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Twin-Row Production and Optimal Plant Population for Modern Maize Hybrids

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TWIN-ROW PRODUCTION AND OPTIMAL PLANT POPULATION FOR MODERN MAIZE HYBRIDS

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Maize (*Zea mays* L.) is widely grown for food, feed, and fuel, and optimal yield will be required to meet increasing demand due to world population growth and increased biofuel usage. This requires matching of the best maize hybrids with optimal plant population and spacing. Modern maize hybrids have increased "crowding stress" tolerance, and Bt (*Bacillus thuringiensis*) hybrids now resist European corn borer and corn rootworm which has created interest in altering row configuration and increasing plant population.

Three Bt hybrids were evaluated from 2009 to 2010 near Mead, NE at target populations from 69136 to 106173 plants ha^{-1} in 76 cm single rows and twin rows. Maximum yield occurred at the highest target population in 9 of 12 year, hybrid, and row configuration combinations although target population had a small effect on yield. Varying hybrid, plant population, and row configuration had small and inconsistent effects on grain yield, yield components, plant morphology and leaf area, interception of solar radiation, and stalk lodging. It appears that the major impacts of altering row configuration occur early in the growing season, and plant growth and other factors occurring later in the growing season have a greater impact on yield.

Two pairs of near isogenic Bt and non-Bt maize hybrids were evaluated under rainfed and irrigated conditions from 2008 to 2010 at target populations from 49383 to 111111 plants ha^{-1} near Mead, NE. For all hybrids and environments, yield increased linearly and the highest target population resulted in the greatest grain yield. Bt hybrids had 0.4 Mg ha^{-1} greater yield than non-Bt hybrids at all populations. Bt hybrids lodged less in three of five environments.

Results indicate that twin-row production has little influence on maize yield and growth in Nebraska. In general, maize yield increased linearly with increasing target population although the rate of yield increase varied across experiments, environments and hybrids. Farmers in East-Central Nebraska should consider increasing maize plant population and planting Bt hybrids to optimize maize grain yield.

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INTRODUCTION

Worldwide demand is continually increasing for food, feed, and fuel. Maize (*Zea mays* L.) is a common crop grown both in the United States and globally that is often used to meet these three uses. This multi-use trait of maize grain has led to a dramatic increase in demand during the past decade.

Petroleum price is rising due to the political instability often found in major oil-exporting countries and demand growth in China, India, and other developing countries (Cassman and Liska, 2007). Producing ethanol from maize grain is profitable without subsidies at a petroleum price above $50 per barrel. Petroleum price is expected to average $98 per barrel in 2011 and $103 per barrel in 2012 (US DOE-EIA, 2011). Improvements in biofuel plant design and co-product usage will further increase biofuel production profit margins (Cassman and Liska, 2007) and maize grain demand. Additionally, the current Renewable Fuels Standard mandates annual production of 136 billion liters of renewable fuel by 2022, with 79 billion liters coming from cellulosic ethanol production (RFA, 2011). The 57 billion liter difference would largely be produced from maize grain. This would require a production increase of 12 billion liters above 2010 production and use a total of 150 million Mg of maize grain, 32 million Mg above 2010 use. Currently, ethanol production requires 37% of the total maize crop grown in the United States (USDA-NASS, 2011).

World population reached 6.9 billion in 2010 (PRB, 2010). Although the rapid growth of the second half of the 20th century has slowed, continuously decreasing mortality due to improved health, increased access to education and economic growth, and slower than expected declines in birth rates guarantee continued world population growth for decades (Bremner et al., 2010). Current world population projections for 2050 range from 9.15 to 9.51 billion. Worldwide, there are over 850 million undernourished people (Cassman and Liska, 2007). Increasing use of food crops such as maize for biofuels production will compound the risk of hunger for the world's poor. The challenge to agriculture is to produce enough food to meet the increased population and biofuel production demands. An increase in research and extension efforts, focusing on increasing rate of gain in crop yields, will be necessary to meet these demands.

Optimizing harvestable maize grain yield requires matching of the best maize hybrids with optimal plant population and spacing. Research indicates that maize plant population has increased dramatically during the past 40 years (Hodgen, 2007). The major genetic contribution to yield increase has been due to increased "crowding stress" tolerance (Duvick and Cassman, 1999). This tolerance has resulted in increased grain yield through planting higher maize plant population, without increasing the number of barren plants or harvest losses due to lodging. The introduction of multiple sources of insect resistance through biotechnology and plant breeding results in improved "plant health", which seed companies are using in sales efforts to spur farmers to increase maize plant population. Although the link between plant health and plant population makes sense, research has not addressed this relationship for grain yield, lodging potential, and number of barren plants for modern maize hybrids.

Maize grain yield is also influenced by plant spacing. Decades of row spacing research has been conducted, with greater maize yield produced by narrowing rows in desirable production environments, and widening rows in more stressful environments (Karlen and Camp, 1985). Row spacing response interacts with maize hybrid and plant population (Farnham, 2001). Altering row spacing influences interception of solar radiation and weed control (Teasdale, 1995), as well as capital investment requirements (Karlen and Camp, 1985). Recent row spacing interest for increasing maize grain yield and resource efficiency has been focused on skip-row systems for water limiting environments (Lyon et al., 2009) and twin-row production systems for high yield environments (Great Plains, 2011). The latter system plants maize in paired rows on 76 (or 90 cm) centers with the paired rows being 17.5 to 20 cm apart. This potentially provides the added advantages of narrowing row spacing while minimizing the capital investment in equipment.

Increases in grain yield will be necessary to meet increased demand for maize grain in the future. This research was conducted to better understand how modern maize hybrids, plant population, and row configuration interact and can be paired in order to help meet future demand.

CHAPTER 1

LITERATURE REVIEW

LITERATURE REVIEW

Modern Maize Hybrid

The dramatic increase in maize yield over the past 50 years can generally be attributed to two sources: (1) plant breeding and improved genetics, and (2) better management and production practices (Duvick, 2005). During that time period, there was little change in maize yield potential of "racehorse" hybrids, grown under ideal conditions, while "workhorse" hybrids, grown in stress limiting environments, have exhibited a great increase in yield potential (Duvick and Cassman, 1999). Plant breeding and improved genetics are evident as newer hybrids now exhibit increased kernel weight, grain starch percentage, grain fill period, leaf rolling, and resistance to leaf senescence, as well as an increase in ears per plant, which indicates a decrease in the number of barren plants (Duvick, 2005). Duvick (2005) also stated that a reduction in tassel size, anthesis-silk interval, and root and stalk lodging has occurred in newer hybrids.

Modern maize hybrids have also advanced through biotechnology in response to the demand for improved insect protection. Bt maize hybrids, first released in 1996 (Seydou et al., 2000), served as the foundation for transgenic crops. Bt maize hybrids have been genetically engineered to contain genes of *Bacillus thuringiensis* (Bt), which are inherently resistant to larvae from first and second generation European corn borer (*Ostrinia nubilalis*) (Koziel et al., 1993). Since 1996, the addition of other genes from *Bacillus thuringiensis* has resulted in resistance to corn rootworm (*Diabrotica* spp.)

(Hellmich et al., 2008). Reduced need for chemical insecticides, yield protection, and improved grain quality has attracted many growers to transgenic maize hybrids. Currently, European corn borer (ECB), and corn rootworm (CRW) resistance is often combined, or stacked, with herbicide tolerance. Herbicide tolerance permits the use of herbicides, without harmful crop effects, and replaces previous herbicides that were more persistent in the environment. The additional benefit for use in no-till or minimum tillage environments has also drawn producers to this technology. Today, transgenic maize hybrids occupy 88% of maize area in the United States (USDA-ERS, 2011).

Maize Plant Population

The most evident improvement in yield potential is a result of adaptation to continual increases in plant population (Duvick, 2005). This was possible with the introduction of maize hybrids that tolerate increased plant population. Duvick (1977) reported that older hybrids out-yielded newer hybrids at lower plant population, while at higher plant population the reverse occurred. This suggests that a hybrid will offer maximum yield potential when grown at the population for which it was developed.

Stickler and Laude (1960) reported that a plant population of 25800 or 38700 plants ha^{-1} resulted in the greatest maize grain yield in Kansas. Another study published by Stickler (1964) stated that under irrigation, the highest yield was obtained with a plant population of 49400 or 59300 plants ha^{-1}, and rainfed maize yielded best at 40000 plants ha^{-1}. Lutz et al. (1971) agreed with Stickler's findings, achieving the greatest maize grain yield at a plant population of 49000 or 62000 plants ha^{-1} in Virginia, unless water was limiting, in which case 37000 plants ha^{-1} resulted in the highest yield. Work published by Knapp and Reid (1981) stated that a plant population of 54340 plants ha^{-1} resulted in the highest grain yield in New York. Porter et al. (1997) found that yield in Minnesota was greatest at 86400 or 98800 plants ha^{-1}, but when limited by climatic conditions, a plant population of 74100 plants ha^{-1} resulted in the greatest yield. Likewise, maize yield in Michigan was greatest at a plant population of 90,000 plants ha^{-1} (Widdicombe and Thelen, 2002). These studies show that the plant population that achieves the maximum grain yield has increased dramatically over time.

Yield can also be related to increasing plant population's influence on plant morphology and physiology. Increased plant population leads to a greater leaf area index (LAI) at silking, which increases interception of photosynthetically active radiation (Tollenaar and Aguilera, 1992). Cox (1996) reported a 40% increase in LAI at high plant population from mid-vegetative to early grain fill even though per plant biomass has been reported to decrease 40 to 60% at high plant population (Maddonni and Otegui, 2004). Unfortunately, this decrease in per plant biomass causes a decrease in photosynthetic rate per plant which can increase plant barrenness (Edmeades and Daynard, 1979) as plant population increases (Maddonni and Otegui, 2004). Cox (1996) found that the high plant population yielded 15% more than the low plant population.

As plant population increases, so does plant stress which affects maize yield components. Yield components consist of the number of ears m^{-2} (or ears $plant^{-1}$), kernels ear^{-1} (or kernels plant^{-1}), and kernel weight. Path coefficient analysis by Agrama (1996) indicated that the number of ears m^{-2} had a larger direct effect on grain yield than did the other yield components. Increasing plant population has been shown to decrease the number of ears plant^{-1} (Tollenaar et al., 1992; Otegui, 1995; Ordas and Stucker, 1977), kernels ear^{-1} (Baenziger and Glover, 1980; Westgate et al., 1997; Maddonni and Otegui, 2006; Karlen and Camp, 1985; Otegui, 1995), and kernel weight (Westgate et al., 1997; Maddonni and Otegui, 2006; Karlen and Camp, 1985). Others report that increased plant population has little effect on kernel weight (Begna et al., 1997; Westgate et al. 1997). Maddonni and Otegui (2006) reported that kernel weight was more stable than other yield components as plant population increased. Kernel weight is influenced by source-sink relationships during grain fill (Borrás and Otegui, 2001; Gambín et al., 2006; Andrade et al., 1999; Schoper et al., 1982; Tollenaar and Aguilera, 1992), with increased kernel weight occurring as irradiance, plant and kernel growth rate, and grain-fill duration increases.

Timing of water stress and defoliation has also been used to verify the relationship between grain yield and yield components. Yield component development is sequential (Munaro et al., 2011; Agrama, 1996) with ears m^{-2} (or ears plant^{-1}) being influenced by early-season growing conditions, kernels ear^{-1} (or kernels plant^{-1}) by mid-season conditions, and kernel weight by late-season conditions. Eck (1986) found that water deficit during vegetative growth reduced the number of kernels ear^{-1} but had little effect on kernel weight. Water deficit during grain filling had little influence on the number of kernels produced but reduced kernel weight (Eck, 1986; Grant et al., 1989).

Pandey et al. (2000) studied deficit irrigation and N rate influence on maize yield components. They found that larger water deficits and lower N rates reduced grain yield, ears m^{-2}, kernels m^{-2}, and kernel weight.

Lodging is a major limitation to maximizing harvestable grain yield in modern maize production (Sibale et al., 1992). Increasing plant population, to obtain maximum yield, results in increased lodging potential. The increase in lodging and harvest loss often nullifies the yield increase that would have been realized from the plant population increase (Olson and Sander, 1988). Stanger and Lauer (2006) found that as harvest population increased from 64220 to 123500 plants ha^{-1}, lodging increased from 5.0 to 15.8%. Similarly, Pedersen and Lauer (2002) stated that an increase in plant population increased lodging potential, and that most lodged plants had broken stalks which were associated with stalk and root rot pathogens. Wilcoxson and Covey (1963) also obtained comparable results and concluded that high plant population resulted in smaller diameter stalks that broke easier when weakened by pathogens. Rind strength also decreases with high plant population, as evidenced by a decrease in rind penetrometer resistance (Stanger and Lauer, 2007). Maize plants were 13% taller with a plant population of 90000 or 120000 plants ha^{-1} when compared to 30000 plants ha^{-1} (Maddonni et al., 2001), which also contributes to the increased lodging potential of maize grown with high plant population.

The introduction of Bt maize hybrids in 1996 (Seydou et al., 2000) served as a catalyst for producers to increase plant population because the Bt trait had been shown to reduce stalk lodging. Stanger and Lauer (2006) found that Bt hybrids lodged 22% less and yielded 6.6% more than non-Bt hybrids. Whereas the plant population to achieve maximum yield was greater for Bt-hybrids, increased seed and harvest costs offset the yield and lodging benefits, resulting in no difference in the recommended planting rate in Wisconsin. The economic optimal plant population was 83,800 plants ha^{-1} for both Bt and non-Bt hybrids, which was 9700 plants ha^{-1} greater than the Wisconsin recommendation at the time.

Row Spacing

As maize plant population has increased, row spacing has narrowed as a means to improve plant spatial arrangement. Narrow-row production systems result in decreased competition among plants for solar radiation, water, and nutrients (Olson and Sander, 1988). Prior to 1940, the distance between rows was generally limited by the width of a horse (*Equus* sp.), approximately 102 cm (Aldrich et al., 1986). The common practice during that time was to check plant maize in hills spaced about 107 cm apart in rows of the same spacing at planting rates of two to four plants hill^{-1} (17600 to 35100 plants ha^{-1}) (Bryan et al., 1940). Cultivation could then occur in both horizontal and vertical directions. As machinery use became more common, matching of planting, cultivating, and harvesting equipment and tractor tire size still favored wider rows (Olson and Sander, 1988). However, the continued improvement in narrow-row planting, cultivating, and harvesting machinery and the use of effective herbicides, such as atrazine, did increase interest in narrowing rows from 102 cm to 51 to 76 cm (Stickler, 1964).

In Iowa, Yao and Shaw (1964) found that a 53 cm row spacing yielded more than an 81 or 107 cm row spacing. Shibles et al. (1966) found that narrowing rows from 102 cm to 76 cm or 51 cm increased yield by 1.5 and 3.5%. In Minnesota, Porter et al. (1997) found that a row width of 51 or 25 cm consistently outyielded 76 cm rows by an average of 7% across nine site years. This yield advantage occurred regardless of plant population. Similarly, Widdicombe and Thelen (2002) stated that decreasing row width from 76 cm to 56 cm and 38 cm increased yield by 2 and 4%. Shapiro and Wortmann (2006) reported that narrowing row spacing from 76 to 51 cm resulted in a 4% increase in grain yield in Northeast Nebraska while Mason et al. (2008) found no yield difference between 76 and 38 cm row widths in East-Central Nebraska.

Narrow rows result in more consistent maize yield increases in northern areas and with early-maturity maize hybrids, as the individual plants are smaller with reduced LAI and the narrow-row spacing increases early-season interception of solar radiation (Hoeft et al., 2000). Paszkiewicz (1997) summarized 84 university and industry row spacing studies across the United States (Table 1.1). The greatest response for narrow rows (< 76 cm) was found in the most northern locations. Yield increased by 8% when compared to 76 cm rows north of the I-90 corridor. South of I-70 a yield reduction occurred with narrow rows.

Table 1.1. Percent yield increase compared to 76 cm rows (Paszkiewicz, 1997).

Row Spacing	Zone 1	Zone 2	Zone 3	Zone 4	Mean
56 cm	3.2	4.9	0.1		3.6
51 cm	8.8	4.4	0.9	-8.7	4.0
38 cm	11.1	2.7	2.2	-13.0	1.3
Mean	8.0	4.1	1.5	-9.8	3.2

Zone 1: N of I-90, roughly MN, ND, SD, ONT
Zone 2: S of I-90 and N of I-80, roughly N. IA, N. NE
Zone 3: S of I-80 and N of I-70, roughly S. IA, S. NE
Zone 4: S. IL, TN

Production under ideal environments can also favor narrow rows. Under ideal conditions, soil is generally moist and narrow rows result in more equidistant plant spacing, increased leaf area and early-season interception of solar radiation, and increased soil shading, which results in reduced evaporative water loss. Transpiration may increase due to more leaf area being exposed to radiation; however, better plant distribution maximizes photosynthesis and offsets transpirational water loss. This contrasts with high stress environments. With a dry soil surface, evaporative water loss is low to begin with; thus, narrow rows do not reduce soil surface evaporation but rather increase water loss by transpiration. This transpiration increase negates any benefits from improved spacing. Due to this, wide rows and skip rows are often used in stressful environments (Hoeft et al., 2000; Lyon et al., 2009).

Interactions between row spacing and plant population have been observed previously, but results were inconsistent. The presence of an interaction often indicates the effect of narrow rows is greater with high plant population. Due to improved plant spacing, increased solar radiation interception and ease of water and nutrient uptake, plant population is often increased in narrow-row production. An experiment performed in Canada (Fulton, 1970), with adequate soil water, reported a yield increase with a plant population of 54,362 plants ha^{-1} over a population of 39,536 plants ha^{-1} and that 50 cm rows yielded more than 100 cm rows. A significant plant population X row spacing interaction was observed in only one of four years. Similarly, Porter et al. (1997) reported a plant population X row spacing interaction at one of three locations in a three year study in Minnesota. The lack of consistent plant population X row spacing interactions indicates that row spacing results do not differ between low and high plant population.

Theoretically, equidistant spacing of maize will maximize yield (Aldrich et al., 1976; Elmore and Abendroth, 2007) due to maximum interception of solar radiation. However, it is difficult to achieve mechanically and impractical to manage due to subsequent cultivation, fertilizer application, and harvest procedures (Karlen et al., 1987). For equidistant plant spacing to occur at 74,100 plants ha^{-1}, a row spacing of 23.4 cm is necessary, which is too narrow for most management practices currently performed. If a higher plant population is desired, the row spacing must narrow even more to maintain equidistant distribution. Broadcast seeding of maize has been tried previously in the U.S. Corn Belt as a way to achieve equidistant spacing but was unsuccessful, resulting in reduced yield when compared to 102 cm conventional row spacing (Mock and Heghin, 1976).

Fig. 1.1. Twin-row planting configuration.

An alternative row configuration that has shown improved maize grain yield is twin-row production (Karlen et al., 1987). Twin rows (Fig. 1.1) split the plant population of one single row into two staggered rows 20 cm apart (Great Plains, 2011). As a result, plant distribution is more equidistant than with conventional 76 cm row spacing. Twin-row production is emerging as an option to attain the benefits of narrow rows while reducing the financial drawbacks (Elmore and Abendroth, 2007; Karlen et al., 1987). Changes in planting, cultivation, and harvest equipment are necessary in order to reduce row spacing (Karlen and Camp, 1985). The costs associated with these changes continue to remain a major barrier to reducing row spacing. With twin-row production, no modifications to the maize combine head or tractor tire width are necessary (Gozubenli et al., 2004) although planting and cultivation changes are still necessary.

Improved plant distribution reduces intra-row competition for solar radiation, water, and nutrients (Karlen et al., 1987; Camp et al., 1985). Incident solar radiation is a finite resource and reducing the row spacing can be done to increase solar radiation interception and utilization (Colville, 1978; Duncan, 1972; Hoff and Mederski, 1960; Yao and Shaw, 1964). The field growing area is also effectively increased, which results in improved root growth (Great Plains, 2011). Root growth is determined by plant spacing, as roots stop growing once another root is encountered. Twin-row production promotes root growth, and, as a result, improves water and nutrient uptake. Reduced intra-row competition is the basis for possible improved growth development and yield capability (Karlen et al., 1987).

Limited twin-row research has been conducted, and with variable row spacing having been used, results are inconclusive. A summary of current published results is presented in Table 1.2. Although inconclusive, previous research suggests that twin rows provide a greater yield advantage when using wider row spacings (96 cm) as opposed to today's standard row spacing of 76 cm. A yield benefit from twin-row production is also more likely to occur when planted with high plant population. Karlen et al. (1987) also reported a hybrid X row configuration interaction, indicating that early-maturity maize hybrids showed the greatest yield advantage for twin-row production. However, Farnham (2001) found that late-maturity hybrids tended to perform better than early-maturity hybrids in narrow rows; thus, selecting hybrids best suited to twin-row production is more complex than just considering maturity classification and the associated plant size.

Table 1.2. Summary of published twin-row research results.†

Location	Year	Irrigation	Row Spacing (cm)	Plant Population (plants ha^{-1})	Yield Advantage (%)	Source
South Carolina	1980-1982	Rainfed/ Irrigated	96/30‡	70000 & 101000	6	Camp et al., 1985
Mississippi	2000-2002	Rainfed	96/24	69100	-	Buehring et al., 2003
Turkey	2000-2001	Irrigated	80/20	60000 - 135000	4	Gozubenli et al., 2004
Canada	1995	Rainfed	76/20	65000 & 130000	9	Begna et al., 1997
South Carolina	1984	Irrigated	76/19	86000	3	Karlen et al., 1987
Iowa	2003-2005	Rainfed	76/19	71600	-	Elmore and Abendroth, 2007; McGrath et al., 2005
South Carolina	1985-1986	Rainfed/ Irrigated	76/19	52000	-9	Karlen and Kasperbauer, 1989
Missouri	2002-2003	Rainfed	76/19	69000	-8.5	Nelson, 2007
Illinois	1982-1983	Irrigated	76/13	80500 & 99000	-	Ottman and Welch, 1989

†Rows arranged by row spacing.
‡Single rows spaced 96 cm apart and twin rows spaced 30 cm apart on 96 cm centers.

The possible yield benefit of twin-row production should theoretically be attributed to improved plant distribution, leading to improved interception of solar radiation, and reduced intra-row competition (Camp et al., 1985). Row configuration influences total radiation intercepted by the crop as well as the distribution of solar radiation within the canopy (Ottman and Welch, 1989). A more uniform distribution of solar radiation within a crop canopy prevents the upper leaves from being radiation saturated and the lower leaves from being radiation starved. The lower leaves are the main source of carbohydrates for the roots, and readily available carbohydrates are necessary for nutrient uptake (Palmer et al., 1973; Fairy and Daynard, 1978). This redistribution of solar radiation can also be beneficial as the plant leaf is more efficient at lower irradiance levels (Loomis and Williams, 1969).

Row configuration did not influence interception of solar radiation in Missouri in 2002 and 2003, and yield was similar or less for twin-row production (Nelson, 2007). Similarly, Ottman and Welch (1989) found no difference in interception of solar radiation between twin and single rows and no yield difference. A hybrid X row configuration interaction occurred in one of two years, suggesting that a difference in interception of solar radiation was greatest with hybrids characterized by upright leaf habits. Karlen et al. (1987) reported that greater than 98% of photosynthetically active radiation (PAR) was intercepted with a plant population of 86000 plants ha^{-1} regardless of row configuration, even though leaf area was greater for twin-row plants than for single-row plants. Conversely, Karlen and Kasperbauer (1989) found no difference in total leaf area between twin rows and single rows at V6 and flower initiation at a population of 52000 plants ha^{-1}. LAI at R2 was 3.5, which was adequate to intercept 98% of PAR and maximize photosynthesis ha^{-1}, as shown by previous research (Karlen et al, 1987; Karlen and Camp, 1985). In this study, single rows yielded 9% more than twin rows (Karlen and Kasperbauer, 1989).

Elmore and Abendroth (2007) stated that if 95% of solar radiation is intercepted at flowering, regardless of row spacing, a row configuration change would not increase yield. Additionally, Gifford and Jenkins (1982) suggest that a row configuration change and the accompanying altercation in canopy architecture does not influence productivity due to maize's relatively linear PAR response curve up to full sun. The limited amount of difference in interception of solar radiation between twin- and single-row plants may also be attributed to the maize plants' ability to reorient its leaves. A study in Argentina showed that maize plants of some hybrids can reorient their leaves based on red-far red light ratios during early vegetative growth in response to neighbor plants (Maddonni et al., 2002). In an unpublished study from Illinois in 2004, twin rows had greater interception of solar radiation at V10; however, grain yield was more closely associated with interception of solar radiation at R2 (Nafziger, 2006). Increased interception of solar radiation during early growth may increase plant size; however, the plant is not able to store photosynthate for use during pollination and grain fill, which may be why increased early-season interception of solar radiation does not translate into increased yield for twin-row production.

Lodging is influenced by the plant properties of plant and ear height and stalk diameter. Karlen and Kasperbauer (1989) reported that at growth stage V6, row configuration had no effect on stalk length. Similarly, plant height measured during reproductive growth stages was unaffected by row configuration (Karlen et al, 1987; Gozubenli et al., 2004). Stalk diameter was 0.6 mm greater and stalk weight was 75 g greater for plants grown under twin-row production in 1984 (Karlen et al, 1987). Karlen and Kasperbauer (1989) also reported that stalk weight was greater under twin-row production. Similarly, Gozubenli et al. (2004) found that stalk diameter was 0.4 mm greater in twin-row plants. Even though twin-row production results in increased stalk strength, plant height was not affected, and as a result, there was no difference in the number of lodged plants between twin- and single-row production (Karlen and Camp, 1985).

Few studies have determined the effect of row spacing on maize grain yield components, even though decreasing row spacing often increases yield. Karlen and Camp (1985) reported that twin-row production increased grain yield by 0.52 to 0.76 Mg ha^{-1}, but in two out of three years, no difference in yield components was found. In the other year, twin-row maize produced slightly more ears m^{-2} but was compensated for by production of fewer kernels ear^{-1}. Begna et al. (1997) found similar kernel rows ear^{-1} and kernel number ear^{-1} for twin- and single-row maize production. Gozubenli et al. (2004) found that twin rows had a higher grain weight ear^{-1} even though ear length and ear diameter were not affected by row configuration, leading to a 4% twin-row yield advantage. Karlen et al. (1987) results supported the increased grain weight ear^{-1}

findings of Gozubenli et al. (2004), stating the average number of rows ear^{-1} was greater for twin-row plants, causing a 3% twin-row yield benefit, which indicated a more favorable early-season growth environment as a result of improved plant distribution and reduced intra-row plant competition. Contrary to previous work, Karlen and Kasperbauer (1989) stated that reduced yield found under twin-row production was caused by a lower number of kernels row^{-1} for the twin-row treatment.

Narrow-row maize has been shown to reduce weed biomoass when compared to wide-row production (Begna et al., 2001; Tharp and Kells, 2001) or to have no effect (Dalley et al., 2004; Esbenshade et al., 2001; Johnson and Hoverstad, 2002; Johnson et al., 1998; Teasdale, 1998). Twin-row production may offer a weed control advantage over single-row production due to improved plant distribution. Nelson (2007) found no difference in weed biomass and population density, when averaged over application timings, between twin- and single-row maize production. Nelson also determined that weed control obtained from various post planting (POST) applications of glyphosate was not affected by row configuration. However, since twin rows may intercept more early-season solar radiation, a single POST herbicide application may adequately control weeds if used with an integrated weed management plan (Johnson et al., 1998; Teasdale, 1995).

Objectives

The objectives of this research were (1) to compare twin-row production and single-row production for optimal plant population, interception of solar radiation, plant and ear height, stalk diameter, lodging potential, and grain yield and components of maize; (2) determine the optimal plant population for grain yield and lodging potential of modern maize hybrids for both irrigated and rainfed conditions in East-Central Nebraska.

Testable Hypotheses

- Twin-row production increases maize grain yield, leaf area index during reproductive growth, early-season interception of solar radiation, and stalk diameter, and decreases plant and ear height and lodging. Grain yield increases quadratically as plant population increases, and optimal plant population is greater for irrigated conditions than rainfed.
- Later maturing maize hybrids and hybrids with ECB and CRW resistance would yield more grain than earlier maturing hybrids, and hybrids without ECB and CRW resistance. Stalk lodging would be less for hybrids with ECB and CRW resistance.
- Row configuration responses interact with plant population and hybrid selection. The increase of grain yield and lodging potential associated with narrowing row spacing in twin-row systems is greater at high plant population and with late-maturity hybrids.

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CHAPTER 2

ROW CONFIGURATION, PLANT POPULATION, AND HYBRID INFLUENCE ON MAIZE YIELD AND LODGING

MATERIALS AND METHODS

Environment

A two-year center pivot irrigated experiment was conducted at the University of Nebraska Agricultural Research and Development Center near Mead, NE (41°9' N, 96°27' W) in 2009 and 2010. The soil type on the experimental area was Filbert silt loam (fine, smectitic, mesic Vertic Argialboll) with 0 to 1% slopes (USDA-NRCS, 2011). The previous crop was soybean (*Glycine Max* (L.) Merrill) in both years.

Experimental Design

A randomized complete block designed experiment with split-split plot treatment arrangement and three replications was used. Main plots were three glyphosate-resistant maize hybrids resistant to both European corn borer (ECB) and corn rootworm (CRW): DKC 57-66 (107-day relative maturity), DKC 61-19 (111-day relative maturity), and DKC 62-54 (112-day relative maturity). Split plots were four target plant populations of 69136, 81481, 93827, and 106173 plants ha^{-1}. Seeding rates were 5% above the target population in an attempt to compensate for non-viable seeds and other causes of incomplete emergence. Split-split plots were row configurations of conventional 76 cm row spacing and twin rows on 76 cm centers (Fig. 1.1). Plots consisted of four single or twin rows (3.0 m wide) by 30.5 m long.

Production

Soil nutrient levels and pH were generally above sufficiency levels (Table 2.1). Soil nutrient applications were made based upon University of Nebraska recommendations for an expected maize grain yield of 15.7 Mg ha^{-1} (Shapiro et al., 2008). In each site year, 224 kg N ha^{-1} as 82% anhydrous ammonia was injected 17 cm deep on 27 Mar 2009 and 14 April 2010, with a 13 knife DMI Nutri-Placr Model 4300 anhydrous ammonia applicator (DMI, Inc., Rt. 150E, PO Box 65, Goodfield, IL 61742-0065). On 22 April 2010, 68 kg P_2O_5 ha^{-1} was surface broadcast with a Gandy Model 10T drop spreader (Gandy Company, 528 Gandrud Road, Owatonna, MN 55060-0528) as 46% dry phosphate. Field cultivation with a John Deere 1010 field cultivator to a depth of 7 cm was used on 4 May 2010, to incorporate phosphate fertilizer.

Table 2.1. Soil nutrient and pH levels, 2009 and 2010 twin-row maize study, Mead, NE.

	Sample	Soil	Organic	FIA	Mehlich-3	Ammonium Acetate			
Year	Date	pH	Matter	Nitrate	P	K	Ca	Mg	Na
			%	----------	----------	----------	ppm	----------	----------
2009†	6/29/09†	5.4	3.5	27.2	5	243	1803	292	33
2010	4/1/10	5.4	3.5	4.4	6	340	1731	292	36

† Sampling occurred after the spring fertilizer application.

Maize was planted 5 cm deep on 6 May 2009, with a mechanical maize finger pickup unit planter and 4 May 2010, with a vacuum planter. Both planters were manufactured by Great Plains Manufacturing, Inc. (Great Plains Manufacturing, Inc., 1525 E. North Street, Salina, KS 67401) and were equipped with row cleaners and 20-wave coulters located in front of the seed disc openers. In 2009, no-till production was utilized by planting maize kernels into undisturbed soybean residue halfway between soybean rows from the previous year. Maize was planted into field cultivated soil in 2010.

Herbicide application was used to control weeds. On 22 April 2009, acetochlor [2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl) acetamide] (2.415 kg a.i. ha^{-1}) and atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino) s-triazine and related triazines] (0.955 kg a.i. ha^{-1}), and glyphosate [(N-(phosphonomethyl) glycine) in the form of its isopropylamine salt] (0.281 kg a.i. ha^{-1}) were surface applied with a John Deere 4710 self propelled sprayer (Deere & Company, One John Deere Place, Moline, IL 61265-8098). A second application of glyphosate [(N-(phosphonomethyl) glycine) in the form of its isopropylamine salt] (1.123 kg a.i. ha^{-1}) was made on 4 June 2009. In 2010, acetochlor [2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl) acetamide] (2.654 kg a.i. ha^{-1}) and atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine and related triazines] (1.319 kg a.i. ha^{-1}), and glyphosate [(N-(phosphonomethyl) glycine) in the form of its isopropylamine salt] (0.281 kg a.i. ha^{-1}) were surface broadcast on 18 May. Glyphosate [(N-(phosphonomethyl) glycine) in the form of its isopropylamine salt] (1.123 kg a.i. ha^{-1}) was applied on 16 June 2010.

The year 2009 had normal seasonal rainfall, and 2010 had above normal seasonal rainfall that was relatively uniformly distributed; thus, only one or two irrigations were all that was needed in both years, based on soil water levels in the rooting zone (Melvin and Yonts, 2009). In 2009, 37 mm irrigation water was applied on

10 and 29 July using a center pivot system. In 2010, a single irrigation application of 37 mm was made on 9 Aug.

Parameter Measurements

Early-season stand counts were taken from 5.3 m sections of the middle two rows of each plot on 4 June 2009 (GS = V3) and 1 June 2010 (GS = V3). Plant spacing uniformity measurements were also taken to determine planter accuracy on 10-11 June 2009 (GS = V4) and 1 June 2010 (GS = V3). Distance between plants was measured for 5.3 m from one of the middle two rows in two replications. In twin rows, distance was measured vertically and diagonally between plants.

Canopy solar radiation interception was measured using a Licor LI-191 Line Quantum Sensor and recorded with a Licor LI-1000 datalogger at two locations per plot, by measuring diagonally between the middle two rows at the soil surface. Full sun solar radiation was also measured adjacent to the field, and these values were compared to plot values with the same time stamp, and percent interception of solar radiation by the crop canopy was determined. Calibration of sensors occurred by comparing light interception values measured for three continuous hours under full sun conditions and an adjustment factor was determined. Measurements were taken between two hours before and after solar noon at Mead, NE, on only sunny days, preventing cloud cover from influencing results. Canopy interception of solar radiation was measured on 25 June 2009 (GS = V9), 6 July 2009 (GS = V14), 9 June 2010 (GS = V5), 25 June 2010 (GS = V9), and 1 July 2010 (GS = V12). In 2010, measurements were also taken from center-to-center of rows, and canopy solar radiation interception values were similar (Appendix A).

Plant height was measured using a measuring stick to the plant whorl on 7-8 July 2009 (GS = V14), and 29 June 2010 (GS = V11). Plant height was measured again on 12-13 Aug 2009 (GS = R2), and 4 Aug 2010 (GS = R4) to the uppermost leaf collar. At this time, ear height was also measured to the node of the primary ear. These measurements were taken on 15 consecutive plants in each of the middle two rows. Stalk diameter was measured using a caliper from 20 consecutive plants in one of the middle two rows in the center of the internode at the widest part of the stalk corresponding with a position 15 cm above the soil surface.

Leaf area index was estimated based upon principles in Elings (2000) and Boomsma et al. (2009). First, destructive leaf area was measured from four consecutive plants from the single-row plots in two replications with the desired plant spacing based on the plant population on 3-4 Aug 2009 (GS = R2) and 28-29 July 2010 (GS = R3). This was used to determine the largest leaf with respect to the hybrid. The length and width of the largest leaf based on the hybrid was then measured with a measuring stick on 15 consecutive plants from one of the middle two rows on 6 Aug 2009 (GS = R2) and on 3 Aug 2010 (GS =R4). Estimating leaf area index occurred by first performing a linear regression of the leaf area of the largest leaf against the total leaf area of the plant by year, resulting in two regression equations. Then individual leaf area for the 15 plants measured in the field was estimated by multiplying leaf length X leaf width X 0.75

(Montgomery, 1911). This value was then inputted into the earlier equation by year, and resulted in an estimate for total plant leaf area. Leaf area index was then determined by dividing the total plant leaf area by the soil surface area occupied by each plant.

Final plant population, number of ears, and stalk and root lodging data were collected from 4.6 m of the middle two rows of each plot on 10-11 Nov 2009 and 13-15 Oct 2010. Maize grain yield was determined by harvesting the entire length of the middle two rows from each plot with a John Deere 3300 combine on 19-20 Nov 2009. A weigh bucket located inside the grain tank equipped with Avery Weigh-Tronix weigh bars (Avery Weigh-Tronix, 1000 Armstrong Drive, Fairmont, MN 56031-1439) and a Model 640 indicator was used to determine grain mass. Grain water content was measured for each plot using a Burrows Digital Moisture Computer 700 (Seedburo Equipment Company, 2293 S MT Prospect Road, Des Plaines, IL 60018) immediately after harvest occurred and grain mass was adjusted to a constant water concentration of 155 g kg^{-1}. In 2010, 4.6 m of the center two rows of all plots were hand harvested on 13, 15 Oct. After physiological maturity, a hail storm caused lodging and dropped ears, making machine harvesting impossible. Whole ears were hand harvested and stored in burlap sacks in metal drums, and then were shelled using an Almaco Single Ear Corn Sheller Model MCS (Almaco, 99M Avenue, Nevada, Iowa 50201-1558), cleaned with an Almaco Air Blast Seed Cleaner, and weighed with an Ohaus Champ SQ series scale (Ohaus Corporation, 7 Campus Drive, Suite 310, Parsippany, NJ 07054 USA) equipped with a CD-11 indicator on 5 Nov. Immediately after harvest, a Burrows Digital Moisture

Computer 700 (Seedburo Equipment Company, 2293 S MT Prospect Road, Des Plaines, IL 60018) was used to determine grain water content and grain mass was corrected to a155 g kg^{-1} water concentration.

Grain samples were retained from all plots. Test weight was then determined using a DICKEY-john GAC 2100 (Dickey-john Corporation, 5200 DICKEY-john Road, Auburn, IL 62615). Kernel weight was measured by counting 100 kernels and massing them with an Ohaus Scout Pro scale and adjusted to a constant water concentration of 155 g kg^{-1} as done for grain yield.

Statistical Analysis

Data were analyzed using the PROC MIXED procedure (Littell et al., 1996) of SAS (SAS Institute, 2008) and an analysis of variance table was determined. Regression for the continuous variable plant population, both main and interaction effects, was performed. Both linear and quadratic effects of plant population were initially included in the ANOVA; however, in nearly all analyses, the quadratic effect was not significant; thus, all data were analyzed for the linear effect. Year, hybrid, target population, and row configuration effects, and their interactions were considered fixed effects. Replication and all interactions with replication were considered random.

Regression equations were developed using PROC Mixed model Type 1 in SAS to describe the responses of dependent variables to target population when interactions with target population were significant at $P \leq 0.05$, and data were presented graphically. The linear regression model is presented below:

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X$$

where $\hat{Y}$ is the predicted response variable and X is target population (plants ha^{-1}), while $\hat{\beta}_0$ (intercept) and $\hat{\beta}_1$ (linear coefficient) are constants that were obtained when the model was fit to the data. Mean separation of discrete variables was performed using paired-wise comparisons at $P \leq 0.05$. Pearson correlations were calculated to identify interrelationships among measured parameters.

RESULTS AND DISCUSSION

Seasonal Climatic Conditions

Seasonal average rainfall and air temperatures were lower in 2009 than in 2010 (Table 2.2; Table 2.3). In 2009, seasonal rainfall was approximately equal to the 52-yr average while in 2010 seasonal rainfall was much higher than the average (Table 2.2). In both years, rainfall was above average during the month of June, and in August 2009, and in July 2010. In 2010, rain storms in late May and the 222 mm June rainfall total led to some water logging problems in low, poorly drained parts of the experimental field. The amount of rainfall and its distribution was conducive to production of high maize yield in both years.

Table 2.2. Seasonal rainfall in 2009 and 2010, Mead, NE.

Month	Rainfall		
	2009	2010	1968 – 2010 Average
	-------------------- mm --------------------		
April	31	91	72
May	41	63	106
June	139	222	103
July	71	174	80
Aug	155	97	91
Sept	48	107	73
Oct	94	6	59
Total April – Oct	579	760	584
Total May – Sept	454	663	453

Monthly average air temperatures were above the 52-yr average in 2010, and below the 52-yr average in 2009 during the months of April, June, July, Aug, Sept, and Oct (Table 2.3). The Oct

Table 2.3. Air temperature in 2009 and 2010, Mead, NE.

Month	Air Temperature		
	2009	2010	1968 – 2010 Average
	-------------------- °C --------------------		
April	9.3	13.2	10.3
May	17.2	15.8	16.3
June	21.6	22.9	22.0
July	21.3	24.7	24.4
Aug	21.2	24.7	23.0
Sept	17.6	18.4	18.2
Oct	7.4	12.8	11.2
Average April – Oct	16.5	18.9	17.9
Average May – Sept	19.8	21.3	20.8

2009 average temperature was more than 5 °C less than in 2010. The cool temperatures in 2009 delayed physiological maturity and in-field drying of grain, and likely contributed to increased grain yield due to an extended grain fill period when abundant solar radiation was present (Egli, 2011; Gambín et al., 2006; Peters et al., 1971; Wilson et al., 1995).

Climatic conditions in 2009 and 2010 (Table 2.2; Table 2.3) combined with productive, high water holding capacity soils (USDA-NRCS, 2011) resulted in high maize yield in both years (Fig. 2.1). The relatively high rainfall in June, July and Aug combined with below to normal air temperatures minimized the need for irrigation; therefore, 37 mm of irrigation water was applied twice in 2009 and once in 2010.

Target populations were 69136, 81481, 93827, and 106173 plants ha^{-1}. Seeding rates were 5% above the target population in an attempt to compensate for non-viable seeds and other causes of incomplete emergence. Emergence differences and plant death in season resulted in a variation of harvest population (Table 2.4). Harvest population was lower in 2010 than in 2009, likely due to greater rainfall in April (Table 2.2) which increased soil water content and lowered air (Table 2.3) and soil temperature, and caused a reduction in germination and emergence.

Table 2.4. Year, target population, and row configuration influence on harvest population.

Target	2009		2010	
Population	Single	Twin	Single	Twin
	---------- plants ha^{-1} ----------			
69136	74623	70919	70588	71385
81481	84911	85322	81423	79671
93827	93278	92318	88753	82539
106173	111660	104938	100226	99270

Average distance between plants decreased as the target population increased (Table 2.5). Plant spacing was greater for twin-row production than single-row production at the same target population. Increased plant spacing is often cited (Camp et al., 1985; Great Plains, 2011; Monsanto, 2009; Elmore and Abendroth, 2007) as one of the advantages of twin-row production leading to increased leaf area and early-season interception of solar radiation and improved root system distribution (AgriGold, 2010; Great Plains, 2011).

Table 2.5. Year, target population, and row configuration influence on plant spacing.

Target Population	2009		2010	
	Single	Twin	Single	Twin
	---------- cm ----------			
69136	17.5	32.0	18.5	32.1
81481	15.1	28.4	16.5	29.3
93827	13.6	26.0	14.5	27.9
106173	11.4	23.6	13.8	25.5

Yield and Yield Components

Grain yield was influenced by the interaction of year X hybrid X target population X row configuration, as well as the year main effect (Table 2.6). Increasing plant population increased maize yield linearly (Table 2.8; Fig. 2.1) in contrast to the expected quadratic response. However, parameter estimates for $\hat{\beta}_1$ were nearly zero, indicating that the target population had only a small effect on maize grain yield. The highest population of 106173 plants ha^{-1} resulted in the greatest grain yield in 9 of 12 year, hybrid, and row configuration combinations while in others the yield declined slightly with increasing target population. Treatments with high y intercepts ($\hat{\beta}_0$) and relatively high yield at a low target population tended to have negative slopes ($\hat{\beta}_1$). These treatments involved hybrids DKC 57-66 and DKC 61-19, with differences between row configurations and years. The hybrid DKC 62-54 was characterized by increased grain yield with increasing target population in both years and row configurations. Row configurations resulted in similar yield in 2009 and twin rows produced approximately 0.8 Mg ha^{-1} greater yield than single rows across the target population range in 2010 (Fig. 2.1C). Begna et al. (1997) found a similar grain yield response for maize at 65000 plants ha^{-1} and one year out-of-two at 130000 plants ha^{-1}. The grain yield of the other two hybrids varied unexpectedly across years, target population, and row configuration (Fig. 2.1A; Fig. 2.1B). Previous research with Bt maize hybrids in Wisconsin (Stanger and Lauer, 2006) and Illinois/Iowa (Coulter et al., 2010) found that increasing plant population increased maize grain yield quadratically with an economic optimal plant population of 79,800 to 83,800 plants ha^{-1}, in contrast to this study's unexpected results of a very small linear response. Previous twin-row research has reported grain yield increases (Camp et al., 1985; Karlen et al., 1987; Gozubenli et al., 2004) or decreases (Karlen and Kasperbauer, 1989; Nelson, 2007) in contrast to the inconsistent response found in this study and by Begna et al. (1997).

Table 2.6. Analysis of variance for the effects of year, hybrid, target population, row configuration, and all interactions on maize grain yield.

Source	DF	Yield
Year	1	0.02
Hybrid	2	NS
Year*Hybrid	2	NS
Pop†	1	NS
Year*Pop	1	NS
Hybrid*Pop	2	NS
Year*Hybrid*Pop	2	NS
Row‡	1	NS
Year*Row	1	NS
Hybrid*Row	2	NS
Year*Hybrid*Row	2	NS
Pop*Row	1	NS
Year*Pop*Row	1	NS
Hybrid*Pop*Row	2	NS
Year*Hybrid*Pop*Row	2	< 0.01

† Pop = Target Population

‡ Row = Row Configuration

Table 2.7. Analysis of variance for the effects of year, hybrid, target population, row configuration, and all interactions on maize ears m^{-2}, ears $plant^{-1}$, kernel weight, and test weight.

Source	DF	Ears m^{-2}	Ears $plant^{-1}$	Kernel Weight	Test Weight
Year	1	NS	NS	< 0.01	0.03
Hybrid	2	0.03	NS	< 0.01	0.04
Year*Hybrid	2	NS	NS	NS	NS
Pop†	1	< 0.01	NS	< 0.01	NS
Year*Pop	1	0.04	NS	NS	0.03
Hybrid*Pop	2	NS	NS	NS	NS
Year*Hybrid*Pop	2	NS	NS	NS	NS
Row‡	1	0.01	NS	< 0.01	NS
Year*Row	1	NS	NS	0.02	NS
Hybrid*Row	2	NS	NS	NS	NS
Year*Hybrid*Row	2	NS	NS	NS	NS
Pop*Row	1	NS	NS	NS	NS
Year*Pop*Row	1	NS	NS	NS	NS
Hybrid*Pop*Row	2	NS	NS	0.01	NS
Year*Hybrid*Pop*Row	2	NS	NS	NS	NS

† Pop = Target Population

‡ Row = Row Configuration

Table 2.8. Parameter estimates from regression models relating target population to maize grain yield by year, hybrid, and row configuration, and yield increase 1000 $plants^{-1}$ (n = 12).

Row Configuration	Hybrid	Year	Parameter Estimates $\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡	Yield Increase
			---------- Mg ha^{-1}	----------	Mg ha^{-1} x 1000 $plants^{-1}$
Single	DKC 57-66	2009	11.4293	0.000033	0.0330
Single	DKC 57-66	2010	13.3093	0.00000189	0.0019
Single	DKC 61-19	2009	15.8827	-0.00000351	-0.0035
Single	DKC 61-19	2010	7.7807	0.000060	0.0600
Single	DKC 62-54	2009	12.8094	0.000029	0.0290
Single	DKC 62-54	2010	12.4467	0.000016	0.0160
Twin	DKC 57-66	2009	15.6740	-0.00002	-0.0200
Twin	DKC 57-66	2010	11.9413	0.000022	0.0220
Twin	DKC 61-19	2009	10.6754	0.000052	0.0520
Twin	DKC 61-19	2010	18.7673	-0.00006	-0.0600
Twin	DKC 62-54	2009	13.3620	0.000023	0.0230
Twin	DKC 62-54	2010	13.0533	0.000018	0.0180

† Standard error for $\hat{\boldsymbol{\beta}}_0$ is 2.2959.

‡ Standard error for $\hat{\boldsymbol{\beta}}_1$ is 0.000026.

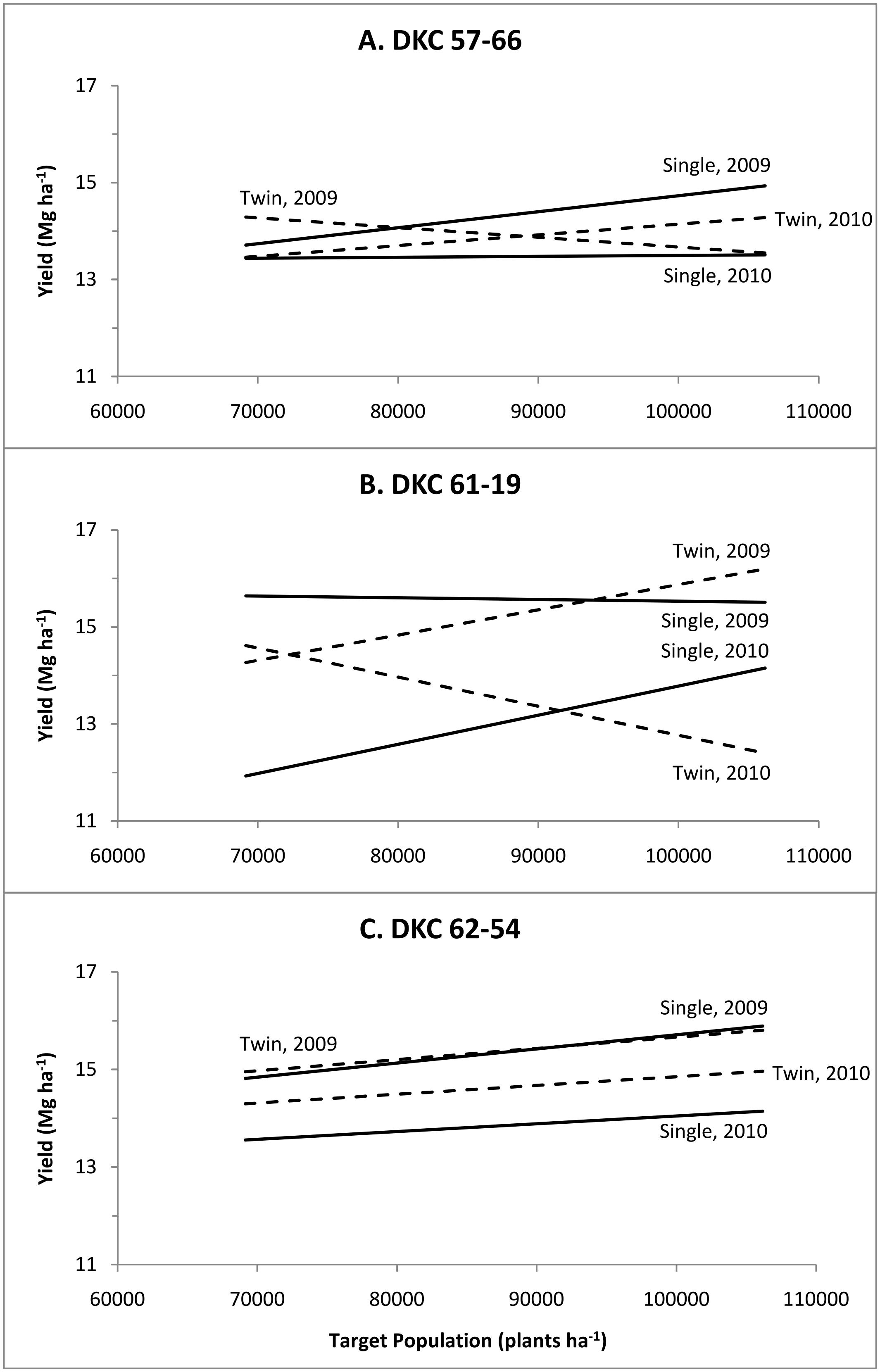

Fig. 2.1. Year, hybrid, target population, and row configuration influence on maize grain yield.

The number of ears m^{-2} was influenced by the main effects of hybrid, target population, and row configuration and the interaction of year X target population (Table 2.7). The number of ears m^{-2} increased linearly as target population increased (Table 2.9; Fig. 2.2), as was also true for grain yield (Table 2.8; Fig. 2.1) as previously reported by Maddonni and Otegui (2004) and Ordas and Stucker (1977). However, the number of ears m^{-2} was greater in 2009 than in 2010 across the target population range and increased with increasing target population at a steeper rate than in 2010 (Fig. 2.2). Cooler temperatures in 2009 (Table 2.3) throughout the growing season likely reduced plant stress and contributed to production of a greater number of ears m^{-2}. The number of ears m^{-2} produced in single rows was 8.6 while twin-row maize produced 8.3 ears m^{-2} in contrast to the results of Karlen and Camp (1985) that row configuration had no effect on the number of ears produced. DKC 57-66 and 62-54 produced 8.5 and 8.6 ears m^{-2} which was greater than DKC 61-19 which produced 8.2 ears m^{-2}.

Table 2.9. Parameter estimates from regression models relating target population to the number of maize ears m^{-2} by year (n = 72).

	Parameter Estimates	
Year	$\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡
	---------- no. ----------	
2009	1.2082	0.000085
2010	2.2981	0.000068

† Standard error for $\hat{\boldsymbol{\beta}}_0$ is 0.5191.

‡ Standard error for $\hat{\boldsymbol{\beta}}_1$ is 0.00000578.

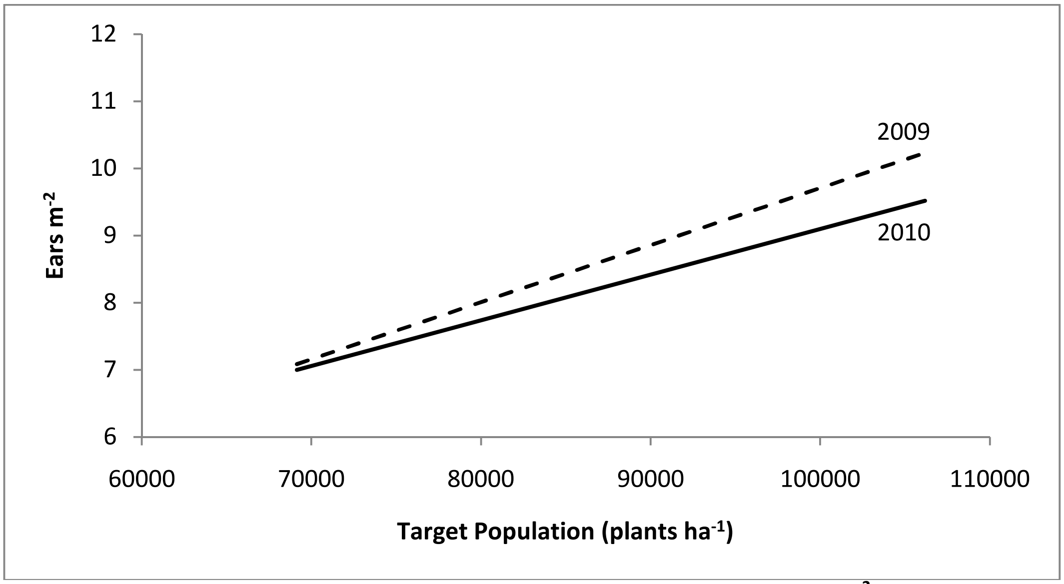

Fig. 2.2. Year and target population influence on the number of maize ears m^{-2}.

Ears $plant^{-1}$ was not affected by any main or interaction effects (Table 2.7). Surprisingly, ears $plant^{-1}$ remained constant at 0.97 ears $plant^{-1}$ over the target population range, which suggests that barrenness did not increase as target population increased. This is in contrast with results of Maddonni and Otegui (2004; 2006), Westgate et al. (1997), and Ordas and Stucker (1977) who found that ears $plant^{-1}$ decreased as plant population increased.

The main effects of year, hybrid, target population, and row configuration, and the two-way interaction of year X row configuration, and the three-way interaction of hybrid X target population X row configuration influenced kernel weight (Table 2.7). Kernel weight was lighter for the earlier maturing hybrids DKC 57-66 and DKC 61-19 than for the latest maturing DKC 62-54 hybrid and decreased with increasing target population (Table 2.10; Fig. 2.3) similar to results reported by Maddonni and Otegui (2004; 2006) and Karlen and Camp (1985). Westgate et al. (1997) found that kernel weight was more stable to changes in plant population than was kernels ear^{-1} and number of ears plant^{-1}. Kernel weight differences can be explained by differences in kernel growth rates between hybrids due to genetic differences (Gambín et al., 2006) and hybrid maturity, with later maturing hybrids having greater grain fill periods (Hilliard and Daynard, 1974). Kernel weight did not differ for row configuration in 2009; however, in 2010, kernel weight was lower for single rows than twin rows (Table 2.11), which differs with the results of Karlen and Camp (1985), who found that row configuration had no effect on kernel weight. Kernel weight was greater in 2009 (Table 2.11), likely due to cooler temperatures (Table 2.3).

Table 2.10. Parameter estimates from regression models relating target population to maize 100-kernel weight by hybrid and row configuration (n = 24).

Row Configuration	Hybrid	Parameter Estimates $\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡
		----- g 100 kernels^{-1} -----	
Single	DKC 57-66	36.0905	-0.00006
Single	DKC 61-19	35.3721	-0.00006
Single	DKC 62-54	40.8497	-0.00004
Twin	DKC 57-66	33.0979	-0.00001
Twin	DKC 61-19	39.3370	-0.0001
Twin	DKC 62-54	43.7965	-0.00007

† Standard error for $\hat{\boldsymbol{\beta}}_0$ is 1.7220.
‡ Standard error for $\hat{\boldsymbol{\beta}}_1$ is 0.000017.

Table 2.11. Year and row configuration influence on maize 100-kernel weight (n = 72).

Year	Row Configuration: Single‡	Twin
	----- g 100 kernels^{-1} -----	
2009†	34.8Aa	35.0Aa
2010	30.8Bb	31.8Ba

† One lower case letter in common indicates no significant difference between values in rows.
‡ One capital letter in common indicates no significant difference between values in columns.

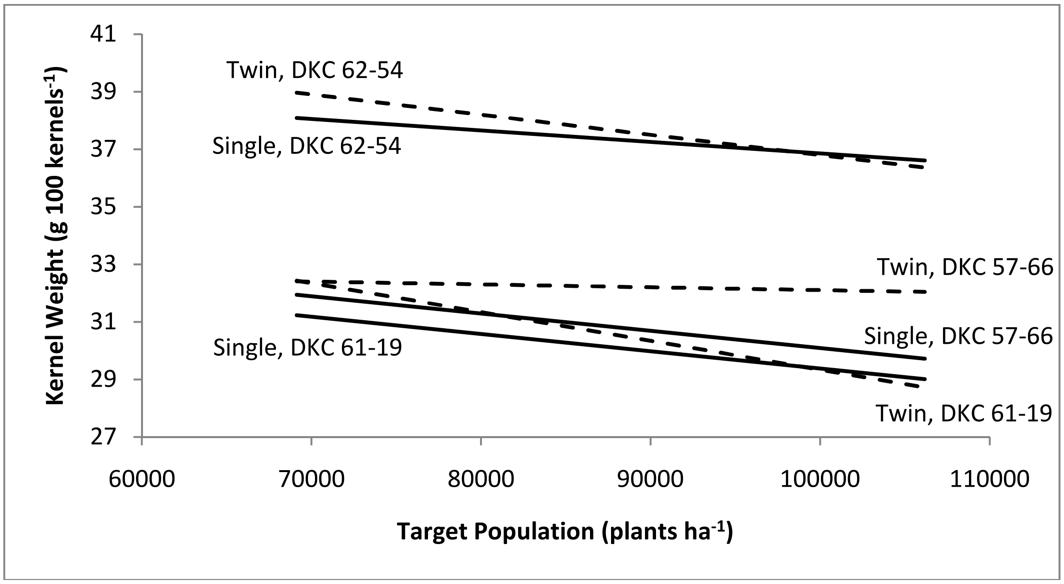

Fig. 2.3. Hybrid, target population, and row configuration influence on maize 100-kernel weight.

Test weight was affected by year and hybrid main effects and the interaction of year X target population (Table 2.7). Test weight was greater in 2010 than 2009 across the target population range (Table 2.12; Fig. 2.4). Heavier test weight was expected in 2009 due to cooler air temperatures, with high irradiance of photosynthetic active radiation, which increased the length of the grain fill period (Wilson et al., 1995; Peters et al., 1971). However, this result agreed with Maddonni et al. (1998) who found that low air temperatures when combined with reduced incident solar radiation resulted in lighter kernel weights due to reductions in photo-assimilate production and grain partitioning. In 2009, test weight appeared to increase slightly as target population increased; although, the slope was not different from zero (Table 2.12; Fig. 2.4). Test weight decreased in 2010. This is in

Table 2.12. Parameter estimates from regression models relating target population to maize test weight by year (n = 72).

	Parameter Estimates	
Year	$\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡
	---------- g L^{-1} ----------	
2009	753.38	0.000041
2010	788.39	-0.00022

† Standard error for $\hat{\boldsymbol{\beta}}_0$ is 7.5693.
‡ Standard error for $\hat{\boldsymbol{\beta}}_1$ is 0.000081.

contrast to work done by Widdicombe and Thelen (2002) that showed a test weight increase as population increased. DKC 62-54 produced a test weight of 766.85 g L^{-1}, which was greater than DKC 61-19, which produced a test weight of 759.76 g L^{-1}. DKC 57-66 produced a test weight of 762.34 g L^{-1} and was not different from DKC 61-19 or 62-54. High test weight is desired for grain to be used for dry mill or alkaline cooked food products (Johnson, 2005; Johnson et al., 2010).

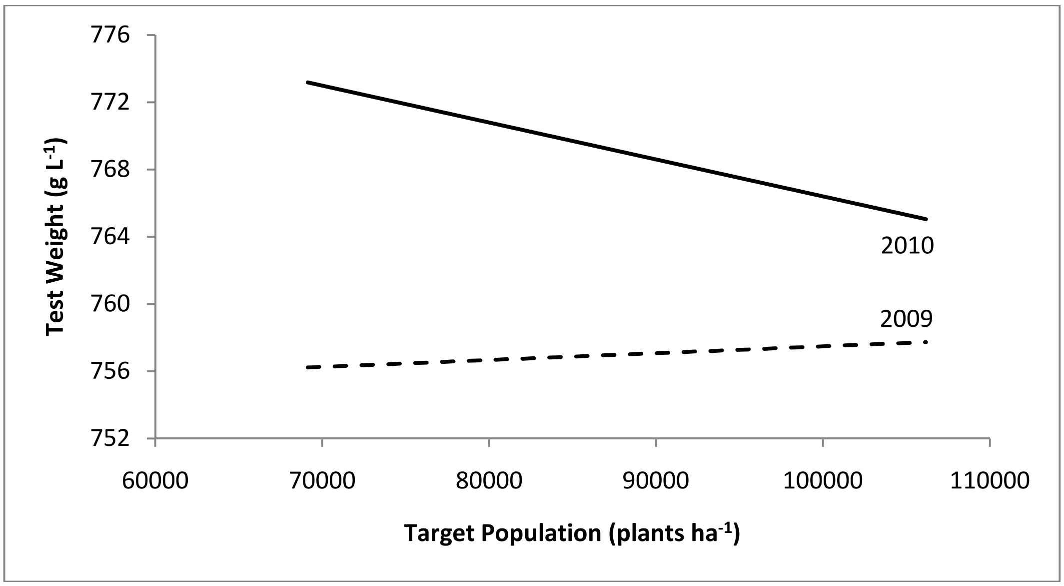

Fig. 2.4. Year and target population influence on maize test weight.

Pearson correlations indicated intermediate (i.e. r = 0.3 to 0.5) correlations between grain yield and the number of ears produced m^{-2} and kernel weight (Table 2.13) similar to results of Agrama (1996). The number of ears produced m^{-2} and kernel weight were not correlated in contrast to results of Agrama (1996) who found them negatively correlated. Previous studies have shown similar relationships between grain yield and yield components with higher correlations between grain yield and ears m^{-2}, kernels ear^{-1} and kernels $plant^{-1}$ when stress was present during vegetative growth

Table 2.13. Pearson correlations for maize yield and yield components, leaf area index and interception of solar radiation, and plant morphology and lodging.†

	Yield	Ears m^{-2}	Ears $plant^{-1}$	Kernel Weight	Test Weight	Leaf Area Index	LI‡ (V5)	LI (V9)	LI (V12-V14)	Plant Height (V11-V14)	Plant Height (R2-R4)	Ear Height (R2-R4)	Stalk Diameter
Ears m^{-2}	0.35**												
Ears $plant^{-1}$	0.05	0.09											
Kernel Weight	0.40**	-0.05	-0.04										
Test Weight	-0.06	-0.15	0.02	0.01									
Leaf Area Index	0.24**	0.84**	0.00	-0.09	0.07								
LI (V5)‡	0.09	0.42**	-0.19	-0.07	0.00	0.43**							
LI (V9)	-0.09	0.16	0.07	-0.39**	0.39**	0.38**	0.47**						
LI (V12-V14)	0.07	0.29**	0.01	-0.27**	0.11	0.39**	0.39**	0.38**					
Plant Height (V11-V14)	0.17*	0.10	0.01	-0.30**	0.06	0.16*	0.25*	0.35**	0.35**				
Plant Height (R2-R4)	0.21*	0.11	-0.04	-0.17*	-0.19*	0.01	0.25*	-0.05	0.04	0.36**			
Ear Height (R2-R4)	0.32**	0.21*	-0.26**	-0.05	-0.40**	-0.03	0.28*	-0.33**	0.05	0.39**	0.56**		
Stalk Diameter	-0.17*	-0.61**	0.21**	0.01	0.41**	-0.23**	-0.25*	0.29**	-0.04	0.13	-0.08	-0.44**	
Stalk Lodging	-0.24**	0.03	-0.07	-0.60**	0.13	0.22**	0.10	0.50**	0.17*	0.11	0.05	-0.16	0.14

† Growth stage indicated in parenthesis.
‡ LI = Interception of solar radiation.
* Significant at the P ≤ 0.05 level.
** Significant at the P ≤ 0.01 level.

(Kamara et al., 2003; Eck, 1986; Otegui and Bonhomme, 1998; Pandey et al., 2000), and higher correlations between grain yield and kernel weight when stress was present during grain fill (Eck, 1986; Maddonni et al., 1998). Due to the lack of obvious stress in this study, correlations between 0.35 and 0.40 for grain yield with ears m^{-2}, kernels ear^{-1}, and kernel weight were logical.

Leaf Area Index (LAI) and Interception of Solar Radiation

Leaf area indices at the R2 to R4 growth stage and canopy interception of solar radiation during vegetative growth were analyzed separately due to different measurement dates and growth stages across years. Hybrid and target population had the main influence on leaf area index (Table 2.14). However, row configuration affected leaf area index in 2009. Leaf area index was slightly greater in 2010 and increased with increasing target population in both 2009 and 2010 (Table 2.15; Fig. 2.5) similar to results of Karlen and Kasperbauer (1989) and Cox (1996). Single rows produced a LAI of 4.9 and twin rows produced a LAI of 4.6 in 2009 across the population range while in 2010, the average LAI across row configurations was 4.9. Karlen and Kasperbauer (1989) found no difference in LAI between twin- and single-row maize while Karlen et al. (1987) found greater leaf area index with twin rows. The hybrids DKC

Table 2.14. Analysis of variance for the effects of hybrid, target population, row configuration, and all interactions on maize leaf area index.

		Leaf Area Index	
Source	DF	2009 (R2)§	2010 (R4)
Hybrid	2	0.03	< 0.01
Pop†	1	< 0.01	< 0.01
Hybrid*Pop	2	NS	NS
Row‡	1	< 0.01	NS
Hybrid*Row	2	NS	NS
Pop*Row	1	NS	NS
Hybrid*Pop*Row	2	NS	NS

† Pop = Target Population
‡ Row = Row Configuration
§ Growth stage given in parenthesis.

57-66 and 62-54 both produced a LAI of 4.9 while DKC 61-19 produced a LAI of 4.5 in 2009. In 2010, DKC 62-54 produced the highest LAI of 5.2, DKC 57-66 produced a LAI of 4.9, and DKC 61-19 again produced the lowest LAI of 4.7. It was expected that the late-maturity hybrid, DKC 62-54, would produce the greatest LAI, and the early-maturity hybrid, DKC 57-66, would produce the lowest LAI; however, DKC 61-19 produced the lowest LAI in both years with no obvious explanation.

Table 2.15. Parameter estimates from regression models relating target population to maize leaf area index at the R2 to R4 growth stage in 2009 and 2010 (n = 72).

	Parameter Estimates	
Year	$\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡
2009	1.4608	0.000038
2010	1.8023	0.000036

† Standard error for $\hat{\boldsymbol{\beta}}_0$ is 0.3044 (2009) and 0.3469 (2010).
‡ Standard error for $\hat{\boldsymbol{\beta}}_1$ is 0.000003404 (2009) and 0.000003828 (2010).

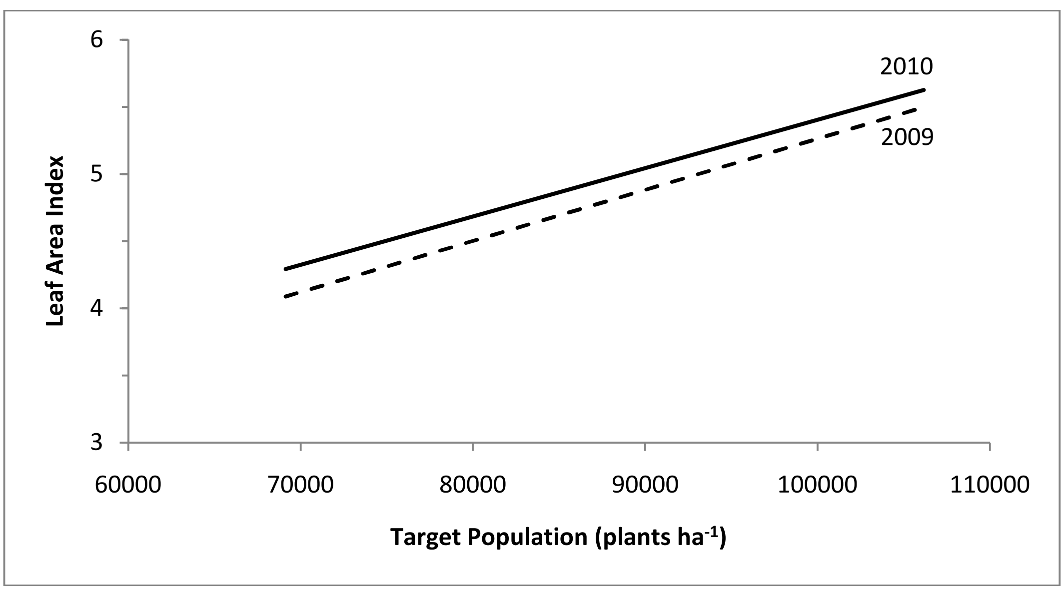

Fig. 2.5. Target population influence on maize leaf area index at the R2 to R4 growth stage in 2009 and 2010.

Analysis of variance indicated that target population had the major influence on interception of solar radiation at all vegetative growth stages measured in both years, and hybrid and row configuration had less influence (Table 2.16). As target population increased, the percent interception of solar radiation increased linearly by 0.1 to 0.24 percent per 1000 plant increase in target population (Table 2.17; Fig. 2.6). Interception of solar radiation increased at a greater rate in response to target population increases at the V5 and V9 growth stages than at the V12 to V14 growth stage. At the V12 to V14 growth stage, differences in interception of solar radiation were less. Interception of solar radiation during vegetative growth was slightly greater in 2010 than in 2009, likely due to greater LAI in 2010 (Table 2.15; Fig. 2.5). Increasing interception of solar radiation with increasing plant population is consistent with results of Tollenaar and Aguilera (1992) and Cox (1996).

Table 2.16. Analysis of variance for the effects of hybrid, target population, row configuration, and all interactions on maize interception of solar radiation.

Source	DF	2009 (V9)§	2009 (V14)	2010 (V5)	2010 (V9)	2010 (V12)
Hybrid	2	NS	0.03	NS	NS	0.01
Pop†	1	0.01	< 0.01	< 0.01	< 0.01	0.02
Hybrid*Pop	2	NS	NS	NS	NS	NS
Row‡	1	0.03	NS	NS	0.05	NS
Hybrid*Row	2	NS	NS	NS	NS	NS
Pop*Row	1	NS	NS	NS	NS	NS
Hybrid*Pop*Row	2	NS	NS	NS	NS	NS

† Pop = Target Population

‡ Row = Row Configuration

§ Growth stage presented in parenthesis.

It was expected that twin-row production would increase interception of solar radiation during vegetative growth due to more uniform canopy distribution (Camp et al., 1985; Ottman and Welch, 1989) and previous results of Nafziger (2006). In this study, twin-row production increased the interception of solar radiation by 4.2% in 2009 and by 2.3% in 2010 at the V9 growth stage, but no difference was found at the V5 and V12 to V14 growth stages (Table 2.16). Nelson (2007) reported no difference in interception of solar radiation between twin- and single-row maize and hypothesized that this was due to plants reordering the leaf direction in response to crowding, as also found by Maddonni et al. (2002). It was expected that target population and row configuration would interact, as this provides more uniform spacing of plants and leaf area in the field, especially early in the growing season; however, no significant interaction was found.

Hybrids differ in plant height, leaf angle (and width), and to crowding stress (Duvick, 2005). Hybrids in this study had differences in maturity classification and plant height (Table 2.18). Hybrid affected interception of solar radiation in both years at the V12 to V14 growth stages (Table 2.16). The hybrid DKC 57-66 had the earliest-maturity classification and shortest plant height but still had greater interception of solar radiation than DKC 61-19 and 62-54. DKC 57-66 intercepted 93.5% of solar radiation, which was greater than the interception of 88.9% of solar radiation by DKC 62-54 in 2009. DKC 61-19 intercepted 90.9% of solar radiation and was not different from the other two hybrids. In 2010, DKC 57-66 intercepted 93.9% of solar radiation, a greater percentage than DKC 61-19 and 62-54, which intercepted 91.1% and 91.6% of solar radiation. Reasons for this result are not obvious although the hybrid DKC 57-66 had either the greatest or intermediate LAI among the three hybrids. The hybrid DKC 57-66 likely had a subtle difference in leaf angle with leaves being slightly less upright than the other two hybrids.

Table 2.17. Parameter estimates from regression models relating target population to maize interception of solar radiation (n = 144).

Growth Stage	Year	Parameter Estimates $\hat{\beta}_0$	Parameter Estimates $\hat{\beta}_1$	Standard Error $\hat{\beta}_0$	Standard Error $\hat{\beta}_1$	Solar Radiation Interception
		---------- % ----------				% x 1000 plants^{-1}
V9	2009	52.2468	0.000213	7.0578	0.000075	0.213
V14	2009	81.8002	0.000106	2.7755	0.000029	0.106
V5	2010	4.4859	0.000141	3.9981	0.000042	0.141
V9	2010	64.1752	0.000244	5.0102	0.000053	0.244
V12	2010	83.6328	0.000098	3.5306	0.000039	0.098

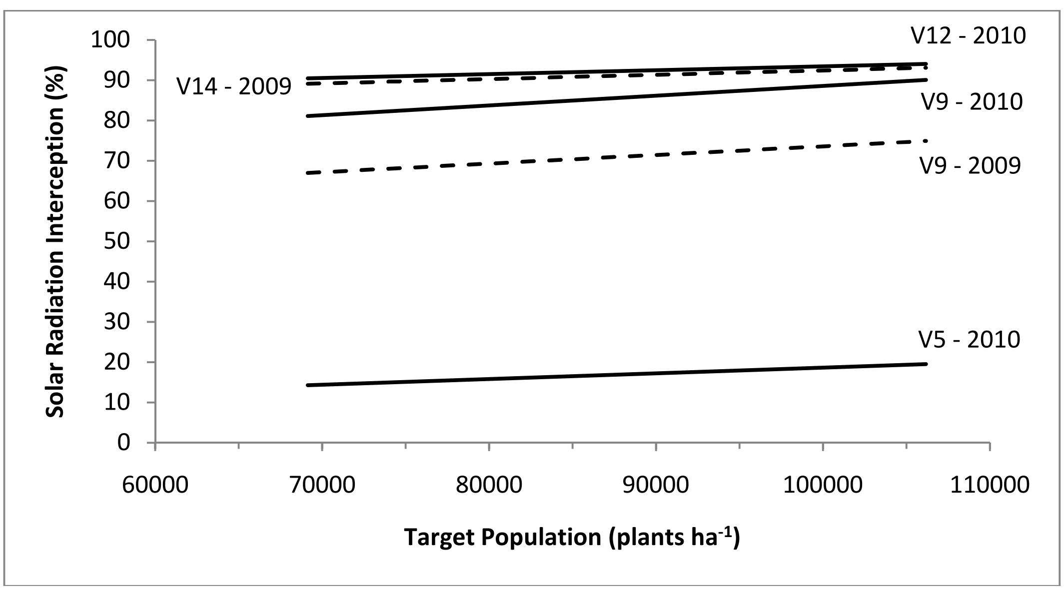

Fig. 2.6. Target population influence on maize interception of solar radiation in 2009 and 2010.

Pearson correlations indicated that the LAI at the R2 to R4 growth stage was positively correlated with interception of solar radiation during vegetative growth (r = 0.38 to 0.42; Table 2.13) as would be expected (Maddonni and Otegui, 1996). Leaf area index at the R2 to R4 growth stage (r = 0.84) and interception of solar radiation during vegetative growth were positively correlated with the number of ears produced m^{-2} (r = 0.15 to 0.42), consistent with results of Yao et al. (1991). Interception of solar radiation during vegetative growth was not correlated with kernel weight, consistent with results of Maddonni and Otegui (2006) and Otegui and Bonhomme (1998) who found that kernel weight was more highly correlated with interception of solar radiation during grain fill than during vegetative growth and that kernel weight was more stable than other yield components. Leaf area index at the R2 to R4 growth stage was positively correlated with grain yield, but interception of solar radiation during vegetative growth was not correlated with grain yield. Nafziger (2006) and Otegui and Bonhomme (1998) found that interception of solar radiation during grain fill was more highly correlated with yield than was interception of solar radiation during vegetative growth, and Elmore and Abendroth (2007) indicated that if 95% of solar radiation is intercepted by the flowering growth stage, changes in row configuration do not increase grain yield.

Plant Morphology and Lodging

Plant height did not differ during vegetative growth among treatments in 2009, but was influenced by row configuration in 2010 (Table 2.18). Plant height at V11 was 1.17 m in twin rows and 1.10 m in single rows in contrast to results of Karlen and Kasperbauer (1989) who found no difference between twin and single rows.

Table 2.18. Analysis of variance for the effects of hybrid, target population, row configuration, and all interactions on maize plant and ear height.

Source	DF	Plant Height				Ear Height	
		2009 (V14)§	2009 (R2)	2010 (V11)	2010 (R4)	2009 (R2)	2010 (R4)
Hybrid	2	NS	NS	NS	< 0.01	NS	<0.01
Pop†	1	NS	NS	NS	NS	NS	NS
Hybrid*Pop	2	NS	NS	NS	NS	NS	NS
Row‡	1	NS	< 0.01	< 0.01	0.02	NS	0.01
Hybrid*Row	2	NS	NS	NS	NS	NS	NS
Pop*Row	1	NS	NS	NS	NS	NS	NS
Hybrid*Pop*Row	2	NS	NS	NS	NS	NS	NS

† Pop = Target Population
‡ Row = Row Configuration
§ Growth stage indicated in parenthesis.

Plant height during reproductive growth was influenced by row configuration in both years (Table 2.18) in contrast to results of Gozubenli et al. (2004) and Karlen et al. (1987) where no difference based on row configuration was found. In 2009, twin-row plant height was 2.36 m and single-row plant height was 2.43 m while in 2010, height of twin-row plants was 2.35 m compared to 2.32 m for single-row plants. Row configuration resulted in only small differences in plant height, with contrasting trends across years, and, therefore, was of little practical importance. No hybrid differences for plant height occurred in 2009, but in 2010, DKC 61-19 produced the tallest plants at 2.4 m while DKC 62-54 and DKC 57-66 produced 2.3 m tall plants.

Ear height was not influenced by treatments in 2009, but was influenced by the main effects of hybrid and row configuration in 2010 (Table 2.18). Average ear height was 1.25 m in 2009. In 2010, twin rows had 1.10 m ear height while single rows had 1.08 m ear height. The hybrid DKC 61-19 had the highest ear height of 1.17 m, DKC 57-66 had intermediate ear height of 1.07 m, and DKC 62-54 had the lowest ear height of 1.02 m.

Stalk diameter was affected by the main effects of year and target population, and the interaction of year X row configuration (Table 2.19). As plant population increased, stalk diameter declined by 0.07 mm per thousands plants (Table 2.20; Fig. 2.7) similar to previous results (Rajcan and Swanton, 2001). Stalk diameter was greater in 2010 than 2009 (Table 2.21). In 2009, there was no difference in stalk diameter between twin and single rows; however, in 2010 twin rows produced plants with 0.7 mm greater stalk diameters, similar to results of Karlen et al. (1987) and Gozubenli et al. (2004).

Table 2.19. Analysis of variance for the effects of year, hybrid, target population, row configuration, and all interactions on maize stalk diameter and lodging.

Source	DF	Stalk Diameter	Stalk Lodging
Year	1	0.01	< 0.01
Hybrid	2	NS	0.02
Year*Hybrid	2	NS	0.04
Pop†	1	< 0.01	< 0.01
Year*Pop	1	NS	< 0.01
Hybrid*Pop	2	NS	0.02
Year*Hybrid*Pop	2	NS	NS
Row‡	1	NS	NS
Year*Row	1	0.05	NS
Hybrid*Row	2	NS	NS
Year*Hybrid*Row	2	NS	NS
Pop*Row	1	NS	NS
Year*Pop*Row	1	NS	NS
Hybrid*Pop*Row	2	NS	NS
Year*Hybrid*Pop*Row	2	NS	0.03

† Pop = Target Population
‡ Row = Row Configuration

Table 2.20. Parameter estimates from regression models relating target population to maize stalk diameter (n = 144).

Parameter Estimates	
$\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡
--------------- mm ---------------	
27.4914	-0.00007

† Standard error for $\hat{\beta}_0$ is 0.6425.
‡ Standard error for $\hat{\beta}_1$ is 0.000005557.

Table 2.21. Year and row configuration influence on stalk diameter.

	Row Configuration	
Year	Single‡	Twin
	--------------- mm ---------------	
2009†	20.8Ba	20.8Ba
2010	22.2Ab	22.9Aa

† One lower case letter in common indicates no significant difference between values in rows.
‡ One capital letter in common indicates no significant difference between values in columns.

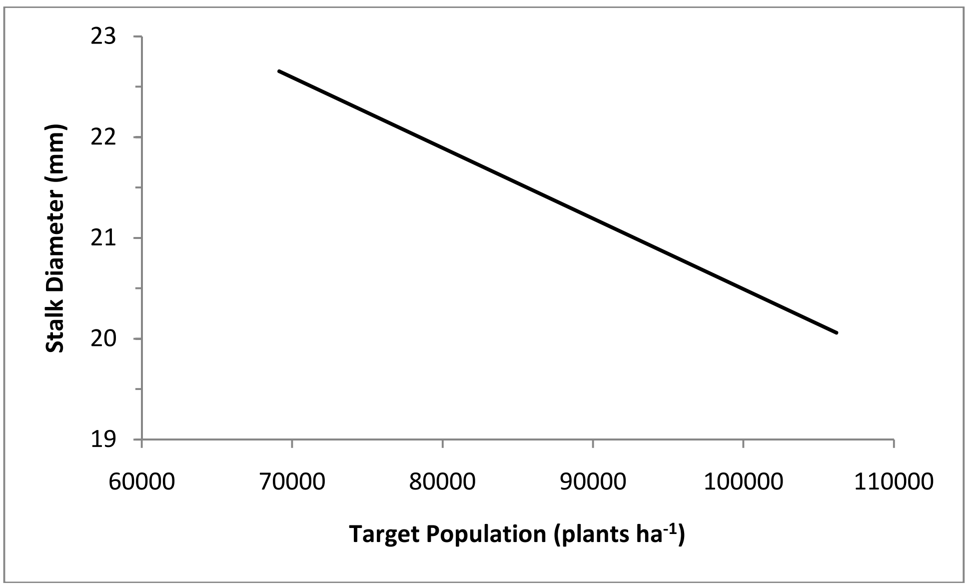

Fig. 2.7. Target population influence on maize stalk diameter.

Stalk lodging is related to crop management factors such as plant population (Olson and Sander, 1988; Sibale et al., 1992; Pedersen and Lauer, 2002; Stanger and Lauer, 2006) and hybrid characteristics such as plant and ear height (Rajcan and Swanton, 2001), and stalk diameter, and rind thickness (Moentono et al., 1984). In this study, stalk lodging was influenced by year X hybrid X target population X row configuration interaction effects (Table 2.19). On 13 Sept 2010, a severe weather system that contained high winds and hail occurred at the research site resulting in much greater lodging in 2010 than 2009. Increasing target population increased stalk lodging in both years as previously reported (Olson and Sander, 1988; Sibale et al., 1992; Pedersen and Lauer, 2002; Stanger and Lauer, 2006), with a greater increase in 2010 than in 2009, especially with high plant population (Table 2.22; Fig. 2.8). The hybrid DKC 61-19 had the greatest stalk lodging in both years and the hybrid DKC 62-54 had the lowest. Twin- and single-row maize had similar lodging in 2009, as found by Karlen and Camp (1985). In contrast, in 2010, twin-row maize had more lodging with high plant population for the later maturing hybrids DKC 61-19 and 62-54 while single-row maize had greater lodging for the early-maturity hybrid 57-66. The hybrid DKC 57-66 had similar lodging to DKC 61-19 in 2010 and similar lodging to DK62-54 in 2009.

Table 2.22. Parameter estimates from regression models relating target population to maize stalk lodging by year, hybrid, and row configuration (n = 12).

Hybrid	Row Configuration	Year	Parameter Estimates	
			$\hat{\beta}_0$†	$\hat{\beta}_1$‡
			--------------- %	---------------
DKC 57-66	Single	2009	0.7354	0.000022
DKC 57-66	Single	2010	-34.0021	0.000742
DKC 57-66	Twin	2009	-7.8913	0.000134
DKC 57-66	Twin	2010	0.03268	0.000373
DKC 61-19	Single	2009	-13.5019	0.000191
DKC 61-19	Single	2010	-32.1902	0.000887
DKC 61-19	Twin	2009	-6.7817	0.000151
DKC 61-19	Twin	2010	-100.85	0.001673
DKC 62-54	Single	2009	1.0992	0.00001
DKC 62-54	Single	2010	2.8514	0.000086
DKC 62-54	Twin	2009	-4.1472	0.000072
DKC 62-54	Twin	2010	-26.8054	0.000468

† Standard error for $\hat{\boldsymbol{\beta}}_0$ is 20.7487.
‡ Standard error for $\hat{\boldsymbol{\beta}}_1$ is 0.000230.

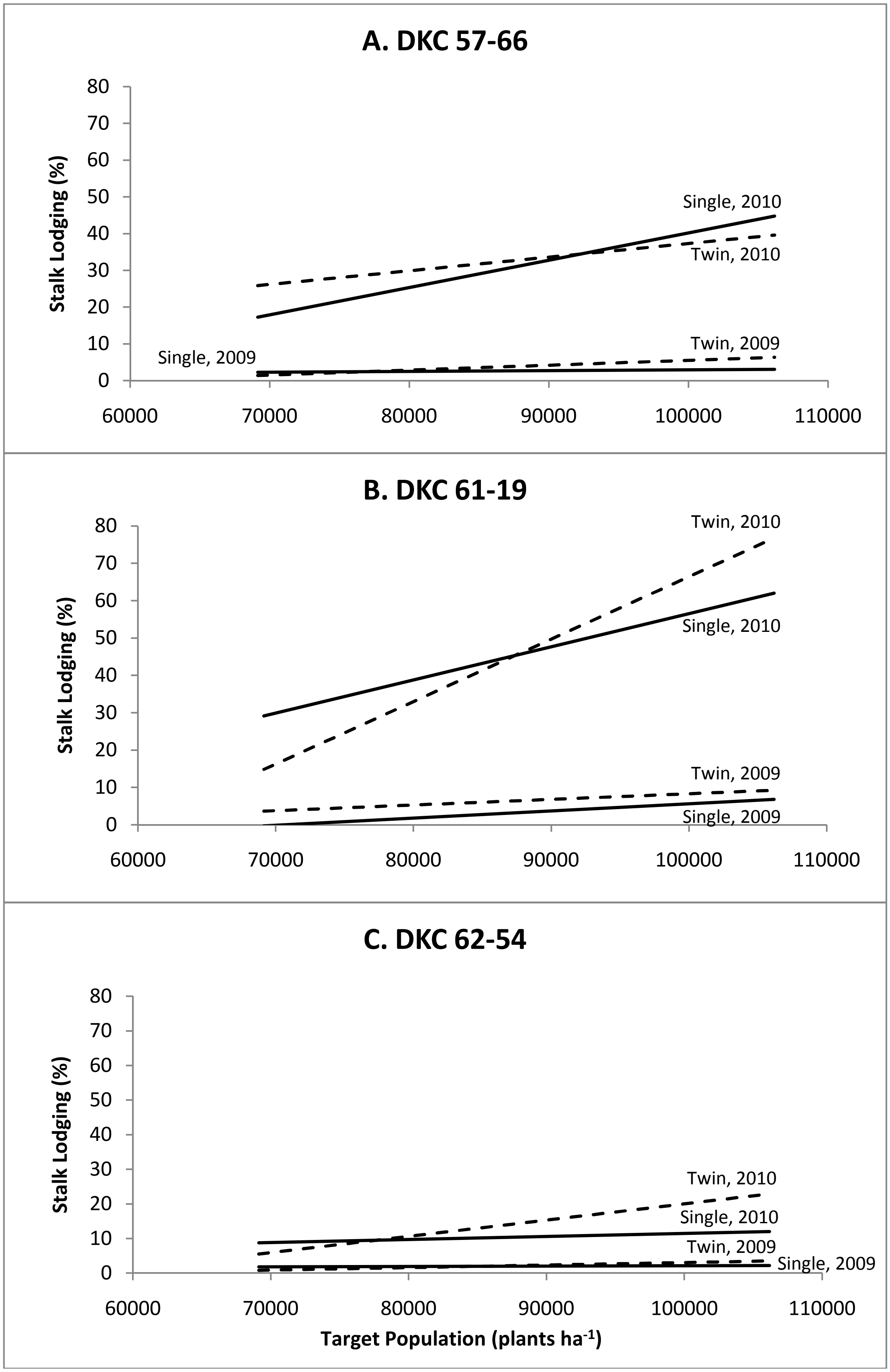

Fig. 2.8. Year, hybrid, target population, and row configuration influence on maize stalk lodging.

Plant and ear height, and stalk diameters were not correlated to stalk lodging (Table 2.13) in contrast to expectations (Rajcan and Swanton, 2001; Moentono et al., 1984). Leaf area index at the R2 to R4 growth stage (r = 0.22) and interception of solar radiation at the V9 (r = 0.50) and V12 to V14 growths stages (r = 0.17) were positively correlated with lodging while grain yield (r = -0.24) and kernel weight (r = -0.60) were negatively correlated. Increases in leaf matter increased stalk lodging, and, not surprisingly, increases in stalk lodging resulted in a decrease in grain yield and kernel weight.

Plant height was positively correlated (Table 2.13) with grain yield (r = 0.17 to 0.21) and negatively correlated with kernel weight (r = -0.17 to -0.30). Ear height was positively correlated to grain yield (r = 0.32) and the number of ears m^{-2} (r = 0.21) while negatively correlated to test weight (r = -0.40). Stalk diameter was negatively correlated to grain yield (r = -0.17) and the number of ears m^{-2} (r = -0.61) while being positively correlated with test weight (r = 0.41). Plant and ear height increases were followed by grain yield increases; surprisingly, this resulted in a decrease in kernel weight and test weight. Stalk diameter decreased as the number of ears m^{-2} increased which resulted in an increase in grain yield.

SUMMARY

The results of this study indicate that varying maize hybrid, plant population, and row configuration had only small and inconsistent effects on grain yield, yield components, plant morphology and leaf area, interception of solar radiation during vegetative growth, and stalk lodging which did not support the hypothesized advantages of twin-row production. Similarly, grain yield response to increasing plant population was small and linear instead of the predicted quadratic response. It was also expected that row configuration would interact with plant population and hybrid; however, this did not occur.

It appears that the major impacts of altering plant population and row configuration occur early in the growing season and even then are small, and plant growth and other factors occurring later in the growing season have a greater impact on grain yield. Based upon these results, current efforts to promote twin-row production and dramatically increase maize plant population are not justified for growing conditions similar to those present in this study.

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CHAPTER 3

PLANT POPULATION INFLUENCE ON

MODERN MAIZE HYBRIDS

MATERIALS AND METHODS

Environment

Field experiments were conducted under rainfed and center pivot irrigated conditions at the University of Nebraska Agricultural Research and Development Center near Mead, NE (41°9’ N, 96°27’ W) in 2008, 2009, and 2010. Filbert silt loam (fine, smectitic, mesic Vertic Argialboll) with 0 to 1% slopes (USDA-NRCS, 2011) was the predominant soil type in 2008 and 2009 on the irrigated site and in 2010 on the rainfed site. The predominant soil type on the rainfed site in 2008 and 2009 was Yutan silty clay loam (fine, silty, mixed, superactive, mesic Mollic Hapludalfs) with 2 to 6% slopes. Maize was the previous crop in all site years.

Experimental Design

A randomized complete block designed experiment with a split-plot treatment arrangement and three replications was used for each environment. Environments were considered to be year – site/water regime combinations. Main plots were six target plant populations: 49383 (26.7 cm plant^{-1}), 61728 (21.3 cm plant^{-1}), 74074 (17.8 cm plant^{-1}), 86420 (15.2 cm plant^{-1}), 98765 (13.3 cm plant^{-1}), and 111111 (11.8 cm plant^{-1}) plants ha^{-1}. Plots were planted at seeding rates of 64444, 87901, and 120000 plants ha^{-1} in 2008 and 2009, and 68395, 93086, and 138519 plants ha^{-1} in 2010 and thinned to the desired plant population at the V4 to V6 growth stage. Seeding rates were increased in 2010 in order to better achieve the target population. Split plots consisted of two pairs of near isogenic hybrids: DKC 58-16 and DKC 58-19 (108-day relative maturity), and DKC 61-69 and DKC 61-72 (111-day relative maturity). All hybrids were glyphosate-resistant; additionally, hybrids DKC 58-16 and 61-69 were resistant to European corn borer (ECB) and corn rootworm (CRW). Plots were six 76 cm rows (4.6 m wide) by 9.1 m long.

Production

If soil nutrient levels and pH (Table 3.1) were not above sufficiency levels, applications were made based on rainfed maize grain yield of 10.0 Mg ha^{-1} and irrigated maize grain yield of 15.7 Mg ha^{-1} using University of Nebraska recommendations (Shapiro et al., 2008). Injection of 140 kg N ha^{-1} 17 cm deep as 82% anhydrous ammonia occurred on 9 Apr 2008, 25 Nov 2008, and 15 Apr 2010 with a 13 knife DMI Nutri-Placr Model 4300 anhydrous ammonia applicator (DMI, Inc., Rt. 150e, PO Box 65, Goodfield, IL 61742-0065) on the rainfed sites. Additionally, 68 kg P_2O_5 ha^{-1} was surface broadcast as 46% dry phosphate to the rainfed site on 20 April 2010 using a Gandy Model 10T drop spreader (Gandy Company, 528 Gandrud Road, Owatonna, MN 55060-0528). Disking occurred immediately after phosphate application with a Sunflower 1434 disk (Sunflower Manufacturing, 3154 Hallie Trail, Beloit, KS 67420-0566).

The irrigated site received applications of 224 kg N ha^{-1} as 82% anhydrous ammonia 17 cm deep with a 13 knife DMI applicator on 7 April 2008 and 26 Mar 2009. On 25 June 2009 84 kg N ha^{-1} was surface broadcast by hand as 46% urea to correct a visual N deficiency on the irrigated site likely due to compaction limiting root growth and excess rainfall leaching N below the root zone.

Table 3.1: Soil nutrient and pH levels, 2008, 2009, and 2010 rainfed and irrigated maize study, Mead, NE.

Environment	Year	Sample Date	Soil pH	Organic Matter	FIA Nitrate	Mehlich-3 P	Ammonium Acetate K	Ammonium Acetate Ca	Ammonium Acetate Mg	Ammonium Acetate Na
				%	----------------------------	----------------------------	ppm	----------------------------		
Rainfed	2009†	6/29/09†	6.0	3.8	1.9	22	295	2268	430	13
	2010	4/2/10	6.0	3.3	3.7	10	340	2427	311	9
Irrigated	2009	6/29/09	5.4	3.3	22.0	5.2	247	1673	367	52

† No soil nutrient and pH data was available for the 2008 crop year.
‡ Sampling occurred after the spring fertilizer application.

A John Deere 7100 MaxEmerge mechanical maize finger pickup unit planter equipped with row cleaners located in front of the seed disc was used to plant maize 5 cm deep on 23 April 2008, 22-23 April 2009, and 29 April 2010 (Deere & Company, One John Deere Place, Moline, IL 61265-8098). Maize was planted into previously tilled soil in all site years. O-[[2-(1, 1-Dimethylethyl)-5-pyrimidinyl]-O-ethyl O-(1-methylethyl) phosphorothioate] (0.164 kg a.i. ha^{-1}) and cyfluthrin [cyano(4-fluoro-3-phenoxyphenyl)-methyl 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate] (0.008 kg a.i. ha^{-1}) was applied at planting for CRW control on hybrids without transgenic CRW resistance.

Weed control was obtained by herbicide application and inter-row cultivation on the irrigated site. Acetochlor [2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl) acetamide] (2.654 kg a.i. ha^{-1}) and atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-striazine and related triazines] (1.319 kg a.i. ha^{-1}) was applied on 5 May 2008 with a FIMCO LG-55 3-pt mounted sprayer (FIMCO Industries, 800 Stevens Port Drive, Suite DD836, Dakota Dunes, South Dakota 57049). Inter-row cultivation was done on 18 June 2008 with a Buffalo 4600 row cultivator (Bison Industries, Inc., 1001 East Eisenhower Ave., Norfolk, NE 68702) to assist with weed control. In 2009, acetochlor [2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl) acetamide] (2.426 kg a.i. ha^{-1}) and atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-striazine and related triazines] (1.206 kg a.i. ha^{-1}) and sodium salt of bentazon [(3-(1-methylethyl)-1*H*-2, 1, 3-benzothiadiazin-4 (3*H*)-one 2,2-dioxide)] (0.560 kg a.i. ha^{-1}) was applied on 4 May. Glyphosate [N-(phosphonomethyl) glycine, in the form of its potassium salt] (1.546 kg a.i. ha^{-1}) was used on 16 June 2009. On 18 June 2009, inter-row cultivation was done to assist with weed control.

Herbicide application was used to control weeds on the rainfed site.   Acetochlor [2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl) acetamide] (2.654 kg a.i. ha^{-1}) and atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-striazine and related triazines] (1.319 kg a.i. ha^{-1}) was surface broadcast on 5 May 2008, with a FIMCO LG-55 3-pt mounted sprayer (FIMCO Industries, 800 Stevens Port Drive, Suite DD836, Dakota Dunes, South Dakota 57049). On 3 June 2008 sodium salt of bentazon [(3-(1-methylethyl)-1*H*-2, 1, 3-benzothiadiazin-4 (3*H*)-one 2,2-dioxide)] (0.560 kg a.i. ha^{-1}) and atrazine [2-chloro-4 ethylamino-6-isopropylamino-s-triazine] (0.560 kg a.i. ha^{-1}) was applied. In 2009, acetochlor [2-chloro-N-ethoxymethyl-N-(2-ethyl-6-methylphenyl) acetamide] (2.654 kg a.i. ha^{-1}) and atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-s-striazine and related triazines] (1.319 kg a.i. ha^{-1}) and sodium salt of bentazon [(3-(1-methylethyl)-1*H*-2, 1, 3-benzothiadiazin-4 (3*H*)-one 2,2-dioxide)] (0.280 kg a.i. ha^{-1}) was applied on 4 May. On 21 May 2009 glyphosate [N-(phosphonomethyl) glycine, in the form of its potassium salt] (0.773 kg a.i. ha^{-1}) was applied. A second application of glyphosate [N-(phosphonomethyl) glycine, in the form of its potassium salt] (1.160 kg a.i. ha^{-1}) occurred on 11 June 2009. On 18 May 2010, S-metolachlor (1.392 kg a.i. ha^{-1}), atrazine [2-chloro-4 ethylamino-6-isopropylamino-s-triazine] (1.120 kg a.i. ha^{-1}), and sodium salt of bentazon [(3-(1-methylethyl)-1*H*-2, 1, 3-benzothiadiazin-4 (3*H*)-one 2,2-dioxide)] (0.560 kg a.i. ha^{-1}) were applied. Sodium salt of bentazon [(3-(1-methylethyl)-1*H*-2, 1, 3-benzothiadiazin-4 (3*H*)-one 2,2-dioxide)] (0.560 kg a.i. ha^{-1}) and atrazine [2-chloro-4 ethylamino-6-isopropylamino-s-triazine] (0.560 kg a.i. ha^{-1}) was applied on 9 June 2010.

In irrigated environments, application of 37 mm irrigation water occurred in 2008 on 25 July, and 2, 15 and 31 Aug using a center pivot system. In 2009, 37 mm irrigation water was applied on 10 and 29 July.

Parameter Measurements

Final plant population, number of ears, and stalk and root lodging data were collected from three of the middle rows of each plot on 3, 6, 9 Oct 2008; 13-14 Oct 2009; and 27 Sep 2010 on the rainfed site and on 16 Oct 2008 and 27 Oct 2009 on the irrigated site. The entire length of three of the middle rows of each plot was harvested with a John Deere 3300 combine and maize grain yield was determined. The irrigated site was harvested on 20 Oct 2008 and 5-6 Nov 2009. Harvest occurred on the rainfed site on 9-10 Oct 2008; 16 and 20 Oct 2009; and 30 Sep and 1 Oct 2010. A weigh bucket located inside the grain tank equipped with Avery Weigh-Tronix weigh bars (Avery Weigh-Tronix, 1000 Armstrong Drive, Fairmont, MN 56031-1439) and a Model 640 indicator was used to determine grain mass. Grain water content was measured for each plot using a Burrows Digital Moisture Computer 700 (Seedburo Equipment Company, 2293 S MT Prospect Road, Des Plaines, IL 60018) and grain mass was adjusted to a constant water concentration of 155 g kg^{-1}.

Grain samples were retained from all plots. Test weight was then measured with a DICKEY-john GAC 2100 (Dickey-john Corporation, 5200 DICKEY-john Road, Auburn, IL 62615). Kernel weight was determined by counting 100 kernels and weighing them with an Ohaus Scout Pro scale (Ohaus Corporation, 7 Campus Drive, Suite 310, Parsippany, NJ 07054 USA), and adjusted to a constant water concentration of 155 g kg^{-1} as done for grain yield.

Statistical Analysis

Data were analyzed using the PROC MIXED procedure (Littell et al., 1996) of SAS (SAS Institute, 2008) and an analysis of variance table was determined. Regression for the continuous variable plant population, both main and interaction effects, was performed. Both linear and quadratic effects of plant population were initially included in the ANOVA; however, in nearly all analyses, the quadratic effect was not significant; thus, all data were analyzed for the linear effect. Environment, target population, and hybrid effects and their interactions were considered fixed effects. Replication and all interactions with replication were considered random.

Regression equations were developed using PROC Mixed model Type 1 in SAS to describe the responses of dependent variables to target population when interactions with target population were significant at $P \leq 0.05$, and data were presented graphically. The linear regression model is presented below:

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X$$

where $\hat{Y}$ is the predicted response variable and X is target population (plants ha^{-1}) while $\hat{\beta}_0$ (intercept) and $\hat{\beta}_1$ (linear coefficient) are constants that were obtained when the model was fit to the data. Mean separation of discrete variables was performed using paired-wise comparisons at $P \leq 0.05$. Pearson correlations were calculated to identify interrelationships among measured parameters.

RESULTS AND DISCUSSION

Seasonal Climatic Conditions

Seasonal average rainfall was lowest in 2009 and greatest in 2008 (Table 3.2). In 2009, seasonal rainfall was approximately equal to the 52-yr average; while in 2008 and 2010, seasonal rainfall was much higher than the average (Table 3.2). In all years, rainfall was above average during the month of June, and in Aug 2009, and in July 2008 and 2010. The amount of rainfall and its distribution were conducive to production of high maize grain yield.

Table 3.2. Seasonal rainfall in 2008, 2009, and 2010, Mead, NE.

Month	Rainfall			
	2008	2009	2010	1968 – 2010 Average
	----- mm -----			
April	101	31	91	72
May	142	41	63	106
June	287	139	222	103
July	110	71	174	80
Aug	14	155	97	91
Sept	96	48	107	73
Oct	115	94	6	59
Total April – Oct	865	579	760	584
Total May - Sept	649	454	663	453

Air temperatures were lowest in 2009, greatest in 2010, and near average in 2008 (Table 3.3). Monthly average air temperatures were near the 52-yr average in 2008 but, in 2009, were 1 °C lower than in 2008 and were approximately 1 °C higher in 2010 than 2008 and the 52-yr average. The Oct average temperature in 2009 was approximately 5 °C less than in 2008 and 2010. The cool temperatures in 2009 delayed physiological maturity and in-field drying of grain, and when combined with abundant solar radiation, contributed to increased grain yield due to an extended grain fill period (Egli, 2011; Gambín et al., 2006; Peters et al., 1971; Wilson et al., 1995).

Table 3.3. Air temperature in 2008, 2009, and 2010, Mead, NE.

Month	Air Temperature			
	2008	2009	2010	1968 – 2010 Average
	°C			
April	8.2	9.3	13.2	10.3
May	15.2	17.2	15.8	16.3
June	22.0	21.6	22.9	22.0
July	24.5	21.3	24.7	24.4
Aug	22.7	21.2	24.7	23.0
Sept	17.8	17.6	18.4	18.2
Oct	12.0	7.4	12.8	11.2
Average April – Oct	17.5	16.5	18.9	17.9
Average May - Sept	20.4	19.8	21.3	20.8

Climatic conditions in 2008, 2009 and 2010 (Table 3.2; Table 3.3) combined with productive, high water holding capacity soils (USDA-NRCS, 2011) resulted in high maize yield in all years. The relatively low rainfall in Aug 2008 and July 2009 caused the need for a 37 mm application of irrigation water four times in 2008 and twice in 2009.

Table 3.4. Environment and target population influence on harvest plant population.

Target	2008		2009		2010
Population	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
plants ha^{-1}					
49383	53104	50315	52108	50554	53542
61728	59916	55056	59039	56091	61111
74074	74815	74456	75333	71894	74695
86420	80352	74616	81787	78460	82862
98765	98877	95770	96447	95633	95172
111111	106247	98638	103100	98743	105371

Target populations were 49383, 61728, 74074, 86420, 98765, and 111111 plants ha^{-1} (Table 3.4). Plots were planted at seeding rates of 64444, 87901, and 120000 plants ha^{-1} in 2008 and 2009, and 68395, 93086, and 138519 plants ha^{-1} in 2010 and thinned to the desired plant population at the V4 to V6 growth stage. Difficulty occurred in achieving the target population in 2008 and 2009; thus, seeding rates were increased in

2010. Although seeding rates were well above the target populations, final populations were sometimes lower than desired at the 61728, 86420 and 111111 target populations due to the initial seeding rate and incomplete germination and emergence. Below average April temperatures in 2008 and 2009 (Table 3.3) and above average rainfall in 2008 and 2010 (Table 3.2) contributed to lower than expected plant germination and emergence.

Yield and Yield Components

Maize grain yield was largely influenced by the two-way interaction effects of environment X hybrid, environment X target population, and target population X hybrid (Table 3.5). Maize grain yield responded linearly to increasing target population for all environments and hybrids (Table 3.6; Fig. 3.1; Fig. 3.2), with the highest target population evaluated of 111111 plants ha^{-1} producing the highest grain yield for all environments and hybrids. However, parameter estimates for $\hat{\beta}_1$ were nearly zero for the 2010 rainfed environment, indicating that target population had only a small effect on maize grain yield. Similarly, Widdicombe and Thelen (2002) found that 90000 plants ha^{-1}, the highest population evaluated, resulted in the highest yield.

Table 3.5. Analysis of variance for the effects of environment, target population, hybrid, and all interactions on maize grain yield, ears m^{-2}, ears plant^{-1}, kernel weight, and test weight.

Source	DF	Yield	Ears m^{-2}	Ears plant^{-1}	Kernel Weight	Test Weight	Stalk Lodging
Env†	4	< 0.01	0.04	0.01	< 0.01	< 0.01	< 0.01
Pop‡	1	< 0.01	< 0.01	NS	< 0.01	< 0.01	< 0.01
Env*Pop	4	< 0.01	< 0.01	NS	NS	< 0.01	< 0.01
Hybrid	3	< 0.01	0.01	< 0.01	< 0.01	< 0.01	< 0.01
Env*Hybrid	12	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Pop*Hybrid	3	< 0.01	NS	NS	NS	< 0.01	NS
Env*Pop*Hybrid	12	NS	NS	NS	NS	NS	0.02

† Env = Environment

‡Pop = Target Population

Table 3.6. Parameter estimates from regression models relating target population to maize grain yield by environment and hybrid and yield increase 1000 plants^{-1} (Environment, n = 72; Hybrid, n = 90).

Environment	Hybrid	Parameter Estimates		Yield
		$\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡	Increase
		----------- Mg ha^{-1}	----------	Mg ha^{-1} x 1000 plants^{-1}
2008, Rainfed		11.1097	0.000018	0.018
2009, Rainfed		11.1446	0.000022	0.022
2010, Rainfed		9.6425	0.000001929	0.001929
2008, Irrigated		9.5144	0.000041	0.041
2009, Irrigated		9.5084	0.000044	0.044
	DKC 58-16	9.1530	0.000038	0.038
	DKC 58-19	9.2086	0.000035	0.035
	DKC 61-69	11.4038	0.000015	0.015
	DKC 61-72	10.9702	0.000014	0.014

† Standard error for $\hat{\boldsymbol{\beta}}_0$ is 0.5508 (environment) and 0.5324 (hybrid).

‡ Standard error for $\hat{\boldsymbol{\beta}}_1$ is 0.000005504 (environment) and 0.000004895 (hybrid).

Greater parameter estimates for $\hat{\beta}_1$ indicate that the irrigated environments were more responsive to increases in target population, with lower yield than the 2008 and 2009 rainfed environments at low plant population and higher yield at high plant population (Table 3.6, Fig. 3.1). The 2010 rainfed environment produced the lowest yield regardless of target population. Rainfall was low in Aug 2008 and July 2009 (Table 3.2), and as a result, 37 mm irrigation water was applied four times in 2008 and twice in 2009 for irrigated environments. Rainfall and fertilization was adequate to support low plant population and low yield; however, irrigation and increased nitrogen fertilizer application was necessary to produce maximum yield at high plant population, which accounted for yield differences between rainfed and irrigated environments in 2008 and 2009. Average air temperature was 1 °C above normal between the months of April and Oct 2010. Increased temperatures reduced grain fill period and likely reduced maize grain yield (Egli, 2011; Gambín et al., 2006; Wilson et al., 1995; Peters et al., 1971) in 2010.

DKC 58-16 and 58-19 were more responsive to increases in target population as indicated by greater parameter estimates for $\hat{\beta}_1$ (Table 3.6; Fig. 3.2). Grain yield of DKC 61-69 and 61-72 was more stable across the target population range, with higher yield at low plant population, and lower yield at high plant population when compared to DKC 58-16 and 58-19. This was expected because DKC 58-16 and 58-19 are earlier maturing hybrids, likely with reduced plant size and leaf area, and should benefit from increased maize plant population and interception of solar radiation more than later maturing hybrids. DKC 58-16 and 61-69 had resistance to ECB and CRW and produced higher yield across the target population range when compared to DKC 58-19 and 61-72, in spite of no observed infestation of either insect. This agrees with Stanger and Lauer (2006) who found that Bt hybrids yielded 6.6% more than non-Bt hybrids. Conversely, Coulter et al. (2010) found no difference in maize grain yield between Bt and non-Bt hybrids when ECB and CRW injury was low. Even though ECB and CRW pressure was not evident, Bt hybrids may have produced healthier plants that produced grain more efficiently and yielded more than non-Bt hybrids at a similar plant population.

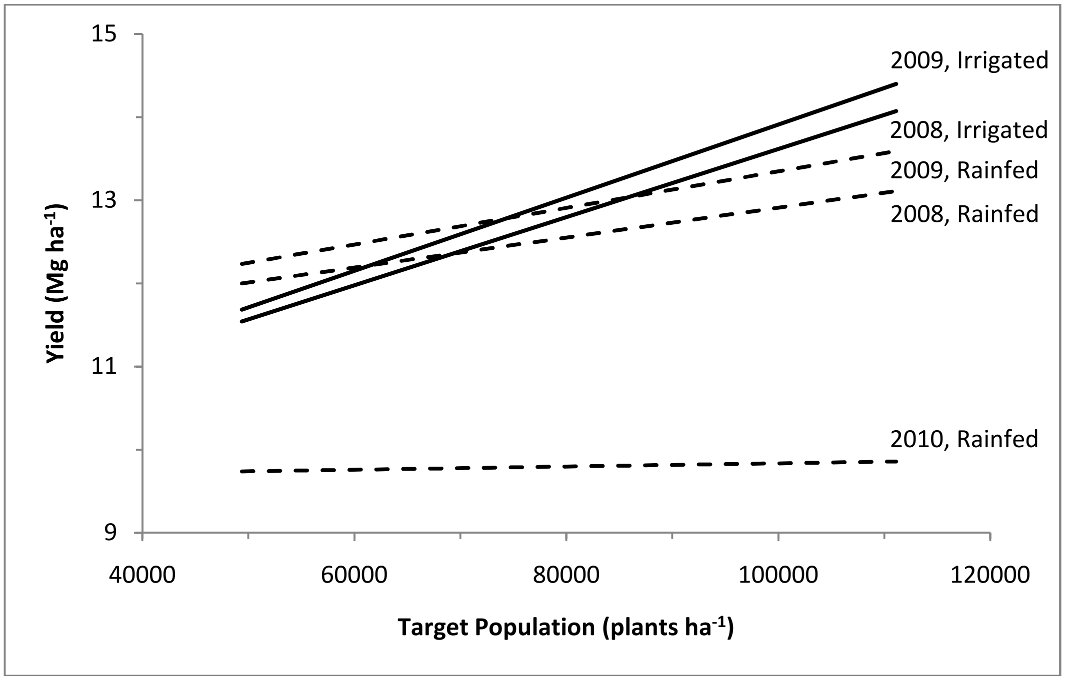

Fig. 3.1. Environment and target population influence on maize grain yield.

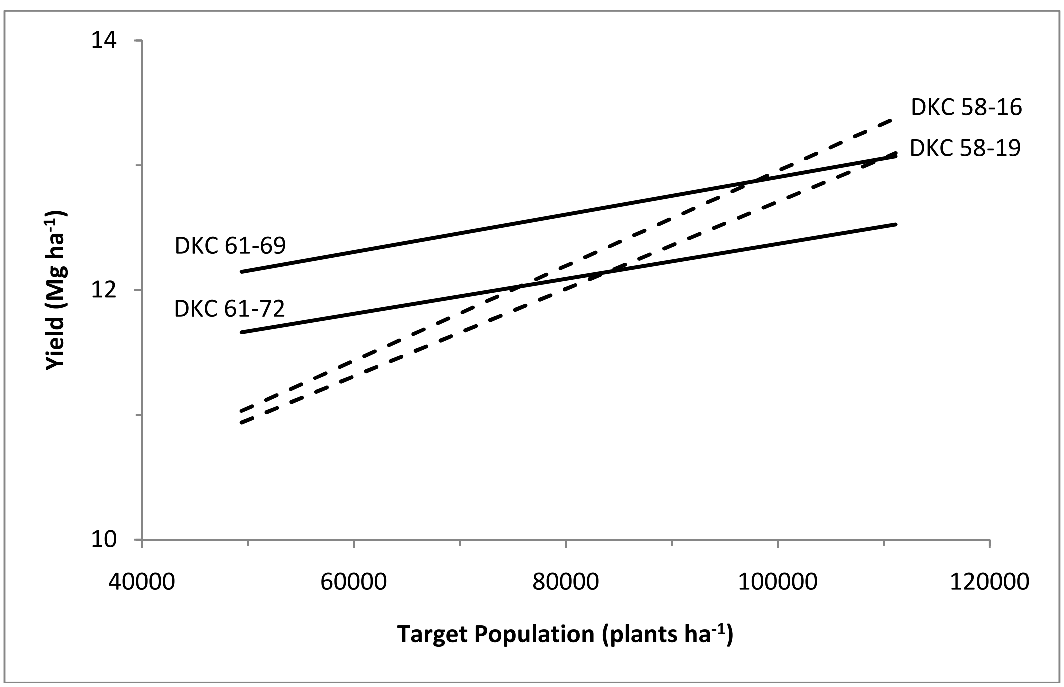

Fig. 3.2. Hybrid and target population influence on maize grain yield.

Averaged across hybrids, the 2010 rainfed environment produced lower grain yield than the other environments, which all produced similar grain yield (Table 3.7). Averaged across environments, DKC 61-69 produced the highest grain yield, with similar yield produced by the other hybrids. The hybrid DKC 61-69 was the latest maturing hybrid and possessed Bt resistance to ECB and CRW. The environment X hybrid interaction effect was significant due to the hybrid response in the 2010 rainfed environment where DKC 61-69 had the lowest grain yield, but the difference in grain yield among hybrids was only 0.6 Mg ha^{-1}. The 2010 rainfed environment was the most stressful environment due to above normal temperatures (Table 3.3), suggesting that DKC 61-69 is a “racehorse” hybrid that will yield well under ideal conditions but will not perform as well under stressful conditions.

Table 3.7. Environment and hybrid influence on maize grain yield.

Environment	Grain Yield				
	DKC 58-16‡	DKC 58-19	DKC 61-69	DKC 61-72	Mean
			---------- Mg ha^{-1} ----------		
2008, Rainfed†	12.7Aab	12.3Ab	13.1Aa	12.1Ab	12.5A
2009, Rainfed	12.9Aab	12.7Ab	13.4Aa	12.8Aab	12.9A
2010, Rainfed	10.2Ba	9.8Bab	9.6Bb	9.7Bab	9.8B
2008, Irrigated	12.8Ab	12.4Ab	13.4Aa	12.5Ab	12.8A
2009, Irrigated	12.6Ac	12.9Abc	13.5Aa	13.2Aab	13.1A
Mean	12.2b	12.0b	12.6a	12.1b	12.2

† One lower case letter in common indicates no significant difference between values in rows.
‡ One capital letter in common indicates no significant difference between values in columns.

Number of ears produced m^{-2} was largely influenced by the two-way interaction effects of environment X hybrid and environment X target population (Table 3.5). The number of ears m^{-2} increased linearly as population increased (Table 3.8; Fig. 3.3), which agrees with the previous findings of Maddonni and Otegui (2004) and Ordas and Stucker (1977). Ears m^{-2} were greatest in the 2008 rainfed environment across the target population range. The 2008 irrigated, 2009 irrigated, and 2010 rainfed environments exhibited similar response to target population as the 2008 rainfed environment, however produced fewer ears m^{-2} at every target population (Table 3.8; Fig. 3.3). The 2009 rainfed environment produced similar ears m^{-2} as the other four environments with low plant population but had the lowest slope coefficient and, thus, the lowest number of ears m^{-2} with high plant population (Table 3.8; Fig. 3.3). This was likely the result of greater stalk lodging in 2009 caused by the combination of low temperatures (Table 3.3) which delayed physiological maturity and gray leaf spot (GLS - *Cercospora zeae-maydis*) infestation which decreased plant health.

Table 3.8. Parameter estimates from regression models relating target population to the number of maize ears m^{-2} by environment (n = 72).

Environment	Parameter Estimates	
	$\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡
	--------------- no. ---------------	
2008, Rainfed	1.697	0.000075
2009, Rainfed	3.629	0.000044
2010, Rainfed	2.0045	0.000067
2008, Irrigated	1.189	0.000075
2009, Irrigated	1.7118	0.000070

† Standard error for $\hat{\boldsymbol{\beta}}_0$ is 0.3241.
‡ Standard error for $\hat{\boldsymbol{\beta}}_1$ is 0.000003848.

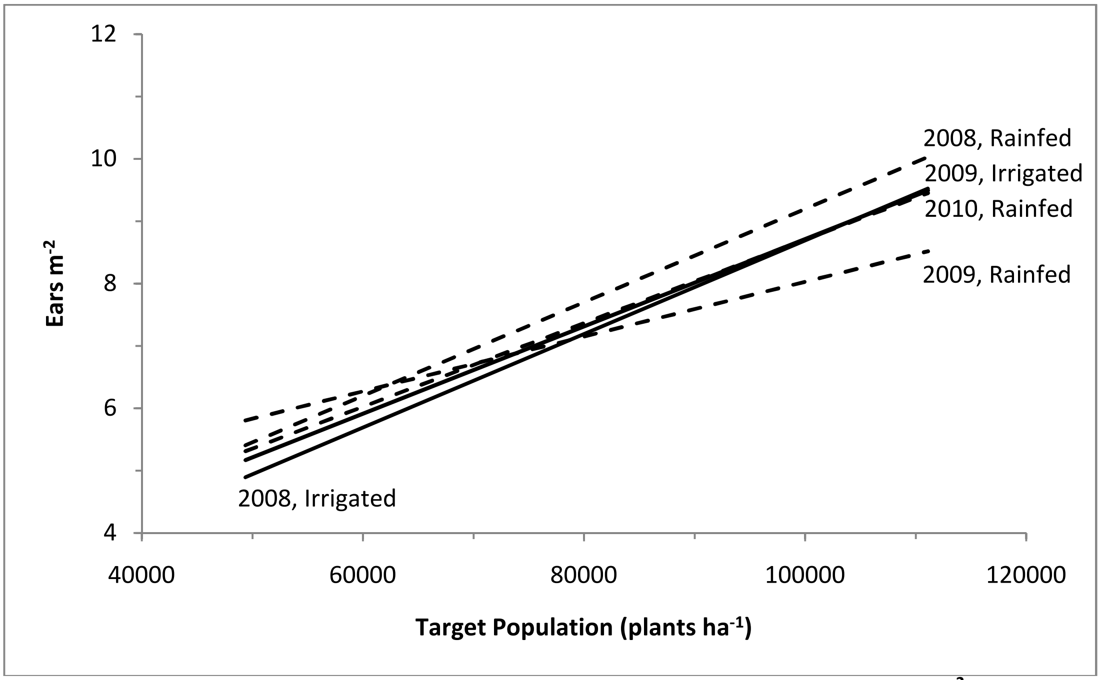

Fig. 3.3. Environment and target population influence on the number of maize ears m^{-2}.

Averaged across hybrids, the greatest number of ears m^{-2} produced was in the 2008 rainfed environment (Table 3.9). Averaged across environments, the hybrid DKC 61-69 produced slightly more ears m^{-2} than the other hybrids; however, this was not consistent over environments. In general, the later maturing DKC 61-69 and 61-72 hybrids produced more ears m^{-2} than the other hybrids in the irrigated and 2010 rainfed environments. There was no difference in the number of ears m^{-2} produced between Bt and non-Bt hybrids.

Table 3.9. Environment and hybrid influence on the number of maize ears m^{-2}.

Environment	DKC 58-16‡	DKC 58-19	DKC 61-69	DKC 61-72	Mean
	-----------------------------------	-----------------------------------	no.	-----------------------------------	
2008, Rainfed†	7.8Aa	7.7Aa	7.7Aa	7.5Ab	7.7A
2009, Rainfed	7.2Bab	7.3Ba	7.0Cb	7.2Aab	7.2B
2010, Rainfed	7.1Bb	7.3Bb	7.5ABa	7.4Aab	7.4B
2008, Irrigated	7.3Bab	7.1Bc	7.4Ba	7.2Abc	7.2B
2009, Irrigated	7.2Bb	7.3Bb	7.6ABa	7.3Ab	7.3B
Mean	7.3b	7.3b	7.4a	7.3b	7.4

† One lower case letter in common indicates no significant different between values in rows.
‡ One capital letter in common indicates no significant difference between values in columns.

Differences in the number of ears plant^{-1} were small (Table 3.10) and were influenced by the two-way interaction of environment X hybrid (Table 3.5). Target population had no effect on ears plant^{-1}, which contrasts with the findings of Maddonni and Otegui (2004; 2006), Westgate et al. (1997), and Ordas and Stucker (1977) who found that ears plant^{-1} decreased as target population increased.

Averaged over all hybrids, the 2008 rainfed, 2008 irrigated, and 2009 irrigated environments produced slightly greater number of ears plant^{-1} than the other environments (Table 3.10). Due to irrigation and the cool, wet 2008 growing season (Table 3.2; Table 3.3) these could all be considered low-stress environments. Stress was present in the 2009 rainfed environment due to GLS pressure and in 2010 due to above average temperatures. Averaged across environments, the Bt hybrids DKC 58-16 and 61-69 produced slightly more ears plant^{-1} than the non-Bt hybrids. The significant interaction effect appeared to be of little importance, and due to random variation in the number of ears plant^{-1} produced by the four hybrids in the five environments in the study.

Table 3.10. Environment and hybrid influence on the number of maize ears produced plant^{-1}.

Environment	DKC 58-16‡	DKC 58-19	DKC 61-69	DKC 61-72	Mean
	------------------	no.	------------------		
2008, Rainfed†	0.998Aa	0.979Ab	0.983Aab	0.977Ab	0.984A
2009, Rainfed	0.968ABa	0.955ABab	0.925Bc	0.942Bbc	0.948BC
2010, Rainfed	0.941Bab	0.929Bb	0.947Ba	0.946Bab	0.941C
2008, Irrigated	0.980Aa	0.969Aab	0.986Aa	0.952ABb	0.972AB
2009, Irrigated	0.985Ab	0.961Ac	1.012Aa	0.972ABbc	0.982A
Mean	0.974a	0.958bc	0.971b	0.958c	.965

† One lower case letter in common indicates no significant different between values in rows.
‡ One capital letter in common indicates no significant difference between values in columns.

Kernel weight was influenced by the target population main effect and the two-way interaction of environment X hybrid (Table 3.5). Kernel weight decreased as target population increased (Table 3.11; Fig. 3.4) as previously reported by Maddonni and Otegui (2006) and Karlen and Camp (1985).

Table 3.11. Parameter estimates from regression models relating target population to maize 100-kernel weight (n =360).

Parameter Estimates	
$\hat{\boldsymbol{\beta}}_0$ †	$\hat{\beta}_1$ ‡
---------- g 100 kernels^{-1} ----------	
43.0890	-0.00008

† Standard error for $\hat{\boldsymbol{\beta}}_0$ is 0.7757.
‡ Standard error for $\hat{\boldsymbol{\beta}}_1$ is 0.000004565.

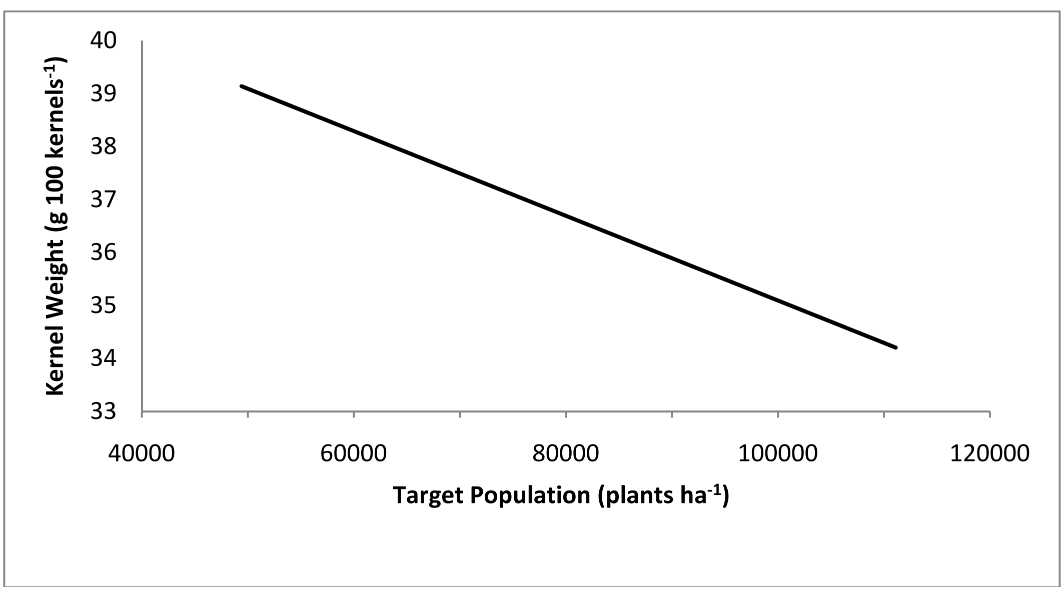

Fig. 3.4. Target population influence on maize 100-kernel weight.

The 2008 irrigated, 2009 irrigated, 2008 rainfed, and 2009 rainfed environments resulted in the heaviest kernel weight, and the 2010 rainfed resulted in the lightest (Table 3.12). Similarly, the 2010 rainfed environment produced the lowest grain yield (Table 3.6; Table 3.7; Fig. 3.2). Above average rainfall in 2008 and below average temperatures in 2009 (Table 3.2; Table 3.3) limited stress in these years. Above average temperatures in 2010 (Table 3.3) likely increased late-season stress and resulted in the lightest kernel weight. Averaged across all environments and the target population range, the ECB and CRW resistant hybrids DKC 58-16 and 61-69 produced the heaviest kernels (Table 3.12), the highest grain yield (Tables 3.6 and 3.7; Fig. 3.1), and the greatest number of ears plant^{-1} (Table 3.10). Even with limited ECB and CRW infestation, insect resistant plants were likely healthier which resulted in increased kernel weight. The interaction appeared to be due mainly to the variable kernel weight of DKC 58-16 and 58-19 across the five environments.

Table 3.12. Environment and hybrid influence on maize 100-kernel weight.

Environment	DKC 58-16‡	DKC 58-19	DKC 61-69	DKC 61-72	Mean
	---------- g 100 kernels^{-1} ----------				
2008, Rainfed†	35.9Bb	34.9Bc	37.9Ba	37.5ABa	36.5B
2009, Rainfed	37.8Aa	37.0Aab	37.1Bab	36.5Bb	37.1AB
2010, Rainfed	32.0Ca	30.9Cb	31.6Cab	31.6Cab	31.5C
2008, Irrigated	38.5Ab	36.7Ac	40.0Aa	38.2Ab	38.3A
2009, Irrigated	38.1Aa	37.7Aa	38.1Ba	37.7ABa	37.9AB
Mean	36.5b	35.4c	36.9a	36.3b	36.3

† One lower case letter in common indicates no significant different between values in rows.
‡ One capital letter in common indicates no significant difference between values in columns.

Test weight was largely influenced by the two-way interactions of environment X target population, target population X hybrid, and environment X hybrid (Table 3.5). The 2008 rainfed and 2009 irrigated environments produced the highest test weight, and test weight increased as target population increased (Table 3.13; Fig. 3.5). The 2010 rainfed environment produced the lowest test weight (Table 3.13; Fig. 3.5), and test weight decreased as target population increased; this was also the environment that produced the lowest grain yield (Fig. 3.1). The four environments that produced the highest grain yield also produced the four highest test weights (Table 3.13; Fig. 3.5). Due to the heavy test weight, grain produced by the hybrid DKC 61-72, especially in the 2008 rainfed and 2009 irrigated environments, would be desirable for use in food products produced by dry milling (Johnson, 2005) and/or alkaline cooking (Johnson et al., 2010).

The DKC 61 near isogenic line of hybrids had higher test weight at nearly all target populations evaluated and also responded with a greater increase in test weight as target population increased (Table 3.13; Fig. 3.6). Widdicombe and Thelen (2002) also found that test weight increased with increasing plant population. The greater test weight is likely due to a difference in base genetics between the DKC 58 and 61 pairs of near isogenic hybrids. In contrast, the DKC 58 near isogenic line of hybrids had similar test weights across the target population range.

Table 3.13. Parameter estimates from regression models relating target population to maize test weight by environment and hybrid (Environment, n = 72; Hybrid, n = 90).

Environment	Hybrid	Parameter Estimates	
		$\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡
		---------------- g L^{-1} ---------------	
2008, Rainfed		749.25	0.000214
2009, Rainfed		735.67	0.000076
2010, Rainfed		734.56	-0.00014
2008, Irrigated		746.61	0.000029
2009, Irrigated		755.87	0.000113
	DKC 58-16	746.47	0.00001
	DKC 58-19	748.56	-0.00002
	DKC 61-69	737.6	0.000123
	DKC 61-72	744.94	0.000118

† Standard error for $\hat{\boldsymbol{\beta}}_0$ is 5.5490 (environment) and 5.4362 (hybrid).
‡ Standard error for $\hat{\boldsymbol{\beta}}_1$ is 0.000043 (environment) and 0.000036 (hybrid).

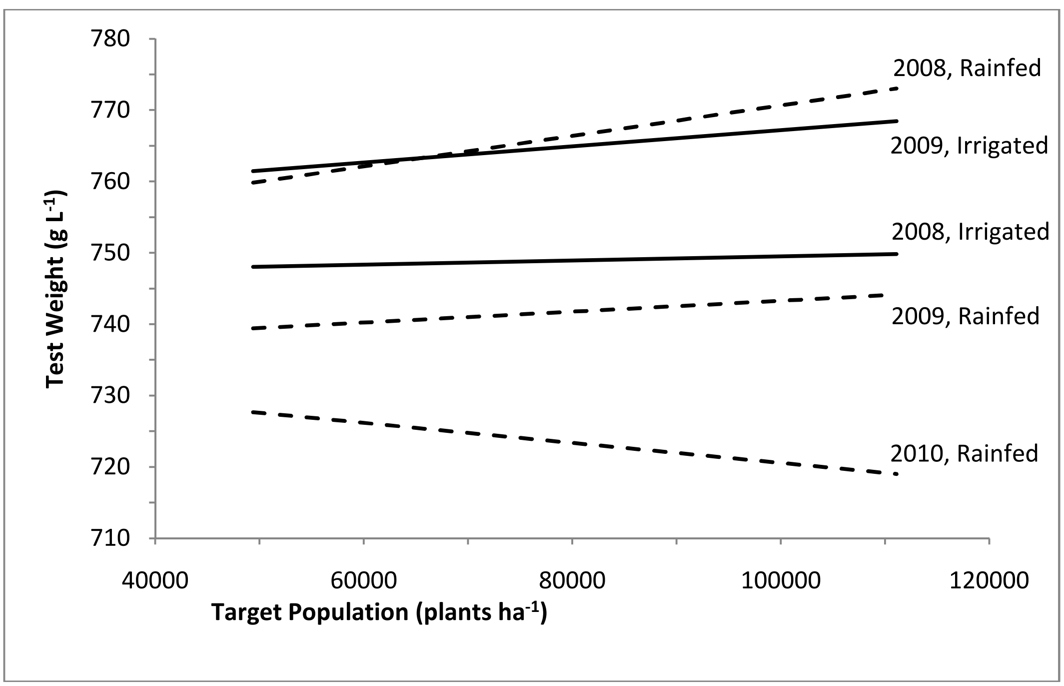

Fig. 3.5. Environment and target population influence on maize test weight.

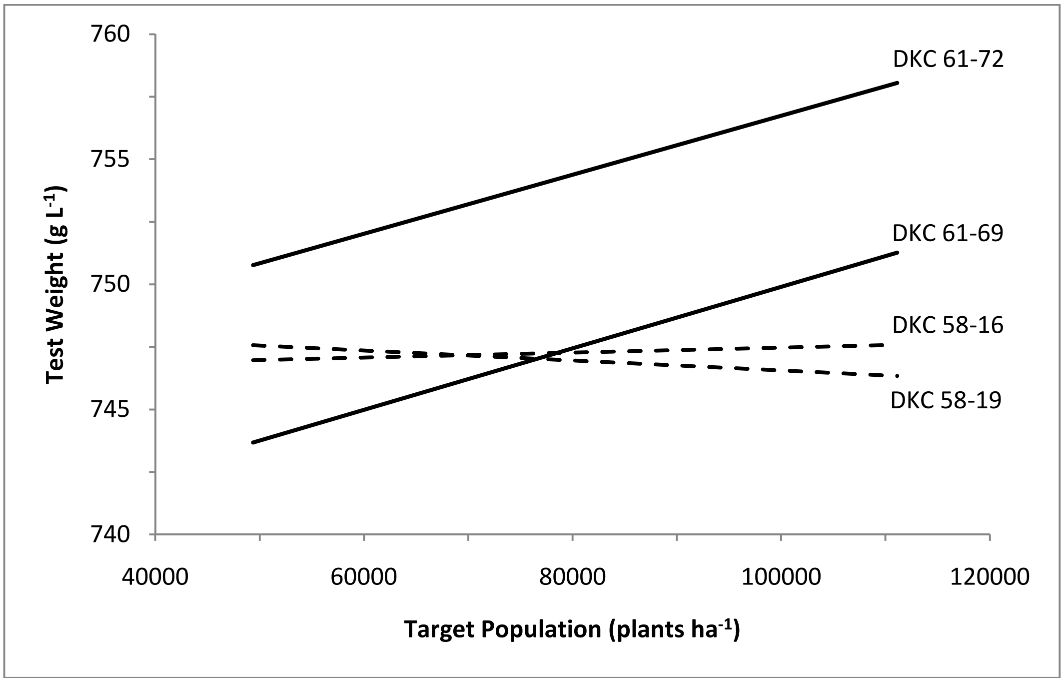

Fig. 3.6. Hybrid and target population influence on maize test weight.

Averaged across hybrids, the 2008 rainfed and 2009 irrigated environments produced the two heaviest test weights while the 2010 rainfed environment produced the lightest test weight (Table 3.14). The later maturing, non-Bt hybrid DKC 61-72 produced the greatest test weight while test weights of the other hybrids were similar. The hybrid DKC 61-72 produced the heaviest test weight in all environments; however, the magnitude of heavier test weight was greatest in the 2010 rainfed environment at 12.1 to 16.2 g L^{-1} compared to 3.2 to 8.8 g L^{-1} for the other environments.

Table 3.14. Environment and hybrid influence on maize test weight.

Environment	DKC 58-16‡	DKC 58-19	DKC 61-69	DKC 61-72	Mean
			g L^{-1}		
2008, Rainfed†	765.5Ab	764.0Ab	766.1Ab	770.1Aa	766.4A
2009, Rainfed	740.6Bb	739.6Bb	740.0Bb	746.8BCa	741.7B
2010, Rainfed	719.2Cbc	718.1Cc	722.2Cb	734.3Ca	723.5C
2008, Irrigated	748.1Bb	752.4ABa	743.3Bc	752.1Ba	749.0B
2009, Irrigated	763.0Ab	762.0Ab	765.7Aab	768.9Aa	764.9A
Mean	747.3b	747.2b	747.5b	754.4a	749.1

† One lower case letter in common indicates no significant different between values in rows.
‡ One capital letter in common indicates no significant difference between values in columns.

Stalk lodging was affected by the three-way interaction effect of environment X target population X hybrid (Table 3.5). Stalk lodging increased linearly as target population increased (Table 3.15; Fig. 3.7). This agrees with the findings of Stanger and Lauer (2006) and Pedersen and Lauer (2002). In the 2008 rainfed, 2008 irrigated, and 2009 irrigated environments, DKC 58-19 and 61-72, the non-Bt hybrids, resulted in the greatest stalk lodging in spite of no observed infestation of ECB or CRW. This agrees with Stanger and Lauer (2006) who found that Bt hybrids lodged 22% less than non-Bt hybrids even with no infestation of either insect. Stanger and Lauer (2007) found no difference in rind strength between Bt and non-Bt hybrids under minimal ECB pressure. The ability of Bt hybrids to resist lodging under low ECB and CRW pressure must be due to some other trait, possibly increased plant health, stalk quality or root mass. DKC 61-72 had the highest stalk lodging in three out of five environments and the lowest in the other two environments. Lodging was greatest in the 2009 rainfed environment. In 2009, cooler temperatures (Table 3.3) delayed physiological maturity and harvest. This combined with GLS pressure that decreased plant health likely accounted for the highest levels of stalk lodging in any environment. DKC 61-69 had the greatest stalk lodging in this environment while DKC 61-72 had the lowest with no obvious explanation.

Table 3.15. Parameter estimates from regression models relating target population to maize stalk lodging by environment and hybrid (n = 18).

Environment	Hybrid	Parameter Estimates	
		$\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡
		--------------- % --------------	
2008, Rainfed	58-16	1.4133	0.00000432
2008, Rainfed	58-19	1.1765	0.000004073
2008, Rainfed	61-69	-0.3770	0.000012
2008, Rainfed	61-72	-0.5433	0.000038
2008, Irrigated	58-16	-0.08562	0.000037
2008, Irrigated	58-19	-1.4738	0.000121
2008, Irrigated	61-69	-0.9791	0.000086
2008, Irrigated	61-72	0.7247	0.000107
2009, Rainfed	58-16	-19.4746	0.000402
2009, Rainfed	58-19	-26.9016	0.000527
2009, Rainfed	61-69	-25.2963	0.000564
2009, Rainfed	61-72	-18.6373	0.000369
2009, Irrigated	58-16	-1.4594	0.000045
2009, Irrigated	58-19	4.0559	0.000011
2009, Irrigated	61-69	-3.0849	0.000073
2009, Irrigated	61-72	5.5523	-0.00000284
2010, Rainfed	58-16	-12.6981	0.000261
2010, Rainfed	58-19	-7.7685	0.000232
2010, Rainfed	61-69	-2.9146	0.000159
2010, Rainfed	61-72	-6.9956	0.000189

† Standard error for $\widehat{\boldsymbol{\beta}}_0$ is 3.5028

‡ Standard error for $\widehat{\boldsymbol{\beta}}_1$ is 0.000041

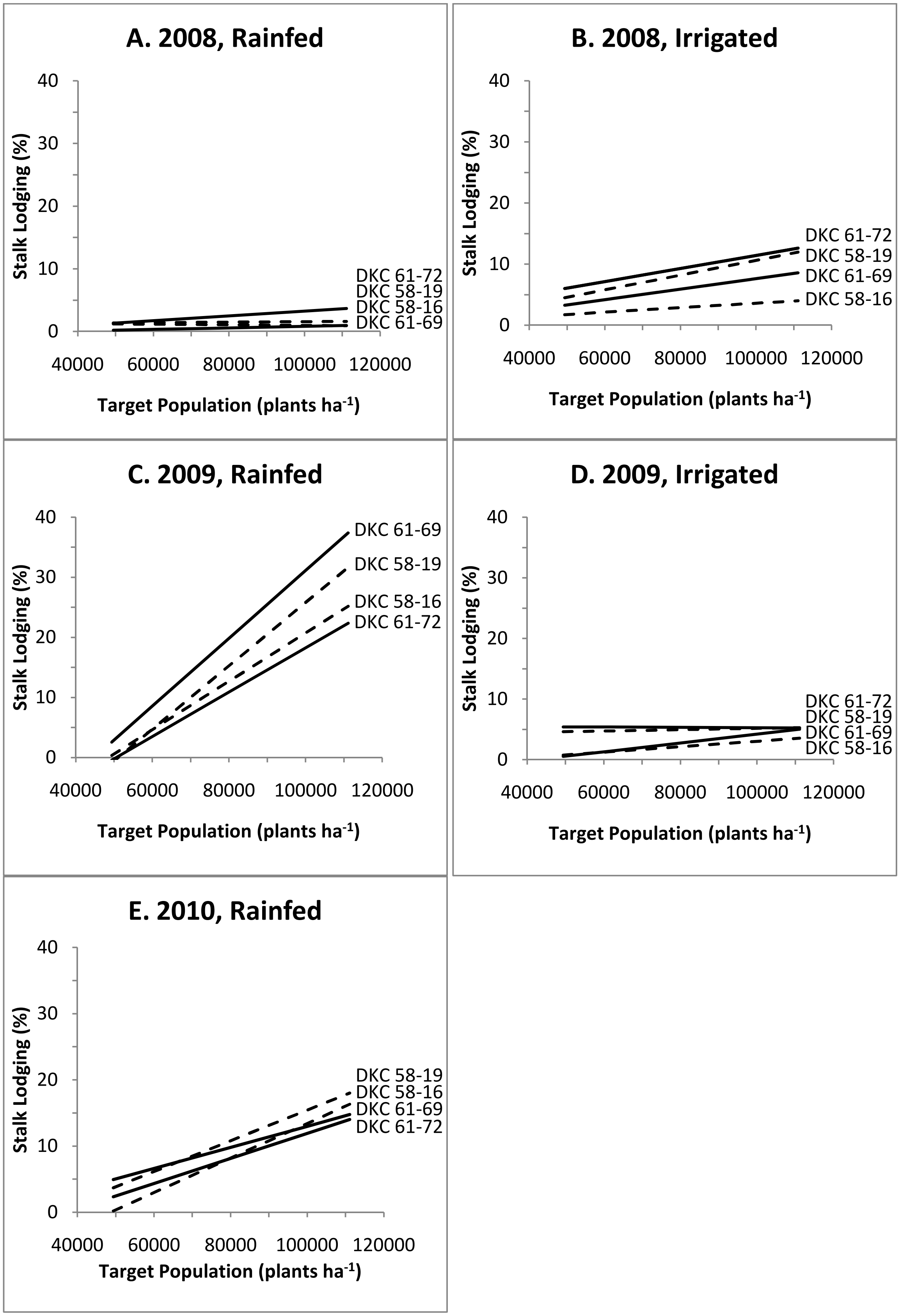

Fig. 3.7. Environment, target population, and hybrid influence on maize stalk lodging.

Maize yield was positively associated (r = 0.35 to 0.55) with the number of ears produced m^{-2} and kernel and test weight (Table 3.16) similar to the results of Agrama (1996). The negative correlation between the number of ears m^{-2} and kernel weight suggests compensation among yield components (i.e. more ears, lighter kernels) as found in previous research (Agrama, 1996). In this study, lodging was not associated with grain yield; however, it was highly, negatively correlated with the number of ears produced and had intermediate, negative association (r = -0.35 to -0.40) with kernel and test weight. These associations with yield components suggest that the lowest yield conditions in this study increased the likelihood of stalk lodging occurring.

Table 3.16. Pearson correlations for maize grain yield and yield components and stalk lodging.

	Yield	Ears m^{-2}	Ears $plant^{-1}$	Kernel Weight	Test Weight
Ears m^{-2}	0.36**				
Ears $plant^{-1}$	-0.01	-0.50**			
Kernel Weight	0.47**	-0.48**	0.54**		
Test Weight	0.54**	0.13*	0.17**	0.46**	
Stalk Lodging	-0.05	0.22**	-0.72**	-0.38**	-0.35**

* Significant at the $P \leq 0.05$ level.

** Significant at the $P \leq 0.01$ level.

SUMMARY

This study indicated that producers should increase maize plant population for growing conditions present in East-Central Nebraska in order to produce optimal yield. For all five environments and all four maize hybrids, maize grain yield responded linearly to increasing population, and the highest target population of 111111 plants ha^{-1} resulted in the greatest maize grain yield which did not support the expected quadratic response. This population produced an average of 9.2 ears m^{-2} (Table 3.9) which is much greater than the current Nebraska average at harvest of 5.0 ears m^{-2} for rainfed production and 7.0 ears m^{-2} for irrigated production (USDA, 2011).

Hybrids containing ECB and CRW traits may offer plant health advantages even under the low insect infestation level found in this study which led to greater grain yield than for the near isogenic hybrids without ECB and CRW resistance, as was hypothesized. In three of five environments the non-Bt hybrids resulted in the greatest stalk lodging, as expected, in spite of no observed infestation of ECB or CRW. Earlier maturing hybrids exhibited a greater yield response to increasing plant population, while later maturing hybrids produced more stable yield increases across the target population range. It was hypothesized that later maturing hybrids would yield more than earlier maturing hybrids; however, this occurred only with low plant population in this study.

Irrigated environments offered greater yield with a greater response to increasing target population; however, with below average temperatures and above average rainfall, yield of rainfed environments was nearly equal to yield of irrigated environments in this study.

Based upon these results, farmers should grow Bt hybrids with insect protection and increase plant population in both rainfed and irrigated environments with similar growing conditions to those present in this study.

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CONCLUSION

Matching of the best maize hybrids with optimal plant population and spacing is essential in order to maximize maize grain yield and meet increasing demand due to world population growth and biofuel usage. Little difference between twin- and single-row planting configurations was found. The highest target population evaluated of 106173 plants ha^{-1} produced the highest maize grain yield in 9 of 12 year, hybrid, and row configuration combinations; however, increasing target population had only a small effect on yield. This linear population response was different from the expected quadratic response. Varying hybrid, plant population, and row configuration had only small and inconsistent effects on grain yield, yield components, plant morphology and leaf area, interception of solar radiation and stalk lodging, which did not support the hypothesized advantages of twin-row production. It appears that the major impacts of altering row configuration occur early in the growing season, and plant growth and other factors occurring later in the growing season have a greater impact on grain yield.

Comparison of Bt and non-Bt hybrids at various plant populations found that Bt hybrids had 0.4 Mg ha^{-1} higher yield than non-Bt hybrids, as expected. For all hybrids and environments, yield increased linearly and the highest target population of 111111 plants ha^{-1} resulted in the highest grain yield. Bt hybrids lodged less than non-Bt hybrids in three of five environments, which does not support the hypothesis that Bt hybrids lodge less than non-Bt hybrids.

These results indicate that twin-row production has little influence on maize yield and growth. In general, maize yield increased linearly with increasing target population although the rate of yield increase varied across experiments, environments and hybrids. Farmers in East-Central Nebraska should consider increasing maize plant population and planting Bt hybrids to optimize maize grain yield.

APPENDIX A

METHOD COMPARISON FOR MEASUREMENT OF INTERCEPTION OF SOLAR RADIATION

The twin-row study was also conducted by Dr. Tony Vyn at Purdue University and by Dr. Peter Thomison at Ohio State University. The methods for collecting data were determined jointly, including measurement of interception of solar radiation. The agreed upon method positioned the LICOR LI-191 Line Quantum Sensor diagonally between rows with each end of the sensor in a row or between the two rows in the twin-row configuration. Commonly, measurements of solar radiation interception are taken from the center of the inter-row to the center of the next inter-row. To assure that the two methods gave similar results, interception of solar radiation was measured on 9 June 2010 (GS = V5) and 25 June 2010 (GS = V9) using both methods under both row configurations at the low (69136 plants ha^{-1}) and high (106173 plants ha^{-1}) target population. Regression of solar radiation measurement methods was performed and resulted in y intercept values near zero and slope values near one (Table A1; Fig. A1). The two methods produced similar values and either can be used to measure interception of solar radiation accurately.

Table A1. Coefficient values for regressing row-to-row measurement method on center-to-center measurement method and R^2 (n = 48).

Target	Row	Coefficient Values		
Population	Configuration	$\hat{\beta}_0$ †	$\hat{\beta}_1$ ‡	R^2
		-------------- % --------------		
69136	Single	5.2266	0.8976	0.9401
106173	Single	4.0012	0.9639	0.9510
69136	Twin	3.2085	0.9569	0.8862
106173	Twin	-0.1495	1.0089	0.9702

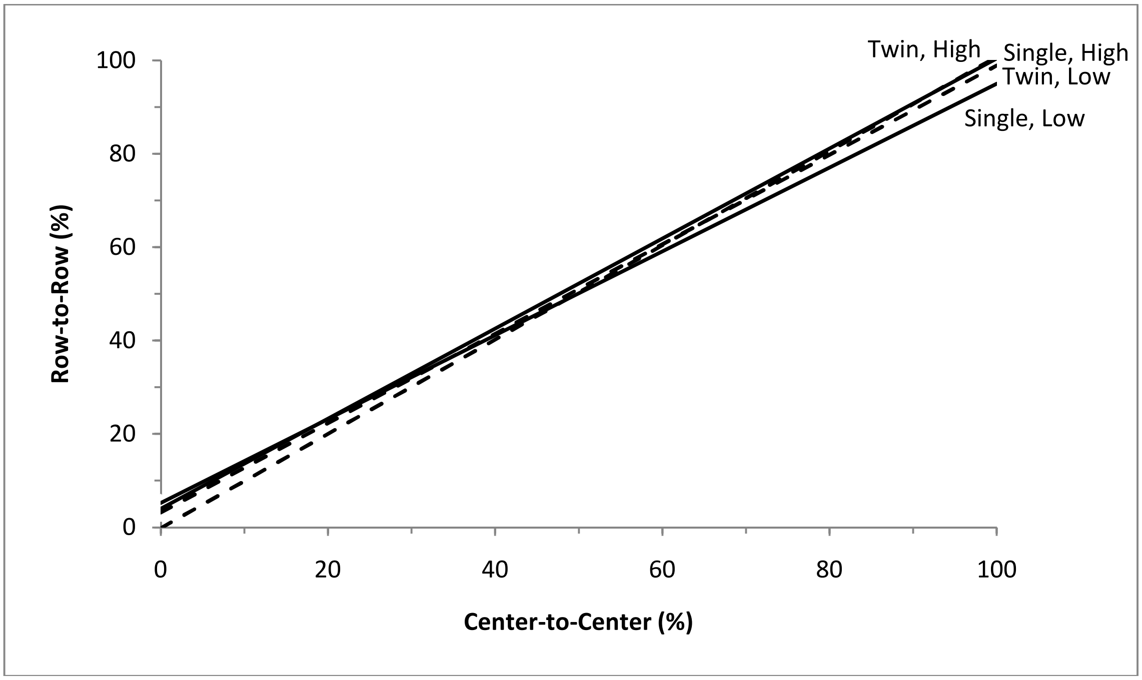

Fig. A1. Measurement method influence on interception of solar radiation.

APPENDIX B

ECONOMIC OPTIMAL PLANT POPULATION

FOR MODERN MAIZE HYBRIDS

Maize grain yield often responds quadratically to increasing plant population (Stanger and Lauer, 2006). Yield increases as plant population increases until a maximum point and then decreases as plant population continues to increase, often due to increases in lodging (Sibale et al., 1992) and plant barrenness (Maddonni and Otegui, 2004). Producers strive to achieve this point of maximum yield; however, producers often fail to realize that maximum yield generally does not result in maximum profit. The cost of the input (seed cost) and the price of the product (grain price) must be considered when determining the profit-maximizing amount of the variable input to use (Boehlje and Eidman, 1984). Marginal factor cost (MFC) is the additional cost due to an additional unit of the variable input, and the value of the marginal product (VMP) is the price of the product times the change in the amount of product produced due to an additional unit of the variable input. Profits are maximized where the value of the marginal product is just greater than or equal to marginal factor cost. Thus, as yield increases due to increases in plant population, there is a point in which the additional yield increase exactly equals the added cost of increasing the plant population to obtain that yield increase. It is at this point that profits are maximized. Economic optimal plant population is defined as the plant population that maximizes net income.

In this study, the target population quadratic effect was rarely significant; thus, all data were analyzed for the linear effect. The linear target population effect on maize grain yield is presented in Table 3.6, Fig. 3.1, and Fig. 3.2. Determining the economic optimal plant population for a linear response is not useful. A small slope value results in the lowest plant population studied being the economic optimal while the reverse is true with a high slope value. Therefore, harvest population rather than the target population (Table 3.4) yield data were fitted to quadratic equations. The quadratic regression model is presented below:

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X + \hat{\beta}_2 X^2$$

where $\hat{Y}$ is the predicted response variable and X is harvest population (plants ha^{-1}) while $\hat{\beta}_0$ (intercept), $\hat{\beta}_1$ (linear coefficient), and $\hat{\beta}_2$ (quadratic coefficient) are constants that were obtained when the model was fit to the data. Coefficient values are presented in Table B1 and graphs in Fig. B1 and B2. Harvest population was occasionally lower than the desired target population and this also contributed to the decision to use the harvest population data. Harvest population data were not used in other statistical analyses because target population was used as a blocking factor in this experiment, and therefore had to be used in the analysis.

Table B1. Coefficient values relating target population to maize grain yield by environment and hybrid (Environment, n = 72; Hybrid, n =90).

		Coefficient Values		
Environment	Hybrid	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$
		------------------------ Mg ha^{-1} ------------------------		
2008, Rainfed		7.198	0.0001191	-0.000000000615
2009, Rainfed		5.331	0.0001767	-0.000000000962
2010, Rainfed		11.965	-0.00005985	0.000000000390
2008, Irrigated		3.562	0.0002069	-0.000000001053
2009, Irrigated		6.228	0.0001326	-0.000000000524
	DKC 58-16	3.864	0.0001852	-0.000000000933
	DKC 58-19	7.748	0.0000742	-0.000000000231
	DKC 61-69	7.783	0.0001172	-0.000000000676
	DKC 61-72	7.798	0.0001021	-0.000000000573

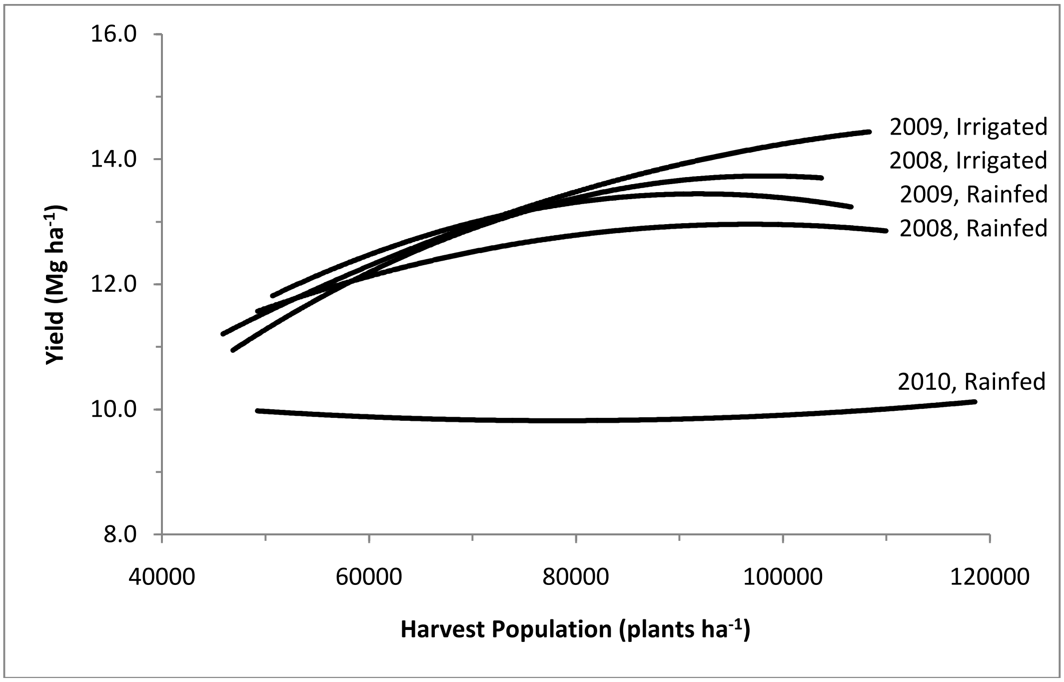

Fig. B1. Environment and harvest population influence on maize grain yield.

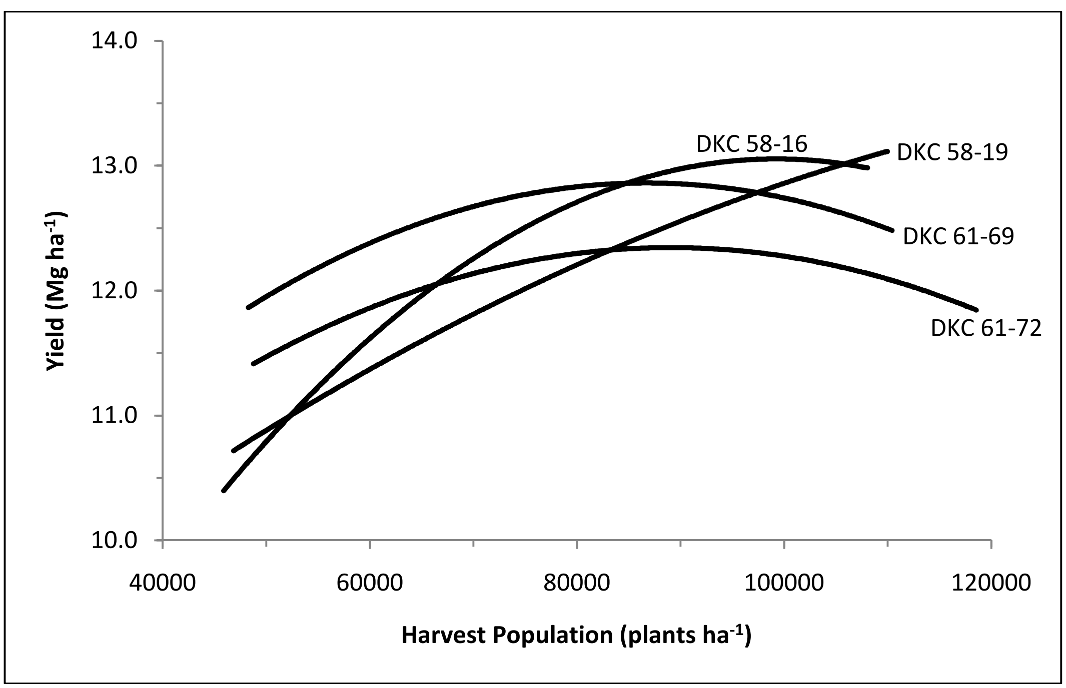

Fig. B2. Hybrid and harvest population influence on maize grain yield.

Economic optimal harvest population was calculated based on the equations found in Table B1. Seed costs over the three year study averaged \$280.00 unit^{-1} (80000 kernels unit^{-1}) for non-Bt hybrids and \$320.00 unit^{-1} for Bt hybrids. During this time period, there was considerable variability in grain market price; and therefore, three market prices of \$118 Mg^{-1}, \$197 Mg^{-1}, and \$275 Mg^{-1} were used in the analysis. Differences in harvest, transportation, storage, and drying costs due to yield differences were not accounted for in this analysis. Differences in N application rate due to expected yield differences also were not considered. Seed costs were calculated using a seeding rate of 10% greater than the harvest population.

Table B2. Environment, hybrid, and market price influence on economic optimal harvest population (Environment, n = 72; Hybrid, n =90).

		Market Price (\$ Mg^{-1})		
Environment	Hybrid	118	197	275
		--------------- plants ha^{-1} ---------------		
2008, Rainfed		68371	79740	84612
2009, Rainfed		73671	80938	84053
2010, Rainfed		49383	49383	49383
2008, Irrigated		81660	88299	91145
2009, Irrigated		93139	106482	112200
	DKC 58-16	79269	87262	90688
	DKC 58-19	90063	118311	130418
	DKC 61-69	59066	70098	74826
	DKC 61-72	60636	72024	76905

Table B3. Environment, hybrid, and market price influence on maximum net return above seed costs (Environment, n = 72; Hybrid, n =90).

Environment	Hybrid	Market Price ($ Mg^{-1}) 118	197	275
		-------------------	$ ha^{-1}	-------------------
2008, Rainfed		1189	2185	3194
2009, Rainfed		1245	2288	3339
2010, Rainfed		972	1755	2539
2008, Irrigated		1249	2315	3389
2009, Irrigated		1271	2393	3531
	DKC 58-16	1148	2157	3177
	DKC 58-19	1135	2160	3215
	DKC 61-69	1197	2184	3185
	DKC 61-72	1169	2118	3080

The economic optimal harvest population increased as grain market price increased for all environments and hybrids (Table B2). The economic optimal harvest population was greater for irrigated environments. The lowest yielding 2010 rainfed environment (Table B1; Fig. B1) resulted in the lowest economic optimal harvest population (Table B2) and lowest net return above seed costs (Table B3). The economic optimal harvest population is the lowest population studied due to the nearly linear response of maize grain yield to increases in harvest population for this environment (Table B1; Fig. B1). The economic optimal harvest population was greater for the non-Bt hybrids DKC 58-19 and 61-72, due to reduced seed costs, than for the Bt hybrids DKC 58-16 and 61-69, even though maximum net return above seed costs was greater for Bt hybrids.

These data indicate that the hybrids with Bt insect resistance produced the greatest net return above seed costs. Higher market price (greater economic return) combined with non-Bt insect resistant hybrids (lower production costs) had the highest economic optimal harvest population. This contrasts with seed company expectations that Bt insect resistant hybrids have higher optimal plant population than non-Bt hybrids due to improved plant health. Therefore, hybrid characteristics, seed costs, and market price should all be considered in determining harvest population/seeding rate goals.

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