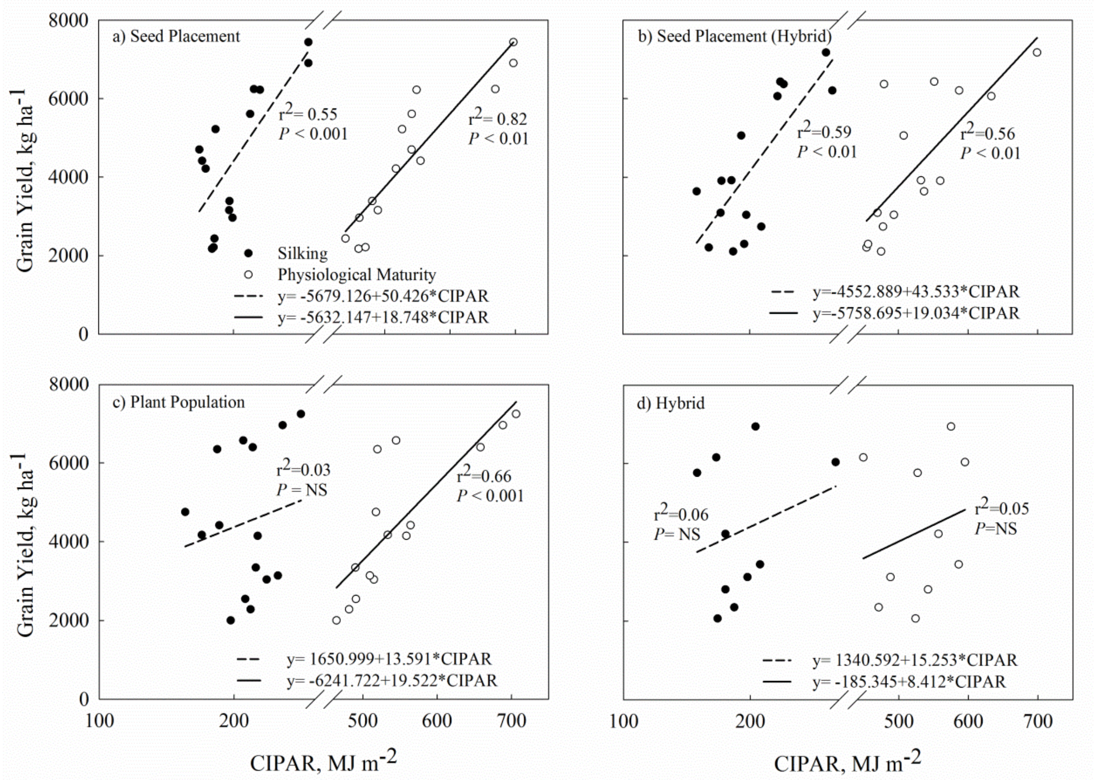

Figure 6. Regression of grain yield as a function of cumulative intercepted active radiation (CIPAR) for a) seed placement; b) seed placement pooled over hybrids; c) plant population; and d) hybrids at silking and physiological maturity. Analysis was performed using combined data over years, locations, and treatment levels.

CHAPTER II

LEAF ORIENTATION, PLANT POPULATION, AND ROW CONFIGURATION EFFECT ON MAIZE PRODUCTION

ABSTRACT

Leaf azimuth controlled by seed placement at planting as a way to influence the crop's ability to intercept and use light has received modest attention. The objective of the research was to evaluate the effect of leaf azimuth orientation, plant population (PP), and row configuration (RC) on grain yield, light interception, and radiation use efficiency of maize. Precision seed placement was used to orient leaf azimuth across-row and with-row which was compared to random leaf orientation of conventionally planted seeds. Seed placement treatments were planted at PP of 37050 and 61750 plants ha^{-1} and two row configurations; single rows and twin rows. On average, 7% higher yield was produced by increasing PP from 37050 to 61750 plants ha^{-1} at Oklahoma and from 83980 to 98800 plants ha^{-1} at Illinois. Radiation use efficiency was improved by twin rows, but single rows had higher light interception. A strong correlation between intercepted radiation and yield was found for trials established at EFAW and LCB, but at Champaign, this relation was weak and not significant. Alternatively, a strong association between RUE and yield was found at Champaign and LCB but not at EFAW. Cumulative intercepted PAR tended to be higher for across-row and radiation use

efficiency was better for with-row leaf orientation. Averaged over locations, precision seed placement used to orient leaf azimuths across-row and with-row increased yield by 541 and 568 kg ha^{-1} compared to random leaf orientation.

INTRODUCTION

The challenge of feeding a growing world population rests on how to achieve this objective with limited resources and in a sustainable way. Therefore, it is extremely important to search for more efficient use of resources. Better use of nutrients and water are usually the primary concerns because of the interest in optimizing returns and because they have a direct impact on production costs. Although, improvements in the use of solar radiation have not been a focus of producers, it has been accomplished with management practices such as reduced row spacing and increased plant population that translate into improved solar radiation use and increased yield.

Pioneering work done by Shibles and Weber (1965) showed a positive linear relation between cumulative intercepted photosynthetic active radiation (CIPAR) and dry matter increase for soybean. Andrade et al. (1992) also observed that dry matter production is proportional to the amount of IPAR accumulated during the growing season. It has been recognized that IPAR and yield are correlated when water and nutrients are at sufficiency levels. Pendleton et al. (1967) and Stinson and Moss (1960) indicated that, when nutrients and water are sufficient, light can be the primary limiting factor for crop production. Among the strategies that can be used to improve light interception are; increased plant population, reduced row spacing, systematic seed placement at planting, leaf architecture of modern hybrids, and hybrid maturity.

Plant population (PP) and row spacing are common management practices used to improve the ability of a crop to intercept more light, because the crop's leaf area is increased by these management practices. Edwards et al. (2005) conducted a study to investigate the effect of narrow row spacing and increased PP using short and full-season maize hybrids were seeded at rates ranging from 5 to 20 plants m^{-1}. They reported that yield of short-season hybrids at 19 plants m^{-1} produced the same yield as a full-season hybrid at 8 plants m^{-1}. This work indicated that cumulative IPAR was increased by increasing PP which compensated for the yield of a short-season hybrid, thereby resulting in similar yield potential of a full-season corn hybrid.

Downey (1971) demonstrated that the relationship between yield and PP was parabolic, because at lower populations yield is restricted due to reduced number of plants and as PP increases, competition increases and this causes yield to be limited. A quadratic response of yield as PP increased was reported by Nafziger (2002) who also found small differences when comparing 0.50 m and 0.76 m row spacing at the same population. Cox and Cherney (2001) investigated the effect of row spacing, plant density and nitrogen rates on corn silage yields and reported greater dry matter production for 0.38 m versus 0.76 m row spacing.

Twin row (TR) configuration has being investigated in the Corn Belt because it allows for increased PP and optimization of the space for each individual plant and the crop's ability to intercept more light throughout the growing season. However, contradictory results have been reported regarding the benefits of the TR system. Nafziger (2006) reported significantly higher light interception at V10 growth stage for 0.20 m TRs with 0.56 m centers when compared to 0.76 m single rows (SR) at PP of

67100 and 85200 plants ha^{-1}. But, no difference between twin and single row configuration was observed at R2 growth stage. Furthermore, it was demonstrated by Nafziger (2006) that advantage in light interception at V10 growth stage did not result in increased yield. Nelson and Smoot (2009) conducted small and large plot trials to compare 0.18 m TR on 0.76 m centers versus 0.76 m single row to determine the effects of row spacing and PP on IPAR and grain yield. Their results showed no significant differences for IPAR and grain yield when these row configurations were compared.

Leaf orientation can be preferentially manipulated with seed placement at planting (Peters and Woolley, 1959). This preferential plant growth allows the leaves of oriented seeds to grow perpendicular in relation to the row thus avoiding overlap of leaves from neighboring plants. Leaves in this system occupied spaces between the rows promoting increased light interception. Because of greater light interception soil shading would be enhanced resulting in reduced evaporative loss, and conserved moisture at the soil surface. Recently, Torres et al. (2011) conducted a greenhouse experiment and documented a significant effect of seed placement at planting on maize leaf azimuth and emergence. Measurements taken at V4 growth stage showed that seeds planted upright, caryopsis pointed down, parallel to the row and laying flat perpendicular to the row, had between 70 to 90% and 77 to 90% of plants with leaf azimuths between 60 to 90°, respectively. Other benefits related to seed position at planting comes from work by Patten and Van Doren (1970) whose showed that seed position influenced emergence rate, root penetration, root length and leaf area.

Even though various experiments have been established with the goal of investigating how IPAR and yield of maize respond to changes in PP and planting pattern

(Lutz et al., 1971; Ottman and Welch, 1989; Maddonni et al., 2001; Gozubenli et al., 2004; Liu et al., 2011), a small number of studies investigate the effects of seed placement and leaf orientation on crop properties (Toler et al., 1999; Paszkiewicz, 2005). Additionally, there is no evidence of research that investigated the interaction between seed placement and resulting leaf orientation, PP, and row configuration on maize light interception, radiation use efficiency, and grain yield.

HYPHOTESIS AND OBJECTIVES

We hypothesize that precision seed placement and the resultant leaf orientation combined with twin row configuration can be used to optimize the light environment, offering a competitive advantage for the maize crop compared to conventionally planted seeds with random leaf orientation. The hypotheses for this experiment were: (1) oriented leaf azimuths can optimize light interception, and increase grain yield compared to random leaf azimuth; (2) improve light interception and grain yield of twin row configuration in relation to single row planting configuration; and (3) higher PP can improve light interception and grain yield.

The objective of this experiment was to determine the effects of maize (*Zea mays* L.) leaf orientation, row configuration, and PP on light interception, radiation use efficiency and grain yield. The main motivation of this work is to support the development of precision planting technology for continue improvement in maize production through better use of solar radiation resources.

MATERIALS AND METHODS

A preliminary experiment was initiated at the Champaign research station located southwest of Champaign-IL, in 2010 on a Drummer silty clay loam, fine-silty, mixed, superactive, mesic Typic Endoaquolls. This experiment used two maize hybrids to investigate the effects of two seeding rates, three leaf orientations, and two row configurations. The experimental design was a randomized block design with two replications. The seeding rates were 83980 and 98800 plants ha^{-1} and hybrids used were P0916XR and P1184XR, that were selected for their differences in their leaf architectures, with P0916XR having an open top with a relatively erect upper canopy, and P1184XR having a more horizontal leaf architecture. The leaf orientations were obtained by adjusting seed position at planting in positions that resulted on across-row, random, and with-row leaf orientations. Row configurations included a 0.76 m single row and 0.18 m twin rows on 0.76 m centers.

Two additional field experiments were conducted near Stillwater during 2012. A factorial treatment structure of leaf orientation, PP, and row configuration was established on a randomized complete block design with three replications at two sites. One experiment was established at Lake Carl Blackwell (LCB) experimental station, on a Port silt loam-fine-silty, mixed, thermic Cumulic Haplustoll and the other at Efaw experimental station, on a Norge loam, fine-silty, mixed thermic Udic Paleustoll.

Experiments were planted using a PO876HR hybrid at PP densities of 37050 and 61750 plants ha^{-1}. A drip irrigation system was installed at both sites to supply water during crop development. Pre-plant fertilization of phosphorus and potassium were determined accordingly based on soil samples collected for each site. Pre-plant nitrogen rates of 180 kg N ha^{-1} and top-dress rates of 60 kg N ha^{-1} were applied using urea ammonium nitrate (UAN, 28%).

In the same way as the experiment conducted at Champaign, seed placements were used to manipulate the crop canopy and promote preferential leaf azimuth orientations. For the treatment with across-row leaf orientation, maize seeds were planted laying flat, embryo up, and perpendicular to the row whereas with-row leaf orientations, maize seeds were planted laying flat, embryo up, but parallel to the row (Torres et al., 2011). Treatments with oriented seeds were hand-planted while the plots with random seed position were planted using a four row vacuum planter. Two row configurations were used; conventional single rows with 0.76 m of row spacing and a twin rows configuration with row spacing of 0.20 m for the narrow rows and 0.76 m centers.

Photosynthetic photon flux density (PPFD, μmol m^{-2} s^{-1}) was measured within one hour of solar noon using a quantum line sensor LI-191A connected to a LI-1400 data-logger (LI-COR, Lincoln, NE). Fraction of PAR (fPAR) was calculated by the following formula as measured by PPFD:

$$\text{fPAR} = 1 - \frac{I}{I_0} \tag{1}$$

where,

I = incident PAR at the soil surface under the crop canopy

I_0 =incident PAR at top of the canopy

Three fPAR measurements were taken per plot under clear skies by placing the quantum line sensor diagonally under the canopy between the central maize rows. Daily intercepted PAR (IPAR) was predicted by regressing fPAR as a function of thermal units (TU, °C d) using TableCurve 2D version 5.01 software (SYSTAT Software Inc. 2002). Subsequently, cumulative IPAR (CIPAR, MJ m^{-2}) was determined from emergence to silking and to physiological maturity for the main effects of leaf orientation (LO), plant population (PP), and row configuration (RC) by the summation of the product of IPAR and incident daily PAR. Total solar radiation for each day of the growing season was transformed into PAR by assuming that 45% of solar radiation is actually photosynthetically active radiation (Meek, 1984). Moreover, radiation use efficiency (RUE, g MJ^{-1}) was calculated as grain yield divided by CIPAR at silking and physiological maturity.

At harvest, the two central rows of each plot were hand-harvested and grain yield was expressed using 15.5% moisture. Data analysis was performed using analysis of variance and orthogonal contrasts in SAS (SAS Inst., Cary, NC) to determine treatment effects on grain yield and fPAR. Regression and simple correlation analysis were used to understand the relationships between grain yield, CIPAR, and RUE.

RESULTS AND DISCUSSION

Grain Yield

Analysis of variance did not reveal significant interaction effects at any location, therefore grain yield means and contrasts for main effects are presented. Hybrid P1184XR with horizontal leaf architecture produced (12088 kg ha^{-1}) significantly higher yield than the hybrid PO916XR (11105 kg ha^{-1}) with more erect leaf architecture at Champaign (P<0.05).

Except at LCB where across-row leaf orientation substantially improved yield, at the other two locations no significant difference was found between leaf orientation treatments. Averaged over locations, grain yield of across-row and with-row leaf orientations increased yield by 541 and 568 kg ha^{-1} compared to random leaf orientation (Table 1). These results represent a yield improvement due to initial seed placement and leaf orientation of approximately 6% compared to random seed planting and random leaf orientation. The crop response to leaf orientation was not consistent depending on location and hybrid. For example, across-row and with-row leaf orientation produced 10 and 12% higher grain yield than random leaf orientation for the hybrid P1184XR at Champaign (Table 1). Likewise, across and with-row leaf orientation improved grain yield by 20 and 11% respectively in relation to random leaf orientation at LCB (Table 1).

In contrast, grain yield reduction was observed for across-row and with-row compared to random leaf orientation at EFAW, and at Champaign reduction of 228 kg ha^{-1} was also observed for across-row compared to random leaf orientation for the hybrid PO916XR. With-row leaf orientation out-yielded the random treatment by 530 kg ha^{-1} for this same hybrid at Champaign (Table 1).

Environmental interactions were likely determinant for the contrasting results found for leaf orientation treatments between sites. According to Toler et al. (1999) biomass and grain yield should increase from with-row to random and from random to across-row leaf orientation. The reason for the yield advantage of across-row leaf orientation was attributed to improved light interception and reduced intra-specific competition for available solar radiation, which was particularly important at higher PP (Toler et al., 1999). In this study, oriented leaves increased grain yield in relation to random leaf orientation independent of being across-row or with-row.

Paszkiewicz et al. (2005) indicated that with-row leaf orientation increased maize yield compared to random and across-row leaf orientations in two out of three years of experiments established near Johnston, IA. The reason for with-row leaf orientation to produce higher yield than random could be attributed to higher light interception by leaves closer to the ear. Allison and Watson (1966) estimated that after flowering, the four leaves in the central portion of the canopy contributed from 35 to 50% to dry-matter production. Substantial yield reduction of hybrids with horizontal leaf architecture has been observed due to the removal of the ear leaf, while hybrids with more erect leaves, the removal of leaves above the ear had a greater impact on yield components (Subedi and Ma, 2004).

Additionally, more uniform light distribution for the bottom leaves of the canopy would likely improve photosynthesis of the entire canopy. As maize crop develops, LAI increases and approaches an optimal LAI, which in theory should be sufficient to intercept up to 95% of incident radiation. The leaves on the upper part of the canopy intercept most of incident light, causing shade to the leaves underneath. Although there are no strong evidences that validate this hypothesis (Ray and Porter, 2006), conceptually the shading effect would cause decreased photosynthesis and increased respiration since the leaves at the lower part of the canopy would act mainly as sink rather than source of photo-assimilates.

Grain yield response to increased PP was consistent for all location and hybrids. At Champaign 98800 plants ha^{-1} produced 754 and 889 kg ha^{-1} higher grain yield than 83980 plants ha^{-1} for the hybrids PO976XR and P1184XR respectively. At EFAW and LCB 61750 plants ha^{-1} increased yield compared to 37050 plants ha^{-1} by 613 and 502 kg ha^{-1} (Table 1). Improved grain yield as PP increased was expected and similar results have been reported. For example, dry-matter yield response was found as PP increased up to 14.5 plants m^{-2} by Major et al. (1991), whereas Tolenaar and Bruulsema (1988) reported grain yield increase for ten hybrids with PP up to 10 plants m^{-2}. Furthermore, Westgate et al. (1997) reported that yield increased with PP up to 10 and 12 plants m^{-2} depending on the hybrid.

Twin row configuration was generally not statistically different from single row configuration which is in accordance with Nelson and Smoot (2009) who reported non-significant effect of RC on IPAR and grain yield. Similarly, contrast analysis revealed non-significant differences between RC treatments for the hybrid P1184XR at

Champaign (Table 1). Yet, twin rows produced greater yield than single rows in three out of four times, with yield advantage ranging from 151 to 1219 kg ha^{-1} (Table 1). Only at LCB, single rows produced more than twin rows, and the yield difference was 502 kg ha^{-1} (Table 1).

Light Interception

Figure 1 shows the effect of across-row, random, and with-row leaf orientations on fPAR as a function of TU at LCB and EFAW as well as for both hybrids at Champaign. Differences in fPAR between leaf orientation treatments were not consistent as TU increased. For example, at Champaign differences in fPAR were observed up to approximately V12 for hybrid PO196XR. For hybrid P1184XR, there was a significant difference in fPAR between leaf orientation treatments only at V6. Most frequently no difference between treatments was observed for this hybrid. There was a tendency for significant differences between leaf orientations at later vegetative growth stages at EFAW and LCB. Table 2 shows the average of fPAR measurements collected during the crop development, indicating that light interception was improved by leaf orientation in the following order: across-row > random > with-row, which is in agreement with Toler et al. (1999).

There was a fundamental difference in light interception between the experiments conducted at Oklahoma and Illinois. The main differences regarding light interception between these locations was related to the magnitude of fPAR measurements and when maximum fPAR occurred at each site. At Champaign, 90% of light interception was generally achieved after approximately 500 °C d (Fig. 1a and 1b). At Oklahoma this critical level was inferior to critical level of light interception at Illinois and the highest fPAR in Oklahoma was observed at EFAW (fPAR=0.83) (Fig. 1c and 1d).

The effect of PP on light interception was consistent across locations, and the high PP had frequent higher fPAR than the low PP on average (Table 2). Significant differences in light interception were observed at LCB, EFAW, and at Champaign for the hybrid PO196XR between V6 and V10 growth stages (Fig. 2a, 2b, and 2c). This was expected since higher PPs have greater LAI that results on greater interception of PAR. Westgate et al. (1997) reported that leaf area development rate and maximum LAI increased with PP independent of hybrid. In contrast, non-significant differences were observed most often for the hybrid P1184XR.

Row configuration had no effect on fPAR and differences between single and twin rows were small (Table 2). Figure 3 shows that the effect of RC was distinct among locations. Light intercepted by single and twin rows was similar for both hybrids used at Champaign, (Fig. 3a and 3b). Single rows had consistently greater fPAR than twin rows at LCB (Fig. 3c); in contrast, at EFAW twin rows had usually higher fPAR than single rows (Fig. 3d). According to Nafziger (2006) twin row configuration intercepted significantly higher PAR at V10 growth stage independent of PP compared to single rows but no difference was found at R2 growth stage.

Cumulative Intercepted Light

Results shown in Table 3 indicated that more light was intercepted by across-row, whereas with-row had the lowest CIPAR among leaf orientation treatments in general. One exception was found at LCB where the random had lower CIPAR than with-row leaf orientation at silking and maturity. Another exception was found at EFAW where the random accumulated 627 MJ m^{-2} of IPAR at maturity, which was higher than the across-row and with-row treatments accumulated (Table 3).

Increasing PP at EFAW and LCB from 37050 to 61750 plants ha^{-1} and at Champaign from 83980 to 98800 resulted in consistent increase in CIPAR at silk stage and physiological maturity. Pooled over locations, the difference in CIPAR between PP ranged from 11 to 24 MJ m^{-2} at silking and from 7 to 44 MJ m^{-2} at physiological maturity (Table 3). At Champaign, CIPAR of 324 and 356 MJ m^{-2} at silk stage and 833 and 840 MJ m^{-2} at physiological maturity was estimated for the hybrids PO196XR and P1184XR respectively. Moreover Table 3 shows that at LCB the PP of 61750 plants ha^{-1} accumulated 188 and 569 MJ m^{-2} of IPAR at silking and maturity while 221 and 621 MJ m^{-2} of IPAR was accumulated at EFAW for the same PP.

In general, single rows had higher CIPAR compared to twin row planting configuration; differences in CIPAR varied from 4 to 15 MJ m^{-2} at silking and 3 to 19 MJ m^{-2} at maturity when pooled over locations (Table 3). This was unexpected, since twin row system should improve the distribution of plants in field and increase the amount of light intercepted during the crop development. The only exception was noted at EFAW where twin rows had 9 and 55 MJ m^{-2} greater CIPAR than single rows at silking and maturity stages respectively.

Radiation Use Efficiency

More efficient use of light was usually found for with-row treatments compared to across-row and random treatments, although, the highest RUE (4.80 g MJ^{-1}) was observed for across-row treatment at LCB (Table 3). At silk stage, mean RUE pooled over locations was 3.89, 3.78, and 3.67 g MJ^{-1} for with-row, across-row, and random treatments, respectively (Table 3). Similarly, at physiological maturity with-row leaf orientation tended to have higher RUE compared to across-row and random. Radiation use efficiency for with-row, across-row, and random was 1.43, 1.40, and 1.35 g MJ^{-1} at physiological maturity (Table 3).

Radiation use efficiency was increased by increasing PP at Champaign at silk stage and maturity for both hybrids. For example, estimated RUE for the hybrid P1184XR increased from 1.40 and 1.49 g MJ^{-1} as PP increased from 83980 to 98800 plants ha^{-1} (Table 3). These results contradict the findings reported by Andrade et al. (1993) that indicated a noticeably decrease in radiation use as PP increased. In contrast, RUE at silking and maturity at LCB was higher for the lower PP, and at EFAW the lower PP had higher RUE at silking but not at maturity (Table 3).

Twin rows used radiation more efficiently than single row at silking at all locations. Better RUE of twin rows occurred because yield levels were relatively higher than yields of single rows configuration, despite the fact that less radiation was intercepted by the twin row system. Radiation use efficiency of twin rows planting configuration ranged from 3.52 to 4.68 g MJ^{-1} at silking stage whereas RUE of single rows ranged from 3.19 to 4.62 g MJ^{-1} (Table 3). At maturity, lower RUE was noted for single rows compared to twin row for both hybrids at Champaign. On the other hand, at LCB and EFAW single rows had higher RUE than twin rows at maturity.

Grain Yield, CIPAR, and RUE Relation

Grain yield response to CIPAR was different at Champaign, EFAW and LCB. With hybrid P1184XR at Champaign, grain yield and CIPAR were negatively related, meaning that higher CIPAR caused grain yield to decrease (Table 4). For the hybrid PO196XR also at Champaign, the relation was positive but weak and non-significant, suggesting that the amount of light intercepted was not associated with yield. Since both hybrids at Champaign reached full light interception relatively early during the crop development, the quantity of light accumulated was likely not a limiting factor. A closer relation of maize grain yield and radiation use rather than the intercepted light have also been noted by others (Tollenar and Bruulsema, 1988; Westgate et al., 1997; Daughtry et al., 1983).

The amount of light intercepted during the crop’s development had greater impact on grain yield at Oklahoma than at Illinois. Table 4 shows a high and significant grain yield response to CIPAR during silking and maturity at EFAW and LCB. This relation was expected since productivity is proportional to the quantity of PAR intercepted (Sinclair and Muchow, 1999). The reason for this discrepancy in the relationship between yield and CIPAR at Oklahoma and Illinois may have occurred since maize crops at Oklahoma never reach the optimal level of light interception for optimum productivity. On the other hand optimal light interception was achieved between V10 and V12 growth stages at Illinois. These results indicate that light was likely not a limiting factor at Illinois, but at Oklahoma, the amount of light intercepted was a limiting factor. Therefore, any increase in light interception at Oklahoma will likely be translated into productivity under irrigated conditions.

The relationship between CIPAR and RUE at silking and maturity was negative in three out of four locations, but only at EFAW, this correlation was actually significant (r=-0.71, *P*<0.10) (Table 4). Reduction in RUE is a critical limitation to yield of maize crops grown under drought stress (Earl and Davis, 2003). Assuming a given yield level, RUE should decrease as more intercepted PAR is accumulated during season.

A positive but not significant correlation was found between CIPAR and RUE at LCB at both growth stages (r=0.30 and r=0.64). The correlation between yield and RUE at LCB was positive at both phenological stages, but only at physiological maturity this correlation was significant indeed (r=0.85, *P*<0.01). Grain yield and RUE were highly correlated (*P*<0.01) at silking and maturity at Champaign (Table 4). This relationship is in agreement with Christy et al. (1986) who suggested a closer relation between maize yield and RUE than with yield and quantity of light intercepted. Variability in conversion of absorbed light due to hybrid and phenological stage was also reported by Tolenaar and Bruulsema (1988).

Different from the other locations, the correlation between grain yield and RUE at EFAW was weak, negative, and not significant at both growth stages (r=-0.35 and r=-0.36 at silking and maturity, respectively). According to Earl and Davis (2003) extremely high temperatures suppressed leaf photosynthetic rates. Extremely high temperatures occurred during the crop development at Oklahoma and affected maize light interception due to reduced effective leaf area and leaf area expansion. Crafts-Brandner and Savucci (2002) showed that at leaf temperatures over 38 °C, net photosynthesis was inhibited, causing transpiration rate to increase. They noted that heat stress inhibited photosynthesis but not due to stomatal closure, since transpiration rate increase was also observed. Damage on the photosynthetic apparatus caused inactivation of Rubisco constraining photosynthesis of maize leaves (Crafts-Brandner and Savucci, 2002).

CONCLUSIONS

Across-row leaf orientation intercepted more light than random, and more light was intercepted by random compared to with-row leaf orientation. Higher RUE was found for with-row leaf orientation, followed by across-row and random leaf azimuths. Light interception and yield increased with PP, although, more efficient use of radiation was usually noted for the low PP. The hypothesis that twin rows intercepted more light was rejected, since single rows intercepted more light than twin rows in three out of four opportunities. Twin rows had higher but not significant grain yield compared to single rows which caused RUE to be generally higher for twin row configuration.

Cultural practices such as leaf orientation, PP, and RC can influence the amount of light intercepted and the efficiency that radiation is utilized by maize crops and impact crop productivity. The use of leaf orientation as a management practice to exploit solar energy can be particularly important as precision planting technology becomes practical. This innovative approach can optimize the use of light resources especially at places where light interception may be reduced due to limited crop growth and development. Future research could investigate the interaction of leaf orientation and hybrid maturity and evaluate the effects on light attenuation produced by the changes in the crop canopy. We found that precision seed placement used to manipulate leaf azimuth orientation improved grain yields by 541 and 568 kg ha^{-1} for across and with-row compared to random leaf azimuth treatments averaged over locations.

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Table 1. Single degree of freedom orthogonal contrasts and grain yield means for leaf orientation (LO), plant population (PP), and row configuration (RC) at Champaign-IL in 2010 and at Lake Carl Blackwell (LCB) and EFAW, OK in 2012.

Main Effect	Leaf Orientation	Champaign		EFAW	LCB
		P1184XR	PO916XR		
		Grain Yield, kg ha^{-1}			
LO†	Across- Row	12397	10777	7459	9092
	Random	11275	11004	7690	7591
	With- Row	12593	11534	7281	8424
PP‡	Low	11644	10728	7170	8118
	High	12532	11482	7783	8620
RC§	Single Rows	11275	11004	7276	8664
	Twin Rows	12494	11155	7677	8074
<u>Contrasts</u>	Across versus Random	NS	NS	NS	*
	Across versus With	NS	NS	NS	NS
	With versus Random	NS	NS	NS	NS
	Medium versus High PP	NS	NS	NS	NS
	Single versus Twin	NS	NS	NS	NS
	SED¶	796	792	1522	1577
	CV (%)	8.1	8.7	25	23

*, **, *** significant at 0.10, 0.05, and 0.01 probability levels, respectively; NS, not significant.

† Leaf orientation predominantly across-row was achieved by planting seeds laying flat, with embryo up, kernel perpendicular to the row. Leaf orientation predominantly with-row was achieved by planting seeds laying flat, with embryo up, kernel parallel to the row. Conventionally planted seeds with random seed placement were used to achieve random leaf orientation.

‡ Low and high plant population densities in Champaign were 83980 and 98800 plants ha^{-1} respectively; at EFAW and LCB, plant population densities were 37050 and 61750 plants ha^{-1} respectively.

§ Row configuration consisted 0.18 and 0.20 m twin rows on 0.76 m centers and 0.76 m single rows.

¶ SED, standard error of the difference between two equally replicated means.

Table 2. Average of all light interception measurements collected during the growing season for the main effects of leaf orientation (LO), plant population (PP), and row configuration (RC), at Champaign-IL, 2010 and Lake Carl Blackwell (LCB) EFAW, OK, 2012

Effect	Leaf Orientation	Champaign PO196XR	Champaign P1184XR	LCB PO876HR	EFAW PO876HR	Overall Mean
		Average fPAR, %				
LO†	Across-Row	77.9	77.7	47.7	57.4	65.2
	Random	76.6	77.5	42.7	59.1	64.0
	With-Row	75.0	76.7	46.2	55.7	63.4
PP‡	Low	75.2	77.1	46.1	55.1	63.4
	High	77.9	77.5	47.6	59.7	65.7
RC§	Single Rows	76.6	77.5	47.3	55.6	64.3
	Twin Rows	76.5	77.2	43.8	59.2	64.2

† Leaf orientation predominantly across-row was achieved by planting seeds laying flat, with embryo up, kernel perpendicular to the row. Leaf orientation predominantly with-row was achieved by planting seeds laying flat, with embryo up, kernel parallel to the row. Conventionally planted seeds with random seed placement were used to achieve random leaf orientation.

‡ Low and high plant population densities in Champaign were 83980 and 98800 plants ha^{-1} respectively; at EFAW and LCB, plant population densities were 37050 and 61750 plants ha^{-1} respectively.

§ Row configuration consisted of 0.76 m single rows or 0.18 and 0.20 m twin rows on 0.76 m centers.

Table 3. Cumulative intercepted active radiation (CIPAR) and radiation use efficiency (RUE) for main effects at Champaign-IL, 2010 and Lack Carl Blackwell (LCB) and EFAW, OK, 2012.

Phenology†	Location	Hybrid	Leaf Orientation‡			Plant Population Density§		Row Configuration¶	
			Across-Row	Random	With-Row	Low	High	Single Rows	Twin Rows
CIPAR, MJ m^{-2}									
Silking	Champaign	PO916XR	322	321	315	312	324	321	317
	Champaign	P1184XR	354	353	348	345	356	354	349
	EFAW	PO876HR	214	213	199	197	221	201	210
	LCB	PO876HR	189	170	182	172	188	188	172
Maturity	Champaign	PO916XR	825	822	814	807	833	822	819
	Champaign	P1184XR	841	839	828	833	840	839	834
	EFAW	PO876HR	606	627	579	584	621	577	632
	LCB	PO876HR	575	515	551	524	569	556	537
RUE, g MJ^{-1}									
Silking	Champaign	PO916XR	3.34	3.43	3.66	3.44	3.54	3.43	3.52
	Champaign	P1184XR	3.50	3.20	3.62	3.38	3.52	3.19	3.58
	EFAW	PO876HR	3.49	3.61	3.66	3.64	3.52	3.61	3.66
	LCB	PO876HR	4.80	4.46	4.62	4.72	4.59	4.62	4.68
Maturity	Champaign	PO916XR	1.31	1.34	1.42	1.33	1.38	1.33	1.36
	Champaign	P1184XR	1.47	1.34	1.52	1.40	1.49	1.34	1.50
	EFAW	PO876HR	1.23	1.23	1.26	1.23	1.25	1.26	1.21
	LCB	PO876HR	1.58	1.47	1.53	1.55	1.52	1.56	1.50

† Determined based on the hybrid’s average thermal units (°C d) requirement to reach silking and physiological maturity.

‡ Leaf orientation in relation to the row.

¶ Low and High plant population at Champaign was 83980 and 98800 plants ha^{-1} and 37050 and 61750 plants ha^{-1} respectively.

§ Single rows were planted on 0.76 m row space; twin rows were sown on 0.18 and 0.20 m between twins on 0.76 m centers.

Table 4. Correlation coefficients between grain yield, cumulative active radiation (CIPAR) and radiation use efficiency (RUE) for Champaign-IL, 2010; Lake Carl Blackwell (LCB), and EFAW, OK, 2012.

			Silking		Maturity	
Location	Hybrid	Variable	RUE	Yield	RUE	Yield
Champaign	P1184XR	CIPAR	-0.26 NS	-0.03 NS	-0.41 NS	-0.29 NS
		RUE		0.97 ***		0.99 ***
	PO916XR	CIPAR	-0.32 NS	0.16 NS	-0.02 NS	0.33 NS
		RUE		0.89 ***		0.94 ***
EFAW	PO876HR	CIPAR	-0.71 *	0.91 ***	-0.67 *	0.93 ***
		RUE		-0.35 NS		-0.36 NS
LCB	PO876HR	CIPAR	0.30 NS	0.92 ***	0.64 NS	0.95 ***
		RUE		0.65 NS		0.85 **

*, **, *** significant at 0.10, 0.05, and 0.01 probability levels, respectively; NS, not significant.

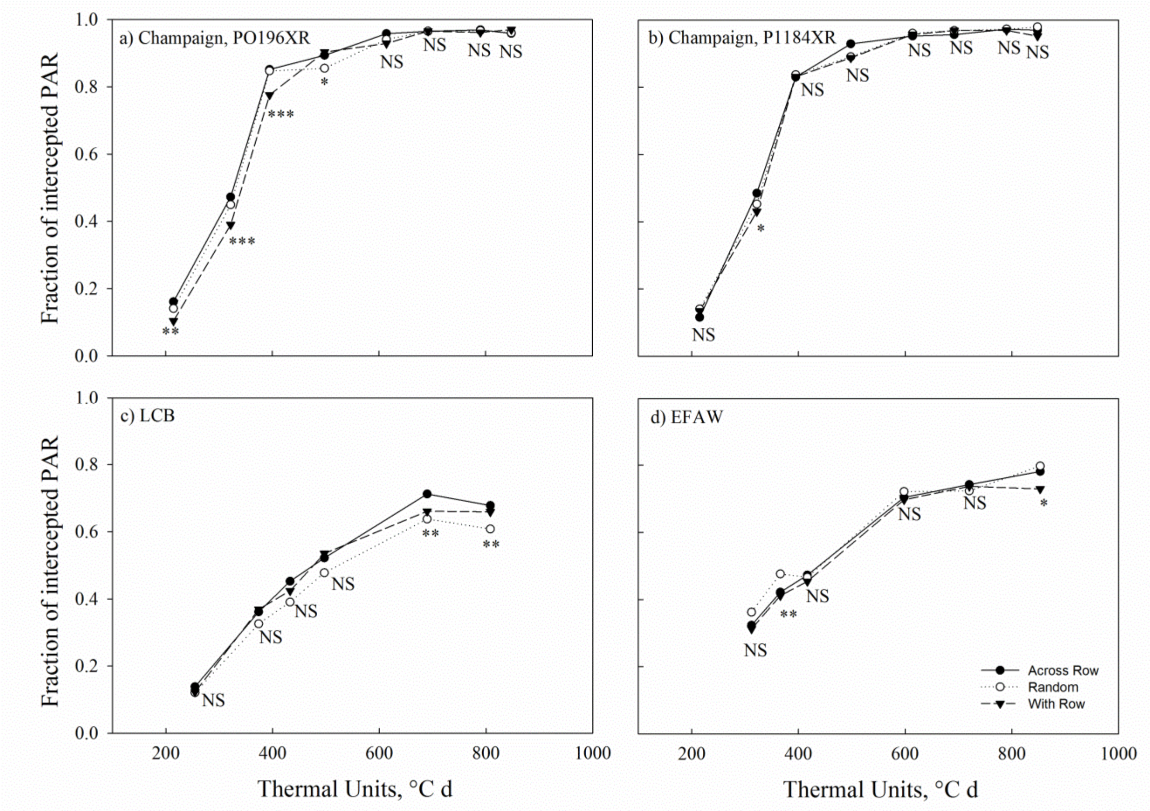

Figure 1. Fraction of intercepted photosynthetically active radiation (fPAR) as a function of thermal units for the leaf orientation effect for hybrids PO196XR and P1184XR at Champaign-IL, 2010 (a and b); Lake Carl Blackwell-OK (LCB) (c), and EFAW-OK (d), 2012. Analysis of variance was performed to compare leaf orientation treatments at each measurement date. Significance at 0.10, 0.05, and 0.01 probability levels are indicated by *, **, and *** respectively; NS, not significant.

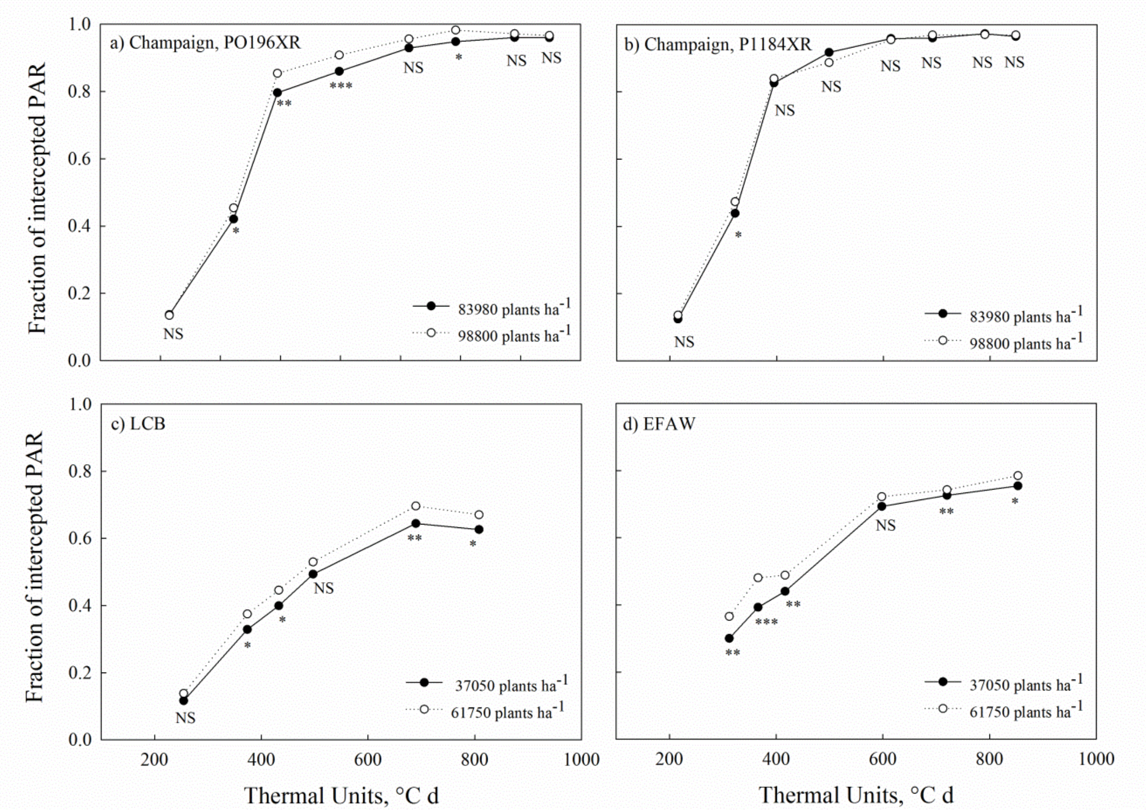

Figure 2. Fraction of intercepted photosynthetically active radiation (fPAR) as a function of thermal units for the plant population effect for hybrids PO196XR and P1184XR Champaign-IL, 2010 (a and b); Lake Carl Blackwell-OK (LCB) (c), and EFAW-OK (d), 2012. Analysis of variance was performed to compare treatments at each measurement date. Significance at 0.10, 0.05, and 0.01 probability levels are indicated by *, **, and *** respectively; NS, not significant.

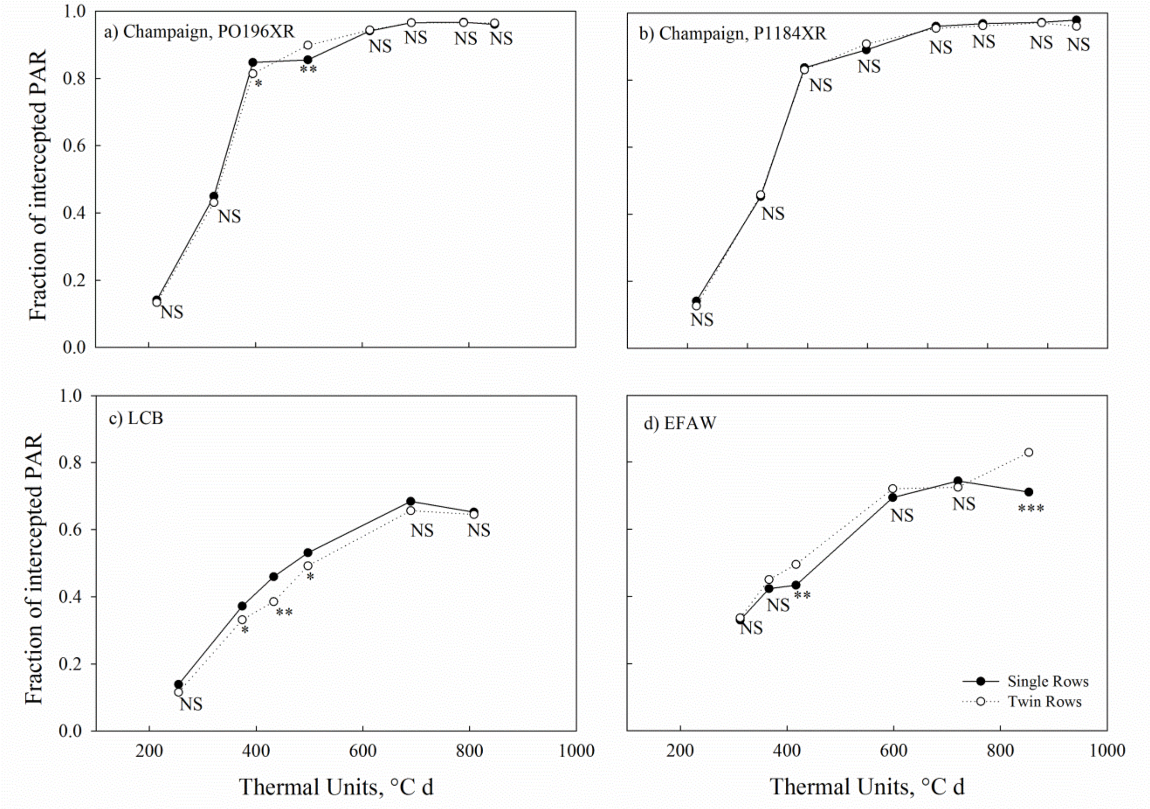

Figure 3. Fraction of intercepted photosynthetically active radiation (fPAR) as a function of thermal units for the row configuration effect for hybrids PO196XR and P1184XR at Champaign-IL, 2010 (a and b); Lake Carl Blackwell-OK (LCB) (c), and EFAW-OK (d), 2012. Analysis of variance was performed to compare treatments at each measurement date. Significance at 0.10, 0.05, and 0.01 probability levels are indicated by *, **, and *** respectively; NS, not significant.

CHAPTER III

USE OF LORENZ CURVES AND GINI COEFFICIENT TO EVALUATE BY-PLANT YIELD INEQUALITY

ABSTRACT

Spatial and temporal emergence variations are the primary sources of variability in maize (*Zea mays* L.) production systems. This work was conducted to determine whether seed placement and its resultant leaf orientation can reduce plant-to-plant yield inequality. The effect of seed-to-leaf orientations and plant space (PS) on by-plant yield and plant-to-plant yield variation were evaluated. Lorenz curves, Gini coefficient (G), and frequency distributions were used to determine and characterize by-plant yield inequality within treatments. Upright-across out-yielded random seed-leaf orientation by 155 kg ha^{-1} at EFAW and flat-across was 310 kg ha^{-1} higher than random at LCB in experiment 1. A significant seed-to-leaf orientation by plant spacing interaction was observed in experiment 2 where flat-across yielded 5726 kg ha^{-1} at plant spacing of 36 cm while random and flat-with row yielded 5706 and 4944 kg ha^{-1}. By-plant yield of flat-across and flat-with row increased by 15% and 27% as plant spacing was reduced from 36 to 21 cm, whereas yield reduction of 19% was noted for random seed-leaf orientation. Lorenz curves and G demonstrated that by-plant yield inequality tended to reduce with precision planting. Lower by-plant yield inequality as indicated by small G was associated with lower CV, lower range, L-skewed, and leptokurtic distributions.

However, plant-to-plant yield variation expressed by CV indicated that seed-leaf orientation had little influence on yield variation. Plant-to-plant yield variation was positively correlated with plant distance variation and by-plant yield decreased as plant-to-plant inequality increased. Precision planting of maize tended to reduce plant-to-plant yield inequality compared to conventionally planted seeds.

INTRODUCTION

Spatial and Temporal Variation

Reduction of spatial and temporal variation has been a common goal among agronomists and producers. Spatial and temporal emergence variation in maize implies that space variability will occur and impact on how individual plants utilize and compete for water, nutrients, and light with neighboring plants. Factors such as planter type, planting speed, seeding depth and seed vigor, in addition to soil temperature, moisture, crusting, and compaction can contribute to spatial and temporal variation. Dickey and Jasa (1993) indicated that planter type and operation can generate skips and doubles, affecting plant spacing uniformity. Lauer (2002) suggested that uneven plant spacing within the row is usually caused by high planting speeds as well as inadequate planter adjustments and maintenance.

Controlling variation due to seeding depth and spacing are among the strategies used in precision planting to counteract spatial and temporal emergence variation by providing a more uniform seed placement and reducing successive sources of variation in the system. Benjamin and Hardwick (1986) speculated that small differences in growth among individuals caused by early events such as emergence accumulate over time. Spatial variability effect on maize grain yield has received considerable attention and contradicting results have been reported. Some studies reported a yield decrease as the standard deviation (SD) of plant spacing increased (Krall et al., 1977) or as SD exceeded a given threshold (Doerge and Hall, 2001; Vanderlip et al., 1988). Nielsen (2001) conducted a studied to evaluate the effect of plant spacing variability on yield and concluded that 156 kg ha^{-1} of yield was lost for every 2.54 cm increase in plant distance standard deviation. On the other hand, research showed that plant spacing variability had no significant effect on grain yield (Liu et al., 2004a; Lauer and Rankin, 2004). Lauer and Rankin (2004) concluded that grain yield should not be affected by plant spacing variability in most farmers' field. In addition, Liu et al. (2004a) reported no significant effect of plant spacing variability on leaf area index, leaf number, plant height, and harvest index.

More consistent results are found regarding the effect of temporal emergence variability on maize yield. According to Liu et al. (2004b) maize yields are more sensitive to temporal than spatial variation. Uneven emergence of maize plants resulted in significant yield reduction according to Nafziger et al. (1991). These variations in spatial and temporal emergence can reduce survival and yield of suppressed individuals (Yoda et al. 1963; Mohler et al., 1978) due to the impact on interactions between adjacent plants.

By-Plant Resolution

Identification and treatment of spatial variability is critical for precision farming. Areas within a field with different production capacities can be treated as independent units, allowing for optimization of production. Field element size or the scale at which variability occurs is a determinant to the interpretation of spatial information and management decisions. Raun et al. (2005) recognized that for maize, this resolution is at the plant level; therefore management practices should be applied by-plant. Maize yield variability at the plant level was investigated by Martin et al. (2005) over a range of production environments. Their results indicate that average plant-to-plant yield variation can be expected to be more than 2765 kg ha^{-1}. Furthermore, they reported that coefficient of variation and range increased as mean by-plant yield increased. Following this concept and aided with remote sensing technology, Freeman et al. (2007) demonstrated that it is possible to identify variation and treat nitrogen deficiencies at the plant level.

Expression of Inequality

Statistical measures that describe size variability in plant populations frequently rely on standard deviation, coefficients of variation, skewness, and kurtosis that include moments around the mean (Sadras and Bongiovanni, 2004). Relationships between mean by-plant yield, standard deviation, coefficient of variation, and range were used by Martin et al. (2005) to understand and quantify the magnitude of within row plant-to-plant variation. Range and coefficient of variation were also used by Stern (1969) and Mack and Pyke (1983) to represent plant population inequality.

Weiner and Solbrig (1984) recommended the use of a Lorenz curve and Gini coefficient as a measure of size inequality between members of a population. The authors suggested that Lorenz curve and Gini coefficient provide a meaningful quantification of inequality and allows for comparisons among populations. Sadras and

Bongiovanni (2004) addressed the relative contribution to total paddock yield of low and high yielding sections of the field using Lorenz curves and Gini Coefficients and concluded that Lorenz curves were particularly pertinent to express yield inequality within paddocks.

The Lorenz curve is a simple way to demonstrate inequality graphically whereas the Gini coefficient is the summary statistic determined in relation to the Lorenz Curve and measures the magnitude of inequality (Sen, 1973; Weiner and Solbrig 1984). Similar to coefficient of variation, the Gini coefficient is also a measure of relative precision and inequality. Some desirable characteristics are associated with the Gini coefficient as a measure of inequality including comparisons of inequality between populations with different means and between populations with different sizes (Sadras and Bongiovanni, 2004; Weiner and Solbrig 1984).

Numerous studies have evaluated plant-to-plant variability using principally coefficient of variation and standard deviation as measures of inequality, but a limited number of studies in agriculture used Lorenz curves and Gini coefficient to determine inequality within a given population (Sharma et al., 1998; Pan et al., 2003; Vega and Sadras, 2003; Sadras and Bongiovanni, 2004). In addition, the effect of seed placement and target plant space on by-plant yield and plant-to-plant yield variation are also reported.

HYPOTHESIS AND OBJECTIVES

Technologies that promote more homogenous crop stands and emergence may lead to yield increase due to reduced plant-to-plant variation (Martin et al., 2005). Precision seed placement of maize has received little attention, principally due to the difficulty of mechanization. However, with recent improvements in precision planting technologies the ability to control seed placement at planting will become more practical.

Research suggests that precision seed placement can promote faster emergence and improve stand uniformity (Paten and Van Doren, 1970; Bosy and Aarssen, 1995). This allows for leaf azimuth orientation (Peters and Woolley, 1959; Torres et al., 2011) which can lead to improved light interception and promote yield increase of maize crops (Toler et al., 1999; Paszkiewics et al., 2005). We hypothesize that precision planting of maize and its resultant leaf orientation should result in more uniform crop stands and reduce plant-to-plant yield variation.

The objectives of this work were to (i) evaluate the effect of seed placement and its resultant effect on leaf orientation on by-plant yield inequality using Lorenz curves and Gini coefficient; (ii) determine the effects of seed placement and target plant space on by-plant yield and plant-to-plant yield variability; and (iii) investigate the relationships of by-plant yield and plant distance.

MATERIAL AND METHODS

Site and Experiment Description

The data for this study were collected from experiments that were established to evaluate seed placement as a means to manage crop canopy and promote optimization of light interception and use in maize production. Experimental design for experiment 1 (Exp. 1) and experiment 2 (Exp. 2) was a RCB with 12 treatments and 3 blocks that were conducted at two sites (LCB and EFAW) in 2012. Out of 12 treatments in Exp. 1 and Exp. 2, only nine and six treatments were used for this analysis, respectively.

For this framework, Exp. 1 treatment structure consisted of a factorial combination of three levels of seed placement and three levels of target plant spacing (27, 18, and 13 cm distance between plants), while Exp. 2, three levels of seed placement and two levels of plant spacing (36 and 21 cm) were used in the analysis. Precision seed placement is a means to manipulate leaf azimuth of maize plants. The term seed placement implies that a given seed position is coupled with its resulting leaf orientation. Torres et al. (2011) found a significant effect of initial seed placement on leaf orientation while Koller (2012, unpublished data) found a strong correlation between initial seed placement and first true leaf for maize grown under protected environment. Hereafter, we refer to seed placement and leaf orientation relationship as seed-leaf orientation.

In Exp. 1, seed placement used to manipulate leaves across the row is described as upright with caryopsis pointed down, parallel to the row (upright-across row); and laying flat, embryo up, perpendicular to the row (flat-across row). Conventionally planted seeds with random seed placement and random leaf orientation were used as the control. In the Exp. 2, in addition to leaf orientation across the row, seed placement that resulted in leaf orientation parallel to the row (with row) was evaluated and compared to random seed-leaf orientation. Seed placements used in Exp. 2 for across row leaf orientation was laying flat, embryo up, perpendicular to the row (flat-across row); and with row leaf orientation seed placement was laying flat, embryo up, parallel to the row (flat-with row); lastly, conventional planting with random seed-leaf orientation.

Experiments were conducted at Oklahoma State University in 2012 at R.L. Westerman Irrigation Research Center, Lake Carl Blackwell (LCB), and at Stillwater Agronomy Research Station, EFAW, both located near Stillwater, OK. Experiments at LCB and EFAW were conducted on a Pulaski fine sandy loam (coarse loamy, mixed, superactive nonacid, Udic Ustifluvent) and on a Norge loam, 3 to 5 percent slope, eroded (fine-silty, mixed active, thermic Udic Paleustolls), respectively. Plots were irrigated using a drip irrigation system at both sites and nitrogen fertilization was the same for all plots, consisting of 180 kg N ha^{-1} as pre-plant and 60 kg ha^{-1} as top-dress applied between V8 and V10 growth stages. Other management practices included phosphorus and potassium applications that were based on soil test recommendations and pre and post-emergence weed control. Plots with oriented seeds were sown by hand using a template to precisely sow seeds at target plant distances within rows. Plots with random placement were planted using a four row John Deere MaxEmerge 2 vacuum planter (Moline, IL). All treatments were sown at row spacing of 0.76 m.

Measurements, Calculations, and Analysis

Data were collected from the two central rows of each plot totaling 108 rows of 6.1 m and 72 rows of 3.1 m in length. A total of 4484 observations of by-plant yield and plant position in the row were recorded and 3130 data points were used in this work. Individual plants were hand-harvested, ears were air-dried and samples were weighed before and after drying. The grain to cob weight ratio value was determined by measuring grain and total ear weight of approximately >400 samples. This value was applied to estimate grain dry weight per plant (g plant^{-1}) for all remaining maize ears weights.

The linear distance occupied by a plant (plant distance) was determined by placing a measuring tape along the maize row and recording the plant's position in the row as distance accumulated from the beginning of maize rows. The linear distance that a single plant occupies was calculated based on equation 1:

$$D_i = \frac{d_i - d_{i-1}}{2} + \frac{d_{i+1} - d_i}{2} \qquad (1)$$

where, D_i is the linear distance (cm) occupied by the i$^{\text{th}}$ plant; d_i, d_{i-1}, and d_{i+1} are the distances to the i-1, i, and i+1 plants. The area (A_i, cm^2) that the i$^{\text{th}}$ plant occupies was thus calculated by multiplying D_i by 76 cm of row spacing. Subsequently, by-plant yield in kilogram per hectare basis was determined as the ratio of grain dry weight per plant and the area occupied by that same plant.

By-plant yield and plant distance, means, standard deviations (SD), coefficient of variations (CV) were calculated for each seed-leaf orientation and target plant spacing treatment. In addition, skewness, kurtosis and Gini coefficient were determined for the frequency distributions of the plant population within a treatment. According to Nagashima et al. (1995) skewness and kurtosis quantifies the degree of asymmetry and peakedness of a frequency distribution. Skewness of zero indicates symmetrical distribution while asymmetrical distributions are expressed by positive and negative skewness (L-shaped or J-shaped distributions, respectively) (Nagashima et al., 1995). The co-existence of subgroups within a population is shown by a bimodal distribution (Vega and Sadras, 2003). When kurtosis is zero, the distribution is normal; positive or leptokurtic kurtosis values indicate more peaked distribution, and negative or platykurtic values indicate bimodal distribution (Nagashima et al., 1995; Vega and Sadras, 2003).

The method for calculating by-plant yield inequality followed the procedures described by Weiner and Solbrig (1984). First by-plant yield within each treatment was ranked from lowest to highest, by location and experiment. Consequently, the cumulative fraction of yield was determined and plotted against the cumulative fraction of population. Absolute equality is represented by a 1:1 line and the departure from the straight line is called Lorenz curves. The Lorenz curve expresses the degree of inequality between treatments which is numerically represented by the Gini coefficient that can be estimated for a random sample of size *n* following the equation suggested by Sen (1973):

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} | x_i - x_j |}{2n^2\bar{x}} \tag{2}$$

where, *i*=1,…*n* and *j*=1,…*n*, and x_i and x_j are the yield levels of the *i*th and *j*th plant respectively, $\bar{x}$ is the mean yield of *n* number of plants. The Gini coefficient (G) ranges between 0, when all members of a population are equal, and 1, the theoretical maximum inequality occurs when all individuals except for one have a value of zero. Subsequently, the estimated G was multiplied by $n\ (n\text{-}1)^{-1}$ to obtain an unbiased G estimate (Weiner and Solbrig 1984; Weiner 1985).

Analysis of variance (PROC GLM), regression analysis (PROC REG), descriptive statistics (PROC UNIVARIATE), and simple correlations (PROC COR) were performed using procedures in SAS software (SAS Inst., Cary, NC) to determine the relationships between mean by-plant yield, plant-to-plant variation, plant distance, and plant distance variability of seed-leaf oriented and randomly planted maize seeds.

RESULTS AND DISCUSSION

Plant-to-Plant Inequality

Calculated G was frequently lower for upright-across and flat-across compared to random seed-leaf orientation in Exp. 1, demonstrating that precision planting reduced plant-to-plant yield inequality compared to conventional planting (Table 1). The only exception in Exp. 1 was noted at EFAW, where higher yield inequality between plants was observed for upright-across orientation (G=0.30), whereas lower inequality was estimated for the random seed-leaf orientation (G=0.21) (Table 1). Overall, G ranged from 0.14 to 0.30 which was greater than G values reported by Sadras and Bongiovanni (2004). They reported G ranging from 0.027 to 0.191 for maize crop grown in farmers' field at 96 m^2 resolution. Differences in resolution was likely the main reason for the relatively higher G values that we observed, at the plant level scale the magnitude of plant yield difference becomes more evident. On average, by-plant yield difference for Exp. 1 was 2373 kg ha^{-1} and for Exp. 2 was 2085 kg ha^{-1} which was relatively less than 2765 kg ha^{-1} average yield variation reported by Martin et al. (2005).

For Exp. 2, flat-with row orientation tended to have greater G values and consequently more variation among individuals within this population compared to random, and flat-across orientations (Table 1). Overall, increased target plant spacing resulted on a linear decrease in G values (r^2=0.17; $P<0.05$) suggesting that yield of individual plants becomes more equal as the available space for each individual increases. This result seems logical, since more area for each plant means more water, nutrients and light availability and less interplant competition.

The comparison between Lorenz curves for the contrasting seed-leaf orientations indicated greater by-plant yield inequality between the individuals within the population with random seed-leaf orientation (Fig. 1A). Plant-to-plant yield inequality for flat-across and upright-across orientations were relatively lower compared to random at plant spacing of 18 cm at LCB, which is mirrored by a lower G value. Gini coefficient of flat-across, upright-across, and random seed-leaf orientations were 0.15, 0.23, and 0.25, respectively (Fig. 1A). In practice the Lorenz curves show inequality since the lowest 50% of plants within upright-across, flat-across, and random population accounted for 39, 34, and 32% of the total yield respectively, when they should contribute 50% of the total yield produced.

In addition, Figs. 1B, 1C, and 1D present the frequency distribution and descriptive statistics of by-plant yield for seed-leaf orientation treatments for Exp. 1 at LCB, OK in 2012. Bendel et al. (1989) recommended the use of histograms to support conclusions based on single summary statistics such as G or CV. Positive skewness (S) and kurtosis (K) was noted for seed-leaf orientations shown in Fig. 1B, 1C, and 1D. There was a trend for L-shaped and leptokurtic frequencies as by-plant yield inequality within a population decreased. Alternatively, as plant-to-plant yield inequality increased, the population tended to have J-shape and platykurtic distribution. According to Ford (1975), the co-existence of two groups or bimodal distribution was attributed to competition among plants. Bimodality for a range of plant populations was also reported by others (Ford, 1975; Mohler et al., 1978; Wyszomirski, 1992). The patterns observed in populations with greater inequality are in agreement with Vega and Sadras (2003) who reported predominantly negative skewed (J-shaped) and platykurtic frequencies for maize seed mass of plants grown at high population density. Notably, Fig. 1D shows a near normal distribution of random seed-leaf orientation population, which was associated with greater G and CV values.

Seed-leaf orientation modified the typical distribution of maize yield and promoted a concentration of plants with similar yield levels. Weiner and Solbrig (1984) suggested that the degree of size hierarchy is correspondent to the contribution of a few individuals to total biomass, and that no hierarchy can occur when all individuals are equal and defined that “size inequality or concentration, not asymmetry, which corresponds to the notion of size hierarchy”. Vega and Sadras (2003) stated that the bimodal distribution characteristic of the reproductive output of sunflower and maize was for the most part due to the presence of barren plants. The presence of barren plants was also noted in this study and likely caused larger by-plant yield inequality and bimodal distribution of by-plant yield.

Coefficient of variation for the upright-across row, flat-across row, and random seed-leaf orientations were 28, 43, and 44% respectively (Fig. 1B, 1C, and 1D), indicating lower plant-to-plant variation for upright-across orientation. Similar conclusions were obtained when using CV or G to make inferences about plant-to-plant yield heterogeneity in terms of inequality. Bendel et al. (1989) compared skewness, CV, and G coefficients as a measure of inequality within populations and pointed that all three statistics have some undesirable properties, but they emphasize that these properties are frequently trivial in practice.

Most important, according to Fig. 1, precision planting of maize resulted on lower plant-to-plant yield inequality, but also caused higher by-plant yield. Average by-plant yield of 6120 kg ha^{-1} was observed for upright-across row compared to 5073 and 5120 kg ha^{-1} for flat-across and random seed-leaf orientations at target plant distance of 18 cm, respectively (Fig. 1B, 1C, and 1D). Moreover, the range of by-plant yield increased as plant-to-plant yield inequality increased. Treatments with greater range are graphically represented by the relatively longer tails in distributions shown in Fig. 1C and 1D compared to Fig. 1B. For example, by-plant yield range of 9917 kg ha^{-1} was noted for upright-across, range of 12625 kg ha^{-1} was observed for flat-across, and range of 11195 kg ha^{-1} random seed-leaf orientations.

Lorenz curves and G coefficients for seed-leaf orientation treatments for Exp. 2 at LCB, OK, in 2012 are shown in Fig. 2A. Flat-across orientation reduced plant-to-plant inequality compared to random and flat-with orientation since its Lorenz curve had the smallest deviation from absolute equality (Fig. 2A). Gini coefficient for flat-across orientation was 0.16, for random G was 0.22, and flat-with row G was 0.23. The CV of by-plant yield followed the same trend observed with G coefficients, in which flat-across row, random, and flat-with row resulted in CVs of 28, 38, and 41%, respectively (Fig. 2B, 2C, and 2D). It is important to mention that G and CV are both measures of relative precision that have in common the property of being invariant to scale changes but variant to location changes (Bendel et al., 1989). Moreover, Bendel et al. (1989)

affirmed that G is a more robust measure whereas CV is more sensitive to the right tail of a frequency distribution

Different from Exp. 1, reduction in plant-to-plant inequality did not result in a yield advantage. For instance, flat-across and random orientations had contrasting G coefficients, but very similar yield means (Fig. 2B and 2C) while the lowest by-plant yield was produced by flat-with row orientation (4950 kg ha^{-1}) (Fig. 2D). Yield range was highest for random (8629 kg ha^{-1}) and lowest for flat-across row seed-leaf orientation (7323 kg ha^{-1}); showing that plants within a population planted with random seed-leaf orientation had larger yield variation than plants of a population planted with precision seed placement.

It is essential to emphasize the relative contribution of low and high yielding plants to total yield for seed-leaf orientations. Figure 2A shows for instance that lowest 30% of the population with flat-across orientation contributed to 21% of total yield whereas the lowest 80% of the population contributed to 71% of total yield. For random and flat-with row treatments the lowest 30% of the plant population accounted for 17 and 15% of total yield while the lowest 80% of population contributed with 69 and 70% of total yield respectively. According to Sadras and Bongiovanni (2004) this information is valuable and not evident in yield maps. Even though yield inequality was higher for random compared to flat-across seed-leaf orientation, their average yield was very similar. These results indicated that high yielding plants in the random treatment had a substantial contribution for the population’s average (Fig. 2C), whereas by-plant yields of flat-across orientation was concentrated around its mean (5728 kg ha^{-1}) with very few individuals producing more than 8000 kg ha^{-1} (Fig. 2B).

The histogram for flat-across row point to positive skewness (S=0.89), meaning that by-plant yield of this population tented to have asymmetrical distribution. In other words, there were a large number of plants with relatively similar yields, predominantly around 5728 kg ha^{-1}, and few plants with relatively higher yields (>8000 kg ha^{-1}) (Fig. 2B). It has been recognized that increasing plant density resulted in more skewed frequency distributions as a consequence of competition (Ford, 1975). Although, Koyoma and Kira (1956) suggested that L-shaped distributions can also occur in the absence of competition between plants if the relative growth rate distribution of plants is normal. The peak in the Fig. 2B reflect on a positive kurtosis (K=0.82) for flat-across row, whereas platykurtic distributions were noted in the yield distribution of random (K=-0.45) and flat-with row seed-leaf orientation (K=-0.83).

Strong bimodality in reproductive output of maize was also noted by Vega and Sadras (2004). The frequency distribution of by-plant yields for random and flat-with row treatments indicate relatively larger individual yield variations (Fig. 2C and 2D). Moreover, skewness and kurtosis shifted from positive to negative as plant-to-plant inequality increased, helping to illustrate the association of increased by-plant yield inequality with CV, skewness, kurtosis, and range (Fig. 2).

An inverse relationship was noted between by-plant yield and G for Exp. 1 and Exp. 2 at EFAW and LCB, OK (Fig. 3), meaning that by-plant yield decreased with increasing plant-to-plant yield inequality. Although, only for the Exp. 2 at EFAW, the linear function between by-plant yield and G had a significant slope indeed (r^2=0.46; P<0.05). In general, a better fit was found with a second polynomial function at both experiments, but especially for Exp.2 (r^2=0.51 at EFAW and r^2=0.63 at LCB); yet, this relationship was not significant. These results are consistent with results reported by Sadras and Bongiovanni (2004), who demonstrated a significant inverse relationship between G and yield for maize crops grown in Argentina. Moreover, an inverse relationship between harvest index and G was reported by Pan et al. (2003) who investigated the inequality in yield of wheat under contrasting water availability.

By-Plant Yield and Plant-to-Plant Variation

The effect of seed-leaf orientation on by-plant yield was inconsistent across sites. Analysis of variance of the Exp. 1 showed that seed-leaf orientation and plant space interaction effect was not significant at any site (Table 2). In addition, no significant main effect was noted on by-plant yield at LCB, where the highest by-plant yield of 5576 kg ha^{-1} was noted for upright-across orientation whereas random and flat-across row produced 5265 and random yielded 5235 kg ha^{-1}, respectively (Table 2). Toler et al. (1999) suggested that intra-plant competition was affected by leaf orientation and that across row leaf orientation promoted yield advantage in particular at high plant density. By-plant yield of flat-across orientation was 155 kg ha^{-1} higher than the random, and 493 kg ha^{-1} greater than upright-across orientation but no significant differences were found at EFAW.

By-plant yield increased from 5143 to 5533 kg ha^{-1} as target plant space decreased from 27 to 18 cm, decreasing to 5399 kg ha^{-1} at target plant spacing of 13 cm at LCB. Downey (1971) represented the relationship between plant population and yield using a parabolic function and suggested that at lower populations, yield is constrained by reduced number of plants, while competition among plants is the main restriction to yield at high plant density. Target plant spacing had a significant effect on by-plant yield that decreased linearly as target plant spacing decreased at EFAW. Plant spacing of 27 cm produced 184 and 765 kg ha^{-1} greater yields than plant spacing of 18 and 13 cm, respectively (Table 2).

Analysis of variance for Exp. 2 indicated a significant seed-leaf orientation by plant space interaction at LCB (Table 3). Results show that mean by-plant yield of flat-across increased from 5726 to 6608 kg ha^{-1} as plant space reduced from 36 to 21 cm, while reduction in target plant spacing caused yield of flat-with row orientation to increase from 4994 to 6313 kg ha^{-1} at LCB. In contrast, by-plant yield of random seed-leaf orientation decreased from 5706 to 4794 kg ha^{-1} as target plant spacing reduced from 36 to 21 cm (Table 3). Likewise, Toler et al. (1999) found significant leaf orientation by plant population interaction and mentioned that grain yield increased with plant density but the magnitude was dependent on leaf orientation.

There was a significant effect of seed-leaf orientation on by-plant yield at EFAW, where random produced 813 and 796 kg ha^{-1} higher yields than flat-across and flat-with row orientations (Table 3). This result contradict the findings of Toler et al. (1999) who reported that at target plant spacing of 24 cm (22000 plant ac^{-1}), grain yield per plant was higher for across row (245 g plant^{-1}) compared to random and with row leaf orientations (231 g plant^{-1}). In addition, at target plant space of 16 cm (33000 plant ac^{-1}), across row leaf orientation produced 240 g plant^{-1} whereas random and with row leaf orientations produced 186 and 145 g plant^{-1}, respectively (Toler et al., 1999).

No effect of target plant spacing on by-plant yield at EFAW was identified and a trend for lower yields was observed as plant spacing decreased (Table 3). This result was expected since reduction of plant space, increases plant population density, consequently enhancing inter-plant competition. Even though, total yield of a given area may increase due high plant density, the yields of individual plants are expected to decrease. Nafziger (1996) reported a decrease from 238 to 179 g (8.4 to 6.32 oz plant^{-1}) in maize grain yield per plant as plant population increased from 44460 to 74100 plants ha^{-1} (plant distance of 30 and 18 cm, respectively), while yield per hectare basis increased from 10600 to 13234 kg ha^{-1} (169 to 211 bu ac^{-1}). Therefore, it can be deduced that seed placement and its resulting leaf orientation improved the crop's competitive ability to intercept light at LCB and it was particularly important as plant space was reduced.

Plant-to-plant yield variation expressed by the CV of by-plant yield was significantly affected by the interaction of seed-leaf orientation and target plant space in Exp. 1 at LCB (Table 4). Plant-to-plant yield variation for upright-across increased from 23 to 42% and for flat-across orientation from 32 to 39% as target plant space decreased from 27 to 18 cm; further reduction in target plant space reduced yield variation to 36% for both seed-leaf treatments. In contrast, plant-to-plant yield variation for the random seed-leaf orientation decreased from 30 to 27% as target plant space decreased from 27 to 18 cm, increasing to 37% at plant spacing of 13 cm distance between plants (Table 4).

Plant-to-plant variability increased by 11% as target plant space reduced from 27 to 13 cm in Exp. 1 at EFAW (Table 4). Furthermore, analysis of plant-to-plant yield variation suggests that seed-leaf orientation did not affect by-plant yield CV. Even though, random seed-leaf orientation had higher yield variation (46%) compared to upright-across (38%) and flat-across (39%) treatments at EFAW.

No main or interaction effects were observed for Exp. 2 at LCB where plant-to-plant yield variation of flat-across, random, and flat-with seed-leaf orientation was 36, 24, and 37% respectively (Table 5). Moreover, Table 5 shows that seed-leaf orientation did not affect by-plant yield CV significantly; albeit, flat-across had lower plant-to-plant yield variation than random, and flat-with row seed-leaf orientations (32, 36, and 38% correspondingly). Similarly, reduced distance between plants promoted a substantial increase in plant-to-plant yield variation increase for Exp. 2 at EFAW (Table 5). An increase of 10% in plant-to-plant yield variability was noted by reducing target plant spacing from 36 to 21 cm between plants.

Yield and Distance Relationships

Descriptive statistics of by-plant yield and plant distance for Exp.1 and Exp. 2 at EFAW and LCB are shown in Table 6. Overall, regression analysis indicated that by-plant yield decreased 142 kg ha^{-1} for each centimeter increase in plant distance SD (r^2=0.12, *P*=0.06). Similarly, Nielsen (1991) reported 156 kg ha^{-1} of yield reduction for every 2.54 cm increase in plant spacing SD. Relationships between by-plant yield and plant distance (D) means, and its measures of variation (SD and CV) are shown in Table 7. By-plant yield mean and SD for Exp. 1 were positively associated, with correlation coefficients of 0.29, 0.51, and 0.38 for upright-across and flat-across, and random seed-leaf orientations (Table 7). These results are in agreement with those reported by Martin et al. (2005). Where a cubic function was used to explain the effect of increasing mean yield and yield SD per plant and demonstrated a r^2 of 0.498. Although, a trend for negative correlations was found between by-plant yield mean and by-plant yield CV, suggesting that as plant-to-plant yield variation increased, yield levels tended to decrease, particularly for random seed-leaf orientation (r=-0.43; *P*<0.01) (Table 7).

By-plant yield CV was significantly correlated with plant distance variation (CV of D), which means that plant-to-plant yield variability increased as plant distance variability increased, especially for upright- and flat-across compared to random seed-leaf orientations (r=0.40, *P*<0.05; and r=0.48, *P*<0.01) (Table 7). According to these results, plant distance variability explained much of the plant-to-plant yield variation. Research has recognized that plant size is determined by distances between plants and sizes of the neighboring plants, which is an indication of competition among plants (Silander and Pacala, 1985; Nagashima et al., 1995). Correlations between mean plant distance and by-plant yield were usually weak and not significant for any seed-leaf treatment (Table 7). Moreover, the correlation of mean by-plant yield and plant distance CV was also weak and not significant.

By-plant yield mean was not correlated with plant distance CV (Table 8) in Exp. 2. However, plant distance CV and yield CV were highly correlated for flat-across and random seed-leaf orientations (r=0.71, *P*<0.01; and r=0.82, *P*<0.01, respectively), whereas for the flat-with row orientation, plant-to-plant yield variation was not correlated with plant distance CV (r =0.32) (Table 8). Lower by-plant yields tended to have greater plant-to-plant variation, but only for flat-across seed-leaf orientation this trend was significant (r=-0.40, *P*<0.10) (Table 8).

CONCLUSION

Similar conclusions were obtained when inferences on plant-to-plant variation were made using G or coefficient of variation. Results suggest that variation in plant distance rather than seed-to-leaf orientation were the main source of by-plant yield inequality. Overall, a large proportion of the plant-to-plant yield variability was explained by the variations in space occupied the plants within the maize row. The use of Lorenz curves, G, and frequency distributions seemed to be a suitable method to express and evaluate by-plant yield variation and the effects of precision planting of maize, complementing the information on variability provided by statistical estimators such as coefficient of variation, range, skewness, and kurtosis. Lower by-plant yield inequality, expressed by a smaller G, was associated with lower coefficient of variation, lower range, L-skewed, and leptokurtic distributions. Conversely, a trend for greater CV and range, J-shaped, and bimodal frequency distributions were coupled with maize plant populations with higher by-plant yield inequality. Moreover, an inverse relationship was observed between G and plant space (r^2=0.17; P<0.05). In conclusion, this study found that by-plant yield decreased as plant-to-plant inequality increased and that precision planting of maize and its effects on crop canopy appears to reduce plant-to-plant yield inequality compared to conventional planting.

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Table 1. Gini coefficients (G) for seed-leaf orientations and target plant space at EFAW and Lake Carl Blackwell (LCB), OK, 2012.

Experiment	Seed Placement†	Leaf Orientation‡	Seed-to-Leaf Orientation§	Target Plant Space	EFAW	LCB
				cm	G¶	
1	Upright	Across	Upright-Across	27	0.20	0.17
	Flat	Across	Flat-Across	27	0.18	0.14
	Random	Random	Random	27	0.21	0.19
	Upright	Across	Upright-Across	18	0.27	0.15
	Flat	Across	Flat-Across	18	0.24	0.23
	Random	Random	Random	18	0.28	0.25
	Upright	Across	Upright-Across	13	0.30	0.21
	Flat	Across	Flat-Across	13	0.27	0.21
	Random	Random	Random	13	0.21	0.22
2	Flat	Across	Flat-Across	36	0.14	0.16
	Random	Random	Random	36	0.22	0.22
	Flat Parallel	With	Flat-With	36	0.24	0.23
	Flat	Across	Flat-Across	21	0.28	0.22
	Random	Random	Random	21	0.21	0.28
	Flat Parallel	With	Flat-With	21	0.25	0.20

† Upright, seeds planted upright with caryopsis pointed down, kernel parallel to the row; Flat, seeds planted laying flat, with embryo up, kernel perpendicular to the row; Random, conventionally planted seeds with random seed placement; Flat Parallel, seeds planted laying flat, with embryo up, kernel parallel to the row.

‡ Leaf orientation in relation to the row.

§ Seed placement and the resultant leaf orientation.

¶ Gini coefficient range from 0 to 1, where 0 represents the absolute equality, and 1 represents the theoretical maximum inequality, when all except one individual is equal to zero.

Table 2. Experiment 1 analysis of variance and treatment means for seed-to-leaf orientation (SL) and plant space (PS) effect on by-plant yield, at EFAW and Lake Carl Blackwell (LCB), OK, 2012.

			EFAW		LCB	
Effect	Seed-to-Leaf Orientation	Target Plant Space	Mean	s.e.	Mean	s.e.
		cm	By-Plant Yield, kg ha^{-1}			
SL	Upright-Across		6455	289	5576	222
	Flat-Across		6948	292	5235	223
	Random		6793	291	5265	226
PS		27	7048	304	5143	235
		18	6864	293	5533	223
		13	6283	278	5399	215
SL*PS	Upright-Across	27	6597	484	5133	372
		18	7070	461	6244	353
		13	5699	439	5350	345
	Flat-Across	27	7601	483	5102	370
		18	6673	457	5187	355
		13	6569	450	5416	342
	Random	27	6947	478	5195	372
		18	6850	477	5167	356
		13	6581	436	5433	345
SL			NS		NS	
PS			*		NS	
SL*PS			NS		NS	
SED†			640		418	
CV (%)			44		37	

*, **, and ***, significant at 0.1, 0.05, and 0.001 probability levels; NS, not significant.

† SED, standard error of the difference between two equally replicated means; error.

Table 3. Experiment 2 analysis of variance and treatment means for seed-to-leaf orientation (SL) and plant space (PS) effect on by-plant yield and plant distance means at Lake Carl Blackwell (LCB), OK, 2012.

			EFAW		LCB	
Effect	Seed-to-Leaf Orientation	Target Plant Space	Mean	s.e.	Mean	s.e.
		cm	By-Plant Yield, kg ha^{-1}			
SL	Flat-Across		4720	572	6167	568
	Random		5533	564	5250	579
	Flat-With		4737	572	5628	569
PS		36	5113	568	5459	543
		21	4880	553	5905	535
SL*PS	Flat-Across	36	4877	619	5726	668
		21	4563	587	6608	642
	Random	36	5415	605	5706	666
		21	5651	578	4794	682
	Flat-With	36	5048	622	4944	673
		21	4426	587	6313	642
SL			***		NS	
PS			NS		NS	
SL*PS			NS		*	
SED†			528		562	
CV (%)			41		38	

*, **, and ***, significant at 0.1, 0.05, and 0.001 probability levels; NS, not significant.

† SED, standard error of the difference between two equally replicated means.

Table 4. Experiment 1 analysis of variance and treatment means for seed-to-leaf orientation (SL) and plant space (PS) effect on plant-to-plant yield variation at EFAW and Lake Carl Blackwell (LCB), OK, 2012.

			Plant-to-Plant Yield Variation†	
Effect	Seed-to-Leaf Orientation	Target Plant Space	EFAW	LCB
		cm	%	
SL	Upright-Across		39	34
	Flat-Across		38	36
	Random		46	31
PS		27	34	28
		18	44	36
		13	45	36
SL*PS	Upright-Across	27	31	23
		18	42	42
		13	46	36
	Flat-Across	27	34	32
		18	43	39
		13	37	36
	Random	27	38	30
		18	46	27
		13	53	37
SL			NS	NS
PS			**	**
SL*PS			NS	*
SED‡			5	3

*, **, and ***, significant at 0.1, 0.05, and 0.001 probability levels; NS, not significant.

† Plant-to-plant yield variation is represented by the coefficient of variation of by-plant yield.

‡ SED, standard error of the difference between two equally replicated means.

Table 5. Experiment 2 analysis of variance and treatment means for seed-to-leaf orientation (SL) and plant space (PS) effect on plant-to-plant yield variation at EFAW and Lake Carl Blackwell (LCB), OK, 2012.

			Plant-to-Plant Yield Variation†	
Effect	Seed-to-Leaf Orientation	Target Plant Space	EFAW	LCB
		cm	%	
SL	Flat-Across		32	36
	Random		36	24
	Flat-With		38	37
PS		36	31	28
		21	40	37
SL*PS	Flat-Across	36	29	33
		21	36	39
	Random	36	33	20
		21	39	28
	Flat-With	36	31	31
		21	45	44
SL			NS	NS
PS			**	NS
SL*PS			NS	NS
SED‡			4	6

*, **, and ***, significant at 0.1, 0.05, and 0.001 probability levels; NS, not significant.

† By-plant yield variation is represented by the coefficient of variation of by-plant yield.

‡ SED, standard error of the difference between two equally replicated means.

Table 6. Descriptive statistics of by-plant yield and plant distance for experiments 1 and 2 at EFAW and Lake Carl Blackwell (LCB), OK, 2012.

Experiment	Site	Seed-to-Leaf Orientation	Target Plant Space	N	By-Plant Yield		Plant Distance	
					Mean	SD	Mean	SD
			cm		— kg ha^{-1} —		— cm —	
1	EFAW	Upright-Across	27	111	6542	2583	28	5.6
		Flat-Across	27	112	7590	2435	27	3.8
		Random	27	116	6920	2678	26	6.1
		Upright-Across	18	149	7033	3256	19	4.4
		Flat-Across	18	152	6599	2813	19	4.9
		Random	18	141	6570	3218	18	6.8
		Upright-Across	13	215	5657	3005	14	4.4
		Flat-Across	13	173	6511	3117	18	6.5
		Random	13	223	6563	2484	13	5.2
	LCB	Upright-Across	27	102	5111	1612	28	3.2
		Flat-Across	27	105	5069	1252	28	4.8
		Random	27	102	5222	1858	28	8.5
		Upright-Across	18	155	6120	1721	19	3.5
		Flat-Across	18	145	5073	2186	20	4.9
		Random	18	152	5120	2269	19	5.5
		Upright-Across	13	194	5352	2012	15	3.5
		Flat-Across	13	201	5335	2056	15	4.3
		Random	13	199	5390	2166	15	4.6
2	EFAW	Flat-Across	36	54	4775	1555	37	7.6
		Random	36	67	5379	2120	29	10.4
		Flat-With	36	53	4972	2115	36	11.0
		Flat-Across	21	82	4498	2226	24	8.1
		Random	21	99	5619	2063	20	6.2
		Flat-With	21	85	4394	1962	24	6.4
	LCB	Flat-Across	36	58	5728	1632	37	7.6
		Random	36	60	5729	2199	32	7.7
		Flat-With	36	57	4950	2014	36	8.3
		Flat-Across	21	87	6624	2489	23	7.3
		Random	21	89	4807	2352	22	8.4
		Flat-With	21	87	6359	2296	23	5.6

Table 7. Experiment 1 simple correlation coefficients and significance levels between mean, standard deviation, and coefficient of variation for by-plant yield and plant distance using combined data from EFAW and Lake Carl Blackwell, OK, 2012.

			Yield		Plant Distance		
Seed-to-Leaf Orientation	Variable	Measure†	SD	CV	Mean	SD	CV
Upright-Across	Yield	Mean	0.29 *	-0.26 NS	0.06 NS	0.30 *	0.12 NS
		SD			-0.24 NS	0.37 **	0.42 **
		CV			-0.28 *	0.26 NS	0.40 **
	Plant Distance	Mean				0.18 NS	-0.33 **
Flat-Across	Yield	Mean	0.51 ***	0.01 NS	0.14 NS	-0.11 NS	-0.15 NS
		SD			-0.36 **	0.27 *	0.36 **
		CV			-0.53 ***	0.33 **	0.48 ***
	Plant Distance	Mean				-0.08 NS	-0.50 ***
Random	Yield	Mean	0.38 **	-0.43 ***	-0.14 NS	-0.06 NS	0.07 NS
		SD		0.61 ***	-0.19 NS	0.04 NS	0.15 NS
		CV			-0.11 NS	0.05 NS	0.09 NS
	Plant Distance	Mean				0.46 ***	-0.32 **

*, **, and ***, significant at 0.1, 0.05, and 0.001 probability levels; NS, not significant.

† Mean, standard deviation (SD) and coefficient of variation (CV) of by-plant yield and plant distance.

Table 8. Experiment 2 simple correlation coefficients and significance level between mean, standard deviation, and coefficient of variation for by-plant yield and plant distance using combined data from EFAW and Lake Carl Blackwell, OK, 2012.

			Yield		Plant Distance		
Seed-to-Leaf Orientation	Variable	Measure†	SD	CV	Mean	SD	CV
Flat-Across	Yield	Mean	0.01 NS	-0.40 *	-0.12 NS	-0.34 *	-0.24 NS
		SD			-0.51 **	0.33 NS	0.66 ***
		CV			-0.45 **	0.42 **	0.71 ***
	Plant Distance	Mean				0.22 NS	-0.48 **
Random	Yield	Mean	0.46 **	-0.12 NS	0.03 NS	0.14 NS	0.12 NS
		SD			-0.39 *	0.48 **	0.78 ***
		CV			-0.46 **	0.45 **	0.82 ***
	Plant Distance	Mean				0.43 **	-0.22 NS
Flat-With	Yield	Mean	0.66 ***	-0.28 NS	-0.48 **	-0.04 NS	0.29 NS
		SD			-0.53 ***	0.09 NS	0.46 **
		CV			-0.17 NS	0.22 NS	0.32 NS
	Plant Distance	Mean				0.33 NS	-0.17 NS

*, **, and ***, significant at 0.1, 0.05, and 0.001 probability levels; NS, not significant.

† Mean, standard deviation (SD) and coefficient of variation (CV) of by-plant yield and plant distance.

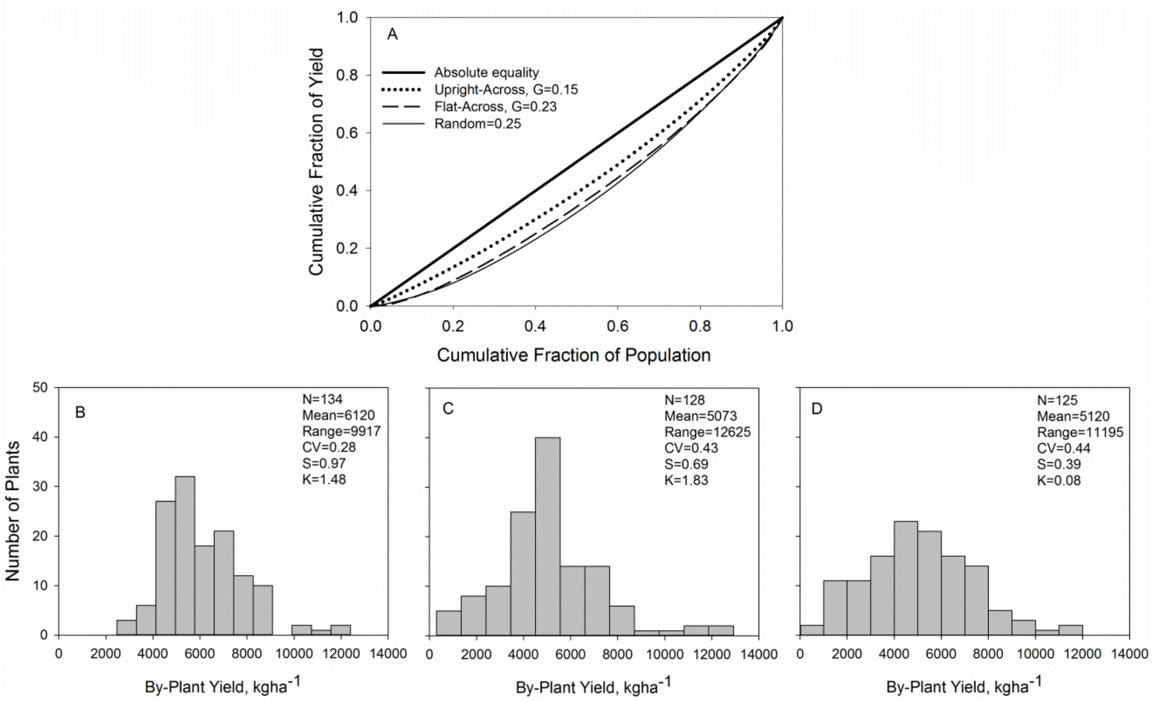

Figure 1. Lorenz curves and by-plant yield distribution for seed placement and leaf orientations at 18 cm of target plant space for experiment 1 at LCB, OK, in 2012. Figure 1A shows the cumulative fraction of yield as a function of cumulative fraction of population for seed-to-leaf orientation treatments and the straight line represents the absolute equality among the yield of individual plants within a population (treatment). Figures 1B, 1C, and 1D show the frequency distribution of by-plant yield for each seed-to-leaf orientation treatment shown in Fig. 1A.

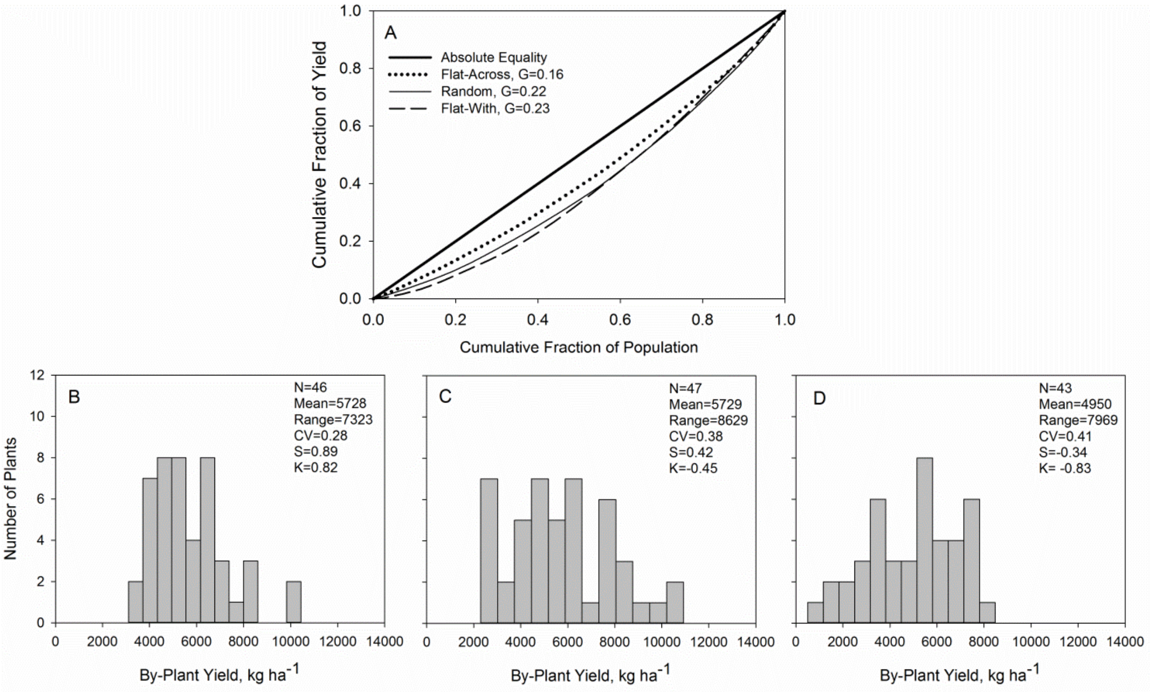

Figure 2. Lorenz curves and by-plant yield distribution for seed placement and leaf orientations at target plant spacing of 36 cm for experiment 2 at LCB, OK, in 2012. Figure 2A shows the cumulative fraction of yield as a function of cumulative fraction of population for seed-to-leaf orientation treatments and the straight line represents the absolute equality among the yield of individual plants within a population (treatment). Figures 2B, 2C, and 2D show the frequency distribution of by-plant yield for each seed-to-leaf orientation treatment shown in Fig. 1A.

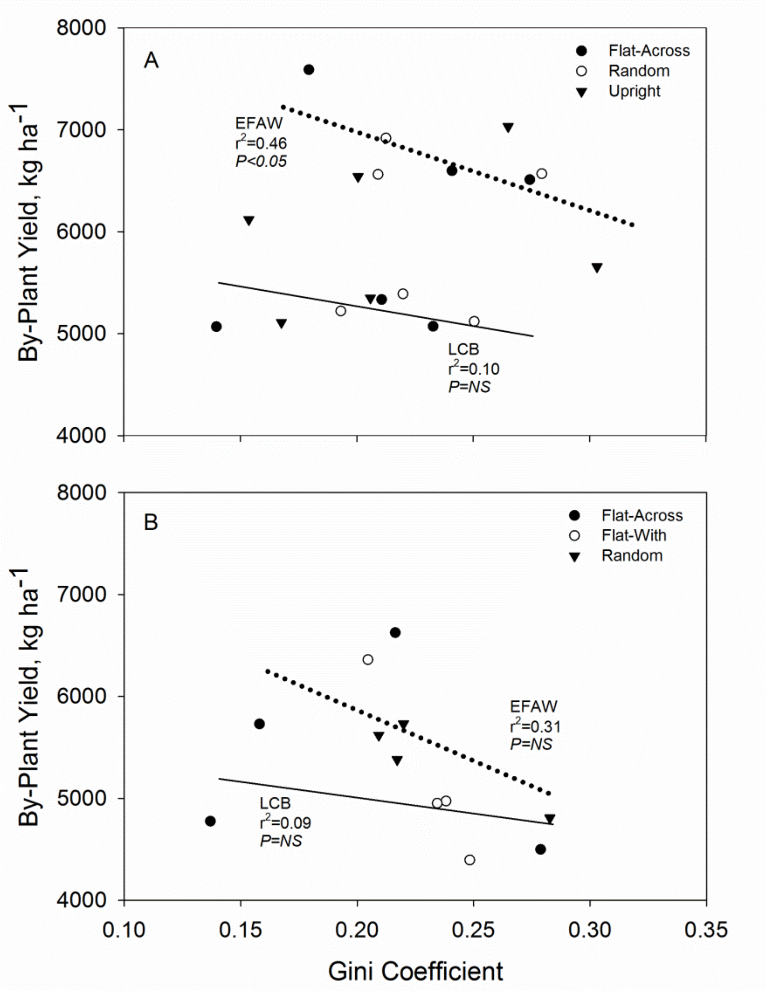

Figure 3. By-plant yield and Gini coefficient relationship for experiments 1 and 2 (A and B) at EFAW and Lake Carl Blackwell (LCB), OK, in 2012.

APPENDICES

Table A.1. Treatment structure for seed placement and resultant leaf orientation, plant population and hybrid canopy architecture for experiments conducted at EFAW and Lake Carl Blackwell (LCB), 2010-2012.

Site	Treatment	Seed Placement†	Leaf Orientation‡	Plant population	Hybrid ‡
				plants ha^{-1}	
EFAW	1	Upright	Across	37050	Planophile
	2	Flat	Across	37050	Planophile
	3	Random	Random	37050	Planophile
	4	Upright	Across	49400	Planophile
	5	Flat	Across	49400	Planophile
	6	Random	Random	49400	Planophile
	7	Upright	Across	61750	Planophile
	8	Flat	Across	61750	Planophile
	9	Random	Random	61750	Planophile
	10	Upright	Across	49400	Erectophile
	11	Flat	Across	49400	Erectophile
	12	Random	Random	49400	Erectophile
LCB	1	Upright	Across	49400	Planophile
	2	Flat	Across	49400	Planophile
	3	Random	Random	49400	Planophile
	4	Upright	Across	74100	Planophile
	5	Flat	Across	74100	Planophile
	6	Random	Random	74100	Planophile
	7	Upright	Across	98800	Planophile
	8	Flat	Across	98800	Planophile
	9	Random	Random	98800	Planophile
	10	Upright	Across	74100	Erectophile
	11	Flat	Across	74100	Erectophile
	12	Random	Random	74100	Erectophile

† Upright, seeds planted upright with caryopsis pointed down, kernel parallel to the row; Flat, seeds planted laying flat, with embryo up, kernel perpendicular to the row; Random, conventionally planted seeds with random seed placement.

‡ Across, leaf azimuth predominantly perpendicular in relation to the row; Random, leaf azimuth randomly oriented in relation to the row.

¶ Planophile, leaf angle is predominantly horizontal; Erectophile predominantly vertical leaf angles.

Table A.2. Soil surface (0-15 cm) test characteristics for experiments established at EFAW and Lake Carl Blackwell, OK, from 2010-2012.

Year	Site	pH	NH_4-N	NO_3-N	P	K
			kg ha^{-1}			
2010	EFAW	5.7	93.0	8.0	95	271
	LCB	5.7	10.5	5.4	55	338
2011	EFAW	5.9	13.1	11.3	25	241
	LCB	5.6	7.6	8.6	53	217
2012	EFAW	5.5	11.7	6.0	62	378
	LCB	6.0	14.2	5.2	60	197

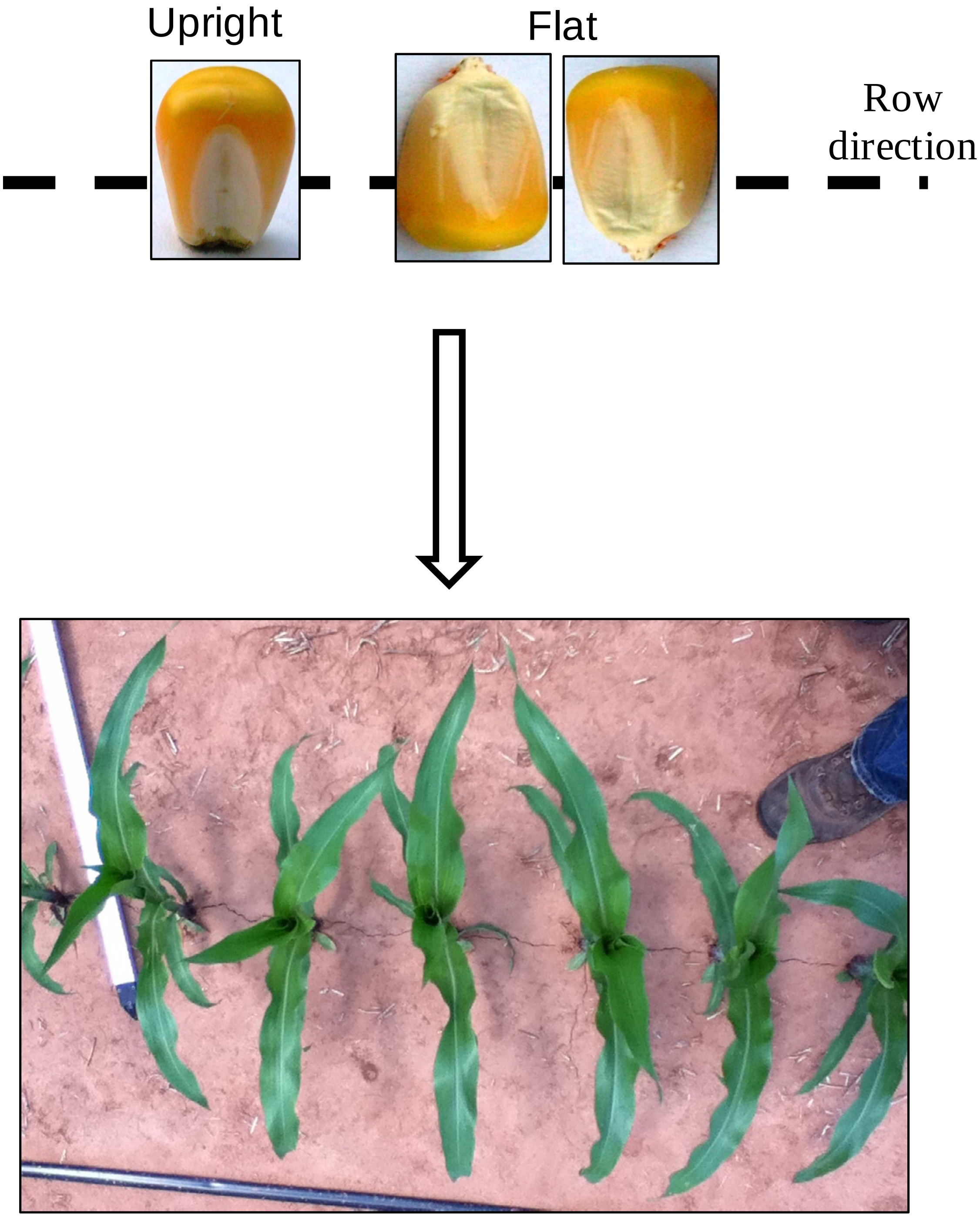

Figure A.1. Seeds planted upright with caryopsis pointed down, kernel parallel to the row (Upright) and seeds planted laying flat, with embryo up, kernel perpendicular to the row (Flat) results in leaf azimuth perpendicular in relation to the row.

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