# Agronomic Responses of Corn to Planting Date, Row Width, and Plant Density

A THESIS

SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL

OF THE UNIVERSITY OF MINNESOTA

BY

Ryan J. Van Roekel

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

Jeff Coulter, Advisor

MARCH 2011

# ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Jeff Coulter for his direction and support in my research. I thank my committee members Dr. Seth Naeve, Dr. Paul Porter, and Dr. Dan Kaiser for their support and input with my research. I thank Eric Ristau for all his help with the trials and data collection. I also thank the staff at the University of Minnesota Southern and Southwest Research and Outreach Centers, specifically Tom Hoverstad and Steve Quiring, for all their work in the field with the trials. This research was funded in part by the Minnesota Corn Research and Promotion Council.

# ABSTRACT

Corn (*Zea mays* L.) grain yield is closely related to plant density and is typically maximized in the northern Corn Belt when planting occurs in late April. However, spring precipitation events often result in wet and cold soil conditions that delay planting. The first objective of this research was to determine whether the economically optimum seeding rate for corn differs with planting date. From 2008 to 2010, the response of corn grain yield to plant density was evaluated for three planting dates at two locations in southern Minnesota. Planting dates occurred on 2-wk intervals beginning in late April. Within each planting date, there were six plant densities ranging from 38,400 to 107,900 plants ha$^{-1}$. The response of corn grain yield and economic return to plant density did not differ with planting date, and yield was maximized with a final stand of 81,700 to 107,900 plants ha$^{-1}$. Grain yield was similar with the first two planting dates, but averaged 15% lower with the late May planting date. Based on a partial budget analysis for net return to seed cost and assuming 5% over-seeding from final stand, seeding rates of 82,700 to 83,900 seeds ha$^{-1}$ were all within $2.50 ha$^{-1}$ of maximum net return for four different scenarios of low and high seed costs and grain prices. In addition to possible interactions with planting date, increased seed costs and the availability of hybrids with greater stress tolerance than in the past make it important for growers to know whether plant density for corn grain production differs with row width or hybrid maturity. A second objective of this research was to determine; a) the optimum plant density and row width to maximize corn grain yield and economic return, and b) whether hybrid maturity influenced these responses. In 2009 and 2010, the response of corn grain yield to plant density was evaluated for two row widths and three hybrids of differing maturity at two locations in southern Minnesota. Three hybrids of 95-, 101-, and 105-d relative maturity were planted on both 51- and 76-cm row widths. Each combination of row width and hybrid was evaluated at six plant densities ranging from 41,700 to 108,700 plants ha$^{-1}$. The response of corn grain yield and economic return to plant density did not differ with row width or hybrid, and yield was maximized with a final stand of 84,500 to 108,700 plants ha$^{-1}$. Grain yield did not differ between 51- and 76-cm row widths and increased with increasing hybrid relative maturity. This research found that in southern Minnesota, corn grain yield can be maximized by planting from late April to mid-May, on either 51- or 76-cm row widths, with 105- or 101-d hybrids, and at plant densities from 81,700 to 108,700 plants ha$^{-1}$.

## TABLE OF CONTENTS

**Chapter 1. Agronomic Responses to Planting Date, Row Width, and Plant Density: A Literature Review**

**Chapter 2. Agronomic Responses of Corn to Planting Date and Plant Density**

**Chapter 3. Agronomic Responses of Corn Hybrids to Row Width and Plant Density**

# LIST OF TABLES

## Chapter 2

**Chapter 3**

# CHAPTER 1

# Agronomic Responses of Corn to Planting Date, Row Width, and Plant Density: A Literature Review

## INTRODUCTION

Since the 1950's, the underlying trend in corn production was a steady decrease in grain prices caused by supply growing faster than demand (Alston et al., 2010a). However, the rate of increase in supply has slowed in recent years (Alston et al. 2010b). Meanwhile demand estimates are forecast to grow with global human population, which is predicted to increase from 6.8 billion in 2010 to 9 billion in the year 2045 (U.S. Census Bureau, 2010). Duvick and Cassman (1999) suggest that the grain yield potential of modern corn hybrids in the absence of stress has not increased when compared with hybrids from the 1960s. As corn grain yield continues to increase, the difference between theoretical potential maximum yield and realized yield continues to narrow, partially explaining the diminishing growth rate of corn grain yield (Alston et al. 2010b).

Additionally, in developed countries like the U.S., agricultural land use is decreasing, especially for rain-fed cropland (Beddow et al., 2010). This has been somewhat offset by an increase in irrigated cropland, but the long-term profitability and sustainability of irrigated corn production remains questionable. If these issues cannot be overcome and corn production increases continue to slow in the U.S., a competitiveness gap could develop with other countries such as China, which have not seen the same reductions in the rate of yield improvement (Alston et al., 2010b). However, if those other countries cannot overcome the global productivity deficit, a gap will develop between demand and supply, leading to grain shortages worldwide.

Methods for increasing corn grain yield are important to help growers remain economically competitive and also to meet the growing demands of the increasing human population. Historical increases in corn grain yield have involved not only corn genetic improvements and advancements in crop management, but also the interaction between the two (Duvick, 2005). New corn hybrids have greater tolerance to abiotic stresses such as temperature and moisture extremes (Duvick and Cassman, 1999), which have facilitated increased grain yield through altered management practices involving planting date, row width, and plant density. Additionally, corn hybrids now turnover at a faster rate than in the past (Duvick and Cassman, 1999) and as corn hybrids evolve, agronomic management practices need to be continually evaluated and altered to maximize the grain yield potential of the newest hybrids available.

## PLANTING DATE

When compared with historic hybrids, modern corn hybrids have greater tolerance to cool and wet soil conditions commonly observed in the spring (Kucharik, 2008), which has allowed growers to plant corn earlier over time. In addition, the use of conservation tillage systems has increased, thereby facilitating earlier planting due to a reduction in the number of spring field operations, even if the soil remains cooler under increased residue levels (Gupta, 1985). Planting early can allow for the use of late-maturity, higher-yielding hybrids with less risk of a fall freeze before the crop is mature (Kucharik, 2008). Early planting can also allow more time for in-field dry-down of the grain, which reduces drying costs. Another advantage of early planting is that it allows pollination to occur earlier in the summer when there is a smaller chance for moisture and heat stress (Kucharik, 2008). Conversely, when planting occurs later than the optimum time frame, grain yield decreases and harvest moisture increases (Lauer et al., 1999). Combinations of the aforementioned factors, along with increased equipment size, have led to earlier planting dates over time. In Minnesota, the date when 10% of the corn is planted statewide averaged 27 April from 2001 to 2005, which was 8 d earlier than the average from 1979 to 1983. Additionally, the date when 75% of corn was planted in Minnesota occurred on average 12 d earlier from 2001 to 2005 compared with that from 1979 to 1983 (Kucharik, 2006). This advance in corn planting date has been estimated to account for 19% of the yield increase in Minnesota over this time period (Kucharik, 2008). Research conducted between 1988 and 2003 in southwestern Minnesota found a quadratic response of grain yield to planting date and that planting dates between 21 April and 6 May produced corn yields within 1% of the maximum yield (Coulter, 2010). While earlier-planted corn yields slightly less than corn planted within the optimum dates, earlier-planted corn can result in lower grain moisture content at harvest and similar economic returns (Lauer et al., 1999).

Long-term data from southwestern Minnesota suggests that when planting is delayed from late April to late May and mid-June, corn grain yield decreases by 20% and 40%, respectively (Coulter, 2010). Over four yr and four locations with three hybrids, Nielsen et al. (2002) found that when planting is delayed from early May to early June in Indiana and Ohio, corn planted in early June needed 14 fewer cumulative days to reaching the silking stage. However, the cumulative number of growing degree days needed from planting to silking was only reduced by 34 growing degree days. The greater reduction in cumulative days from planting to silking, when compared with the cumulative thermal time from planting to silking, was attributed to warmer temperatures available for early growth of the late-planted corn. In addition, silking to physiological maturity time took 5 cumulative days longer for the early June planting compared with the early May planting; however, the cumulative thermal time from silking to physiological maturity was 110 growing degree days shorter. The mechanism for this reduction in the thermal requirement to physiological maturity was not examined, but the authors suggest that cool temperatures during the late grain filling stages caused premature formation of the kernel black layer (Nielsen et al, 2002).

In the northern Corn Belt, cold winters with high levels of snowfall frequently result in cooler, wetter springs when compared with regions to the south, which delays corn planting (Kucharik, 2008). Additionally, spring rainfall events can further delay planting progress. For example, Kucharik (2008) found a relationship between April precipitation and the departure of planting date from the 27-yr average in 11 of 12 states in the Corn Belt, illustrating that above-average April rainfall leads to later than normal planting dates. The detrimental effects of planting corn when the soil is too wet include sidewall compaction, incomplete furrow closure, and inadequate seed-to-soil. Although growers strive to plant corn during the optimum planting window to achieve full yield potential, wet soil conditions sometimes necessitate late planting. Knowing how fast yield will decline with delayed planting and if practices like plant density need to be modified will help growers make agronomic decisions that minimize yield loss and raise yield levels overall.

## ROW WIDTH

Another agronomic management practice that has contributed to increased corn grain yield over time is row width. Cardwell (1982) attributed 4% of the yield gain from 1930 to 1979 to a reduction in row widths from 107 cm to 90 cm. While the average row width in 2009 was 73 cm in Minnesota (USDA-National Agricultural Statistics Service, 2009), Porter et al. (1997) found that 25- or 51-cm rows yielded 7% more than 76-cm rows in Minnesota. Thus, in pursuit of further increases in corn grain yield, narrowing the row width may provide an advantage over the standard 76-cm row width that is most commonly used today. In addition, the adoption of narrow-row corn production provides an opportunity for growers to also plant soybean [*Glycine max* (L.) Merr.] in narrow rows. Soybean grown in 25-cm rows was found to have a 7% yield advantage compared with 76-cm rows in Minnesota (Naeve et al., 2004) and soybean grown in 38-cm rows was found to have a 5% yield advantage over 76-cm rows in Iowa (De Bruin and Pedersen, 2008).

Further interest in narrow rows, particularly in the northern Corn Belt, has been related to concerns associated with the short growing season. Although the northern latitudes experience longer summer day lengths than growing regions further south, a shorter growing season with less cumulative growing degree days can challenge corn to reach full canopy before flowering (Lee, 2006). Two review studies have found a greater percentage of positive yield responses to narrow rows in the northern Corn Belt states rather than in states further south (Lee, 2006; Butzen and Paszkiewicz, 2008). The authors suggest that more efficient moisture extraction or radiation interception may have occurred with the narrow rows in those northern regions (Butzen and Paszkiewicz, 2008).

Westgate et al. (1997) demonstrated that in west-central Minnesota, corn which achieved full canopy and ≥95% intercepted photosynthetically active radiation (IPAR) at the silking stage maximized yield. The percentage of IPAR in corn at the silking stage has also been shown to be positively correlated to both kernels per ear (Kiniry and Knievel, 1995) and maximum kernels per hectare (Andrade et al., 1993). In Argentina, Andrade et al. (2002) found that when corn in narrow rows out-yielded corn in wide rows, it was related to increased IPAR at the silking stage. Another study in Argentina demonstrated a yield increase of 27 to 47% for 35-cm rows compared with 70-cm rows in the presence of N stress (Barbieri et al., 2000). This yield increase was attributed in part to greater IPAR at the silking stage with the narrow rows. The increased yield advantage under N stress may also be due to better N use efficiency by narrow rows. However, even with adequate N fertilizer, IPAR at the silking stage and grain yields were higher in narrow rows. The increase in yield was found to be related to an increase in kernel number, which exhibited a positive linear response to IPAR at the silking stage. The authors suggested that the lack of yield response to narrow rows reported by Ottman and Welch (1989) and Westgate et al. (1997) may have occurred because the corn planted in wide rows was not at a disadvantage in IPAR. Westgate et al. (1997) suggested that no advantage of IPAR at silking was observed with narrow rows because as the row width was narrowed, the increased IPAR between the rows was offset with less IPAR between plants within the row due to the rigid, opposite and alternate leaf pattern of corn.

While the yield advantage of narrow rows has been tied to IPAR, other factors also affect the response of corn yield to changes in row width under differing circumstances, such as water stress. Increased IPAR levels throughout the growing season in narrow rows compared with 76-cm rows have been documented to lower soil temperatures and occasionally reduce soil water evaporation (Sharratt and McWilliams, 2005). This research, conducted in west-central Minnesota, also found higher root densities in narrow rows compared with 76-cm rows. Although the corn in narrow rows was able to extract more water due to the larger, more equally spaced root systems, water use efficiency was found to remain the same (Sharratt and McWilliams, 2005). Increased uptake of water may be beneficial in most years, but it has been suggested as a limitation when severely dry conditions are present, as corn in narrow rows can create a greater water sink and deplete the soil water profile faster than corn in 76-cm rows (Thelen, 2006). For example, in research conducted on irrigated corn in Kansas, where water was not limiting, grain yield was 12.7 Mg ha$^{-1}$ in 38-cm rows compared with 11.4 Mg ha$^{-1}$ in 76-cm rows. However, in the rain-fed corn trials with severe water stress, the larger corn canopy in 38-cm rows due to greater water extraction early in the season was detrimental to final grain yield as 2.4 Mg ha$^{-1}$ and 3.6 Mg ha$^{-1}$ yields were reported in 38-cm and 76-cm rows, respectively (Staggenborg et al., 2001).

Additionally, hybrid characteristics, such as relative maturity, may influence the response of corn grain yield to row width. Farnham (2001) hypothesized that early-maturity hybrids would respond more positively to narrow rows compared with late-maturity hybrids due to the narrower architecture of early-maturity hybrids. However, in Iowa, Farnham (2001) found that one late-maturity hybrid had 2% greater yields in a 38-cm row width than in a 76-cm row width, and that one early-maturity hybrid had 5% greater yields in a 76-cm row width than in a 38-cm row width. Conversely, research in southern Minnesota and New York did not find any interactions between hybrid and row width (Porter et al., 1997; Cox et al., 1998; 2006).

Beyond contradicting evidence as to the corn grain yield advantage with narrow rows, limitations to adopting narrow rows include the logistics of various field activities such as fertilizer application, soil insecticide application, herbicide application, inter-row cultivation, and harvesting. The cost of implementing narrow rows into a corn production system is can be a limiting factor because of the need to purchase specialized planting and harvesting equipment (Porter et al., 1997). Additionally, a 12-row 76-cm row width planter is 9.1 m wide; a 51-cm row width planter of the same overall width includes 18 rows, which can increase the cost and weight of the equipment. However, if a grower is already planning on purchasing a new planter and/or harvesting head, the adoption of narrow-row corn production may become more feasible. As mentioned earlier, soybean growers using a separate planter may be able to lower production costs by utilizing one planter for all crop needs, or if they are currently using one 76-cm planter for corn and soybean, switching to a narrow-row planter could potentially increase the yields of both crops. Although the costs of adopting narrow-row corn production are large, evolving corn hybrids and the pursuit of higher yield stimulates continued interest and questions regarding narrow-row corn production.

## PLANT DENSITY

A significant result of corn breeding over time has been the enhanced ability of corn hybrids to tolerate high plant density stresses and respond with decreased lodging, fewer barren plants, and higher yields (Tollenaar, 1989; 1991; Duvick, 2005; Hammer et al., 2009). Historic yield improvements in corn are the result of interactions between new hybrids and agronomic management, particularly in the ability of new hybrids to tolerate higher plant densities (Tollenaar and Lee, 2002). In Minnesota, the average corn plant density was 75,600 plants ha$^{-1}$ in 2009, compared with 49,800 plants ha$^{-1}$ in 1979 and 30,700 plants ha$^{-1}$ in 1930 (Cardwell, 1982; USDA-National Agricultural Statistics Service, 2009).

Obtaining the optimum plant density is important for corn production because corn has a much lower ability to tiller and produce additional grain from those tillers than other cultivated grasses like wheat and barley (Harris et al., 1976). At low plant densities, some corn hybrids will develop additional ears. However, these secondary ears often suffer from poor pollination due to late silk emergence and contribute little to yield (Harris et al., 1976). Other yield component responses to plant density in corn include the number of kernels per row and kernel weight, which can both display an inverse linear response to increases in plant density (Hashemi et al., 2005). Thus, a plant density high enough to produce the optimal trade-off between decreasing kernel weight and increasing kernel number per unit area will maximize yield. Additionally, it is important to note that the economically optimum plant density is lower than the plant density that maximizes yield due to the diminishing returns to seed cost. In Minnesota, the economically optimum plant density for corn grain yield has been documented at 86,500 plants ha$^{-1}$ by Porter et al. (1997) and at 79,100 to 84,000 plants ha$^{-1}$ by Coulter (2009).

In a previous plant density study in Illinois, Nafziger (1994) found that the maximum yield of 10.2 Mg ha$^{-1}$ occurred with 74,900 plants ha$^{-1}$ when averaged over two locations and four yr, but during the dry year of 1988, maximum yield occurred with 61,800 plants ha$^{-1}$. In New York, Cox (1997) reported that the optimum plant density for grain yield was 88,900 plants ha$^{-1}$ with abundant precipitation and 75,300 plants ha$^{-1}$ in a dry growing season. In research in Michigan, it was found that maximum corn grain yield occurred at the highest tested plant density of 90,000 plants ha$^{-1}$, even with below average rainfall (Widdicombe and Thelen, 2002).

These discrepancies in the optimum plant density to maximize yield could be the result of newer hybrids having greater tolerance to higher plant densities and abiotic stresses. Research from Brazil found that reduced dry matter partitioning to the tassel, a shorter corn canopy with fewer, more up right leaves, and lower ear height resulting in decreased lodging have contributed to higher yields associated with increasing optimum plant densities over time (Sangoi et al., 2002). Hammer et al. (2009) points to changes in corn root system architecture and the resulting improved water extraction as a major reason for historical yield increases and higher plant density tolerance.

As the root angle decreases, the rooting system penetrates deeper in the soil profile to extract greater amounts of plant-available water (Campos et al., 2004) which allows for increased plant growth and grain production and a reduced interval between anthesis and silking (Borras et al., 2007) and further adds to the increased plant density stress tolerance of modern hybrids. Another contributing factor for increased tolerance to high plant densities is the change in leaf erectness. Leaves that are more erect allow more light to penetrate deeper into the canopy, enhancing the photosynthetic rate of leaves near the ear, which can increase carbohydrates available for ear development and kernel set (Zinselmeier et al., 1999).

Corn plant characteristics that change with plant density include plant height, stalk diameter and leaf area per plant, which have all been shown to decrease with increased plant density (Boomsma et al., 2009). Research from Minnesota found a lower harvest index with higher plant densities, which was attributed to an increase in barren plants (Westgate et al., 1997). More recent work found no barrenness and that the harvest index remained stable across a range of plant densities (Edwards et al., 2005). Boomsma et al. (2009) also found no effect of plant density on the harvest index when adequate N fertilizer was present.

The risk of stalk lodging increases with plant density and can still be a concern for modern hybrids at a high plant density (Pedersen and Lauer, 2002; Stanger and Lauer, 2006). Lodging can cause higher harvesting costs through increased time and labor expenses, grain harvest losses, higher grain moisture at harvest, and increased grain drying costs (Olsen and Sander, 1988). In Wisconsin, it was found that as plant density increased from 64,200 to 123,500 plant $ha^{-1}$, the stalk rind penetrometer resistance fell from 3.9 to 3.7 load-kg $plant^{-1}$ and stalk lodging increased from 6 to 18% (Stanger and Lauer, 2007). Greater reduction rates in rind penetrometer resistance were observed as plant density was increased from 64,200 to 93,900 plants $ha^{-1}$ compared with the increase from 93,900 to 123,500 plant $ha^{-1}$. A similar response was observed for stalk diameter in Indiana, where increasing plant density from 54,000 to 79,000 plants $ha^{-1}$ resulted in a greater decrease in stalk diameter than was observed with the increase from 79,000 to 104,000 plants $ha^{-1}$ (Boomsma et al., 2009). Although stalk diameter may be related to lodging potential, lodging was not observed in that Indiana study.

## AGRONOMIC INTERACTIONS WITH PLANT DENSITY

Narrow row widths result in less intra-row competition between plants compared with wider row widths at the same plant density and present an opportunity to increase plant density without decreasing the intra-row spacing as dramatically as with wider row widths. Research in high-yield irrigated environments in Kansas comparing 38- , 51-, and 76-cm rows with plant densities from 79,000 to 128,500 plants $ha^{-1}$ found that maximum yield occurred with 38-cm rows and 128,500 plants $ha^{-1}$, and that plant densities should be increased with narrow rows (Staggenborg et al., 2001). However, it has been more firmly established elsewhere that the optimum plant density does not differ with row width (Porter et al., 1997; Farnham, 2001; Widdicombe and Thelen, 2002).

Research from Illinois has also shown that the optimum plant density for corn grain yield is consistent across different planting dates (Nafziger, 2009). However, the seeding rate needed to achieve a given final plant density may change with planting date if soil conditions differ. In addition, late planting can result in taller corn plants due to more vigorous early growth and greater internode elongation in warmer temperatures (Cirilo and Andrade, 1994). Higher temperatures during vegetative growth associated with delayed planting dates in Argentina increased IPAR at the silking stage by hastening leaf area development, but yield was still lower with delayed planting dates due to reduced amounts of cumulative IPAR (Cirilo and Andrade, 1994). Altering plant density with planting date may be one way to offset yield losses or decrease economic losses associated with delayed planting.

Hybrid maturity can influence optimum corn plant density, with the optimum density being lower for the larger, late-maturity hybrids compared with early-maturity hybrids (Edwards et al., 2005, Paszkiewicz and Butzen, 2007, Sarlangue et al., 2007). A 4-yr study conducted across the Corn Belt found that hybrids with relative maturities >113-d had an optimum plant density for yield of 85,200 plants ha$^{-1}$, while the optimum plant density for yield with hybrids in the 109- to 113-d, 101- to 108-d, and ≤100-d relative maturity groups were 86,500, 89,000, and 93,900 plants ha$^{-1}$, respectively

(Paszkiewicz and Butzen, 2007). Edwards et al. (2005) illustrated the extremes in Arkansas with corn hybrid relative maturities ranging from 73- to 114-d. Results showed that the early-maturity hybrids needed 130,000 plants ha$^{-1}$ to achieve the same grain yield and 200,000 plants ha$^{-1}$ to achieve the same amount of cumulative IPAR as the late-maturity hybrids at 80,000 plants ha$^{-1}$.

Biomass plasticity and reproductive partitioning have also been tied to differences in the optimum plant density (Sarlangue et al., 2007). Hybrids that are better able to adjust their per plant biomass and grain production have a lower optimum plant density. These characteristics were shown to be influenced by hybrid maturity in Argentina, where late-maturity hybrids exhibiting higher biomass plasticity and reproductive partitioning, had a lower optimum plant density than did the early-maturity hybrids. Early-maturity hybrids are shorter and have fewer leaves than late-maturity hybrids (Edwards et al., 2005); however, whether these differences are large enough among regionally-adapted hybrid maturities to affect the optimum plant density remains unclear.

Re-evaluating corn responses to plant density periodically with new hybrids in different environments has been strongly encouraged since optimum crop management practices can vary with environment and genetics (Cox, 1997; Widdicombe and Thelen, 2002; Stanger and Lauer, 2006). In addition, the interaction between hybrid and row width has been inconsistent and is not well understood. Furthermore, although early-maturity hybrids have tended to have a higher optimum plant density when trials from across the U.S. are summarized, the interaction between hybrid relative maturity and plant density may differ for regionally adapted hybrids with a narrower range in maturity.

In an effort to answer some remaining questions and understand the basis for the corn responses to planting date, row width, hybrid relative maturity, and plant density, two studies were conducted in southern Minnesota. One study evaluated the grain yield and agronomic responses of corn to six plant densities within each of three planting dates. The second study evaluated six plant densities within all combinations of two row widths and three hybrids of differing relative maturity.

# CHAPTER 2

## Agronomic Responses of Corn to Planting Date and Plant Density

## MATERIALS AND METHODS

Field experiments were conducted at University of Minnesota research and outreach centers near Lamberton (44°14’ N, 95°19’ W) and Waseca, MN (44°04’ N, 93°32’ W) from 2008 to 2010. The experimental design for each site-year was a split plot arrangement in a randomized complete block design with four replications. Main plots were three planting dates starting in late April or as early afterwards as possible, and occurred on approximately 2-wk intervals thereafter (Table 1). Split plots were six final plant densities ranging from 38,400 to 107,900 plants ha$^{-1}$ on intervals of 13,900 plants ha$^{-1}$. Plots were four 76-cm rows (3.0 m) wide by 8.5 m long. In all experiments, plots were over-planted at 128,500 plants ha$^{-1}$ and hand-thinned to the proper final plant densities at the fifth leaf collar stage (Ritchie et al., 1993), leaving a uniform stand with approximately even within-row interplant spacing.

Soil types were Normania loam (fine-loamy, mixed, mesic Aquic Haplustolls) at Lamberton and Webster silty clay loam (fine-loamy, mixed, mesic Typic Haplaquolls) at Waseca. The previous crop was soybean in all experiments. Soil P, K, and pH levels were maintained according to Rehm et al. (2006). Each year 157 kg N ha$^{-1}$ as anhydrous ammonia was injected 15 cm deep in the spring prior to seedbed preparation. Tillage at each location involved chisel plowing to a depth of 20 cm in the fall, followed by field cultivation to a depth of 9 cm in the spring before planting. Weeds were controlled with a preemergence herbicide followed by postemergence herbicide applications as needed, which varied by location and year. Corn was planted 5 cm deep using a 4-row John Deere 7300 MaxEmerge II planter (Deere and Co., Moline, IL) at Lamberton and a 4-row John Deere 7100 MaxEmerge planter at Waseca. The hybrid in all site-years was Dekalb ‘DKC52-59’, a 102-d relative maturity hybrid with transgenic resistance to glyphosate, European corn borer [(*Ostrinia nubilalis* (*Hübner*)], and corn rootworm (*Diabrotica* spp.).

Intercepted photosynthetically active radiation and leaf area index (LAI) were measured using an AccuPAR LP-80 (Decagon Devices, Pullman, WA) between 1130 and 1430 h on clear and calm days from all plots when the corn maturity of the last planting date was at the silking stage (Ritchie et al., 1993). Four independent measurements were taken from the center portion of the center two rows of each plot by placing the 0.8 m-long sensor diagonally across the row, with the external sensor simultaneously held level and above the top of the canopy. Stalk diameter was measured on the internode directly above the brace roots using an electronic caliper from all plots when the corn maturity of the last planting date was at the silking stage. Ten plants were measured in the center two rows of each plot. Plants chosen for measurement were at least 1 m from the edge of the plot. Lodging notes were taken from the center two rows of each plot just prior to harvest, ignoring the first and last four plants in each row. Plants were considered stalk lodged if the stalk was broken below the ear, and root lodged if the stalk was angled >45° from vertical.

Ear samples were collected from ten plants in the center portion of the center two rows of each plot just prior to machine harvest. The ears were shelled through a single ear electric sheller, weighed, and the moisture content measured using a Perten Aquamatic 5100 grain analyzer (Perten Instruments, Stockholm, Sweden). A subsample of the grain was dried in a forced-air oven at 60ºC until constant moisture content, after which, kernel weight was determined by weighing a sample of 500 kernels. Kernels per square meter was determined by converting the weight of the grain from the 10-plant ear samples to yield per square meter at 0 g kg$^{-1}$ moisture content, and then dividing by kernel weight. Machine grain yield and moisture content were determined by harvesting the entire length of the center two rows with a plot combine. Yield from the machine harvest and the 10-plant ear samples were adjusted to 150 g kg$^{-1}$ moisture. Plot yield was determined by combining the yields from both the 10-plant hand sample and the machine harvest as a proportional average based on the area harvested.

Economic return was determined using partial budget analyses which included only those costs and revenues that changed with the treatments. Due to changing seed costs and volatile grain prices, four economic scenarios were developed and analyzed involving all combinations of a high and low seed cost and a high and low corn grain price, which were based on the ranges of quotes from local grain elevators and seed dealers during the time of this experiment. Economic return was calculated by subtracting productions costs from gross revenue. Gross revenue was the product of corn price and grain yield, minus dockage. Production costs included seed cost, drying, dryer bin rental, and handling costs, hauling to farm and market, and storage (Table 2). Storage costs were estimated by assuming half the crop was sold immediately, 25% was sold 90 d later, and 25% was sold 180 d later. Dockage, drying, dryer bin rental, handling, and hauling to the farm costs were only calculated for half of the grain yield. All variables were considered constant across locations and years. Seed costs were estimated by assuming seeding rates were 5% greater than final plant densities due to stand establishment losses (Carter et al., 2007), thus all seeding rates expressed as seed ha$^{-1}$ are 5% greater than the final stand.

Data were analyzed using the MIXED procedure of SAS (SAS Institute, 2003). Planting date, plant density, and the interaction between planting date and plant density were considered fixed effects. Location, year, block (nested within location and year), and all interactions among these effects were considered random. When the main effect of planting date was significant, mean comparisons were made using Fisher’s protected LSD test ($\alpha = 0.05$). Regression equations were developed to describe the response of the dependent variables to plant density when significant at $\alpha = 0.05$. Linear and quadratic regression models were developed for stalk diameter, LAI, kernel weight, kernels per square meter, and economic return using the MIXED procedure of SAS when appropriate

(SAS Institute, 2003). Nonlinear quadratic-plateau regression models were developed for IPAR and grain yield using the NLIN procedure of SAS which is defined by the following equations:

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X + \hat{\beta}_2 X^2 \; if \; X < X_0$$

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X_0 + \hat{\beta}_2 {X_0}^2 \; if \; X \geq \mathrm{X}_0$$

where $\hat{Y}$ is the predicted value, $X$ is plant density, $\hat{\beta}_0$ is the intercept, $\hat{\beta}_1$ is the linear coefficient, $\hat{\beta}_2$ is the quadratic coefficient, and $X_0$ is the plant density at the intersection of the quadratic and plateau segments of the model. The regression models that were selected to describe the dependent variables to plant density had the lowest model-fit residuals, had normal and randomly distributed model-fit residuals vs. predicted values scatterplots, and were significant at $\alpha = 0.05$. Seeding rates within \$2.50 ha$^{-1}$ of the maximum net return to seed cost were determined by using the parameter estimates from the quadratic regression models.

## RESULTS AND DISCUSSION

Monthly average rainfall and air temperature varied more among years than between locations (Table 3). In 2008, April air temperature averaged 2.9°C cooler than the 30-yr average at both locations (data not shown). Additionally, May and June air temperature averaged 1.4 and 0.9°C cooler than the 30-yr average, respectively. The cool temperatures caused soil conditions to remain too wet for planting and resulted in later planting dates than desired at both locations (Table 1) but the planting dates represent the earliest planting date possible at each location. The 2009 growing season was cooler than the 30-yr average in every month except September (Table 3). Rainfall was 3 to 76 mm below the 30-yr average in every month of the 2009 growing season; however, yields up to 15 Mg ha$^{-1}$ were still obtained. Temperatures in the 2010 growing season were near the 30-yr average for all months except August, which averaged 2.4ºC higher than average. Excessive rainfall occurred in June and September at both locations, averaging 83 and 260% higher than the 30-yr average.

## Grain Yield and Yield Components

Grain yield was affected by planting date and plant density but not by the interaction between planting date and plant density (Table 4). When averaged across six plant densities, grain yield was not significantly different between the first two planting dates but yield averaged 15% less with the last planting date (Table 5). These results agree with the long-term data from southwestern Minnesota, in which grain yields within 1% of the maximum occurred with planting dates of 21 April to 6 May and that delaying planting until late May reduced yields by 20% (Coulter, 2010). In comparison, Lauer et al. (1999) reported a 30% reduction in corn grain yield when planting was delayed from early May to late May across Wisconsin. Of all the random variability in corn grain yield, covariance parameter estimates indicate that 36% was accounted for by the main effect of year, and 27% was accounted for by the interaction between environment and year. Thus, overall variation in grain yield among experiments was primarily due to differences among years, and was most likely associated with the weather patterns, which differed between locations (Table 3).

When analyzed across three planting dates, there was a quadratic-plateau response of corn grain yield to plant density (Table 6). An estimated maximum corn grain yield of 12.5 Mg ha$^{-1}$ (Table 8) occurred with 81,700 to 107,900 plants ha$^{-1}$ (Table 6). Similarly, previous research in southern Minnesota found that grain yield was maximized with plant densities 86,500 to 101,300 plants ha$^{-1}$ over two yr at Lamberton and one yr at Waseca (Porter et al., 1997). More recent research in Wisconsin found a quadratic response of corn grain yield to plant density, and that estimated maximum yield occurred with 104,500 and 98,800 plants ha$^{-1}$ for hybrids with and without the Bt trait, respectively (Stanger and Lauer, 2006). Research from Illinois and Iowa also found that grain yield had a quadratic response to plant density (Coulter et al., 2010). When corn followed soybean, grain yield was maximized at 16.1 Mg ha$^{-1}$ with 94,000 to 96,000 plants ha$^{-1}$ for Illinois and Iowa, respectively. These values, both the yield and plant density at maximum yield, are higher than those observed in this study in southern Minnesota (Tables 6 and 8) and indicate that the response of corn grain yield may differ based on yield level. Another possible reason for the discrepancy is that only one hybrid was evaluated in this study.

Grain moisture content at harvest was not affected by planting date or the interaction of planting date and plant density (Table 4). This was likely due to the fact that harvest was delayed until the last planting date had dried sufficiently to not interfere with plot combine functionality. Grain moisture was affected by plant density and decreased from 194 to 179 g $kg^{-1}$ as plant density increased from 38,400 to 107,900 plants $ha^{-1}$ (data not shown), possibly due to reduced kernel weights with increased plant density (Table 8). Although significant (Table 4), this reduction in grain moisture content was small and did not follow a trend suitable for regression analysis. The main effect of year accounted for 64% of the total random variability in harvest moisture, and was primarily related to differences weather patterns (Table 3) and the amount of in-field grain dry-down prior to harvest.

Kernel weight was affected by planting date and plant density but not the interaction of planting date and plant density (Table 4). In contrast, kernels per square meter was affected by plant density but not planting date or the interaction of planting date and plant density. These results indicate that the yield loss due to delayed planting is primarily the result of reduced kernel weight and not a reduction of kernels per square meter. When averaged across six plant densities, kernel weight did not differ between the first two planting dates, but averaged 7% less with the last planting date, which was similar to the response of grain yield to planting date (Table 5). The main effect of year accounted for 77% of the total random variability in kernel weight and was most likely due to differences weather patterns (Table 3) and the amount of kernel mass accumulation.

There was a quadratic response of kernel weight and kernels per square meter to plant density (Table 6). As plant density increased from 80,100 to 107,900 plants ha$^{-1}$, kernel weight decreased by 4%, but this was offset by a 7% increase in the number of kernels per square meter (Table 8) and grain yield did not differ ($P$ = 0.350). Hashemi et al. (2005) also found that kernel weight decreased with plant density, but with a linear response rather than a quadratic response, which may have been due to differences in environment and the use of older hybrids with lower tolerance to stresses associated with high plant densities (Tollenaar and Lee, 2002).

## Phenotypic Characteristics

Stalk diameter was affected by plant density but not by planting date or the interaction between planting date and plant density (Table 4). When averaged across three planting dates, there was a quadratic response of stalk diameter to plant density (Table 6). Stalk diameter decreased 17% as plant density increased from 38,400 to 80,100 plants ha$^{-1}$, but only by 7% as plant density increased from 80,100 to 107,900 plants ha$^{-1}$ (Table 7). Stalk lodging was affected by plant density but not by planting date or the interaction between planting date and plant density (Table 4). While stalk lodging did increase as plant density increased, stalk lodging with the highest plant density averaged just 0.4% (data not shown). The lack of widespread stalk lodging may be related to the small reduction in stalk diameter as plant density increased from 80,100 to 107,900 plants ha$^{-1}$ (Table 7). Root lodging was not affected by planting date, plant density, or the interaction between planting date and plant density (Table 4), and was rare in all locations and years.

Intercepted photosynthetically active radiation and LAI were both affected by plant density but not planting date or the interaction of planting date and plant density (Table 4). Cirilo and Andrade (1994) found that IPAR at the silking stage increased when planting was delayed, however the range in planting dates examined in that study were twice as large as those examined in this study. When averaged across planting dates, there was a quadratic-plateau response of IPAR to plant density, in which estimated IPAR was maximized at 97.7% with 98,600 to 107,900 plants ha$^{-1}$ (Table 6 and 7). When averaged across planting dates, there was a linear response of LAI to plant density (Table 6). Maximum grain yield occurred with ≥97.0% IPAR and with LAI values ≥6.1. Covariance parameter estimates indicate that the main effects and interaction of year and environment did not account for more than a total of 14% of the random variability for any of these phenotypic variables indicating that these variables did not vary significantly over years or between locations.

## Economic Return

Economic returns presented in Tables 5 and 9 are based on partial budget analyses, and are higher than actual returns because they only account for those costs and revenues affected by the treatments. All four economic scenarios responded similarly to the treatments (Table 4). Economic return was affected by planting date and plant density but not the interaction between planting date and plant density (Table 4). When averaged across six plant densities, economic return did not differ between the first two planting dates, but averaged 21% less with the last planting date (Table 5). Similar responses to planting date occurred for grain yield and kernel weight. Of the total random variation in economic return, covariance parameter estimates indicate that the interaction of year and environment accounted for 36%.

When averaged across planting dates, there was a quadratic response of economic return to plant density (Table 6). The seeding rate that maximized economic return ranged from 79,000 to 86,400 seeds ha$^{-1}$, depending on seed cost and grain price (Table 10). However, seeding rates of 82,700 to 83,900 seeds ha$^{-1}$ resulted in economic returns that were within \$2.50 ha$^{-1}$ for all four economic scenarios. In comparison, Stanger and Lauer (2006) reported an economically optimum plant density of 83,300 plants ha$^{-1}$ for Wisconsin and Coulter et al. (2010) reported an economically optimum plant density of 79,800 plants ha$^{-1}$ for Illinois, and both of these studies also assumed 5% over-seeding. These economically optimum plant densities reported for Wisconsin and Illinois were calculated using values most similar to the low seed cost and low grain price scenario analyzed in this study, which resulted in an economically optimum seeding rate of 79,000 seeds ha$^{-1}$. Coulter et al. (2010) also reported an economically optimum plant density of 91,500 and 90,200 plants ha$^{-1}$ in Iowa for corn following corn and soybean, respectively, and were also calculated using values most similar to the low seed cost and low grain price scenario analyzed in this study. The yields found by Coulter et al. (2010) in Illinois and Iowa were similar and averaged 3.4 Mg ha$^{-1}$ higher than those reported in this study. However, the final plant density which maximized economic return was 4,800 plants ha$^{-1}$ higher in Illinois and 15,800 plants ha$^{-1}$ higher in Iowa than those calculated in this study. These differences indicate that the factor influencing the economically optimum final plant density is not simply the yield level, and that the degree of the yield response to plant density can differ greatly among environments.

## CONCLUSIONS

Over three yr at two locations in southern Minnesota, corn response to plant density was similar for planting dates ranging from late April to late May. Planting dates from late April to mid-May resulted in similar yields, which averaged 12.4 Mg ha$^{-1}$, while delaying planting until late May reduced yield by 15%. These results illustrate the importance of timely corn planting in Minnesota, and should therefore be taken into account when considering other management decisions such as expanding corn hectares or utilizing winter cover crops.

The final plant densities that maximized yield in this study were 81,700 to 107,900 plants ha$^{-1}$. Seeding rates between 82,700 to 83,900 seeds ha$^{-1}$ resulted in economic returns within \$2.50 ha$^{-1}$ of the maximum for four different grain price and seed cost scenarios analyzed in this study. In Minnesota, the average final plant density for corn in 2009 was 75,600 plants ha$^{-1}$ (USDA-National Agricultural Statistics Service, 2009). Assuming 5% over-seeding, our results indicate that southern Minnesota growers who are currently growing corn at the statewide average final plant density are near maximum economic return, and that no further increases in seeding rate are needed for those growers, even when planting is delayed until late May. However, due to the large variability of corn grain prices and seed costs, these recommendations should be modified as grain prices and seed costs change.

Two limitations to this research are that only one hybrid and one cropping system were evaluated in all experiments. Both were chosen to best represent the majority of southern Minnesota corn growers, but differing genetics and cropping systems could have produced different results. Future research should evaluate the response of corn to plant density with new hybrids of contrasting genetics in environments with varying weather patterns, soil types, and cropping systems.

Table 1. Planting dates at Lamberton and Waseca, MN from 2008 to 2010.

| | | Target planting date | | |
|---|---|---|---|---|
| Location | Year | Late April | Mid-May | Late May |
| Lamberton | 2008 | 12 May | 25 May | 9 June |
| | 2009 | 24 April | 8 May | 21 May |
| | 2010 | 25 April | 9 May | 23 May |
| Waseca | 2008 | 30 April | 14 May | 28 May |
| | 2009 | 24 April | 8 May | 21 May |
| | 2010 | 22 April | 6 May | 20 May |

Table 2. Values used to determine net return to seed cost for the 3-yr planting date and plant density study.

| Variable | Value |
|---|---|
| Seed cost | |
| High seed cost (\$ 80,000 seeds$^{-1}$) | 275.00 |
| Low seed cost (\$ 80,000 seeds$^{-1}$) | 225.00 |
| Grain price | |
| High grain price (\$ Mg$^{-1}$) | 236.25 |
| Low grain price (\$ Mg$^{-1}$) | 157.50 |
| Dockage (\$ Mg$^{-1}$ for each 10 g kg$^{-1}$ > 105 g kg$^{-1}$) | 3.15 |
| Harvest, storage, and transportation costs† | |
| Drying (\$ Mg$^{-1}$ for each 10 g kg$^{-1}$ > 105 g kg$^{-1}$) | 1.97 |
| Dryer bin rental (\$ Mg$^{-1}$) | 2.91 |
| Handling by auger (\$ Mg$^{-1}$) | 2.60 |
| Hauling to farm storage (\$ Mg$^{-1}$) | 2.40 |
| Hauling to market, assuming 40 km one-way (\$ Mg$^{-1}$) | 5.79 |
| On-farm storage (\$ Mg$^{-1}$ for 30 d) | 0.91 |

† Edwards and Johanns (2010).

Table 3. Monthly rainfall and average air temperature during the 2008 to 2010 growing seasons at Lamberton and Waseca, MN. Departures from the 30-yr (1978-2007) mean are shown in parentheses.

| Location | Year | May | June | July | August | September |
|---|---|---|---|---|---|---|
| | | ——— Monthly rainfall, mm ——— | | | | |
| Lamberton | 2008 | 82 (-5) | 91 (-14) | 85 (-10) | 15 (-84) | 54 (-22) |
| | 2009 | 41 (-46) | 102 (-3) | 42 (-53) | 87 (-12) | 71 (-5) |
| | 2010 | 51 (-36) | 159 (54) | 96 (1) | 122 (23) | 269 (193) |
| Waseca | 2008 | 98 (-3) | 108 (-7) | 133 (19) | 55 (-76) | 34 (-54) |
| | 2009 | 49 (-52) | 70 (-45) | 38 (-76) | 85 (-46) | 38 (-50) |
| | 2010 | 83 (-18) | 244 (129) | 168 (54) | 59 (-72) | 322 (234) |
| | | ——— Monthly average air temperature, °C ——— | | | | |
| Lamberton | 2008 | 13.3 (-1.4) | 19.4 (-0.8) | 22.6 (0.4) | 20.8 (0.2) | 16.6 (0.6) |
| | 2009 | 14.6 (-0.1) | 19.0 (-1.2) | 19.4 (-2.8) | 19.8 (-0.8) | 17.8 (1.8) |
| | 2010 | 14.6 (-0.1) | 20.9 (0.7) | 23.6 (1.4) | 23.3 (2.7) | 15.1 (-0.9) |
| Waseca | 2008 | 13.1 (-1.3) | 19.2 (-0.9) | 22.0 (0) | 20.2 (-0.5) | 17.0 (0.9) |
| | 2009 | 14.4 (-0.2) | 18.8 (-1.3) | 19.0 (-3.0) | 19.1 (-1.6) | 17.8 (1.7) |
| | 2010 | 15.1 (0.5) | 19.4 (-0.7) | 22.6 (0.6) | 22.8 (2.1) | 14.9 (-1.2) |

Table 4. Significance of *F*-values for fixed sources of variation from statistical analyses of the 3-yr planting date and plant density study.

| | Fixed source of variation | | |
|---|---|---|---|
| Dependent variable | Planting date (P) | Plant density (D) | P × D |
| | | $P > F$ | |
| Stalk diameter | 0.187 | 0.001 | 0.128 |
| IPAR† | 0.671 | <0.001 | 0.084 |
| LAI‡ | 0.706 | <0.001 | 0.056 |
| Root lodging | 0.467 | 0.460 | 0.564 |
| Stalk lodging | 0.527 | <0.001 | 0.425 |
| Grain yield | 0.038 | <0.001 | 0.857 |
| Grain moisture | 0.170 | 0.010 | 0.960 |
| Kernel weight | 0.021 | <0.001 | 0.770 |
| Kernels $m^{-2}$ | 0.329 | <0.001 | 0.820 |
| High S, low G§ | 0.036 | <0.001 | 0.855 |
| Low S, low G | 0.036 | <0.001 | 0.855 |
| High S, high G | 0.037 | <0.001 | 0.858 |
| Low S, high G | 0.037 | <0.001 | 0.858 |

† Intercepted photosynthetically active radiation (IPAR) measurements when after the last planting date was at the silking stage.

‡ Leaf area index (LAI) measurements when after the last planting date was at the silking stage.

§ Net return to seed costs (S) and grain prices (G) based on a partial budget analyses for both a high and low S of 275 and 225 ($ 80,000 $seeds^{-1}$), respectively, and a high and low G of 236.25 and 157.50 ($ $Mg^{-1}$), respectively.

Table 5. Grain yield, kernel weight, and net return to seed cost based on partial budget analyses for both a high and low seed cost (S) and grain prices (G)† as affected by planting date, across plant densities.

| Planting date | Grain yield | Kernel weight | High S low G | Low S low G | High S high G | Low S high G |
|---|---|---|---|---|---|---|
| | Mg ha$^{-1}$ | mg kernel$^{-1}$ | $ ha$^{-1}$ | | | |
| Late April | 12.6 a‡ | 313 a | 1488 a | 1536 a | 2476 a | 2524 a |
| Mid-May | 12.2 a | 309 a | 1423 a | 1471 a | 2386 a | 2434 a |
| Late May | 10.6 b | 288 b | 1108 b | 1156 b | 1939 b | 1987 b |

† High and low S were 275 and 225 ($ 80,000 seeds$^{-1}$), respectively. High and low G were 236.25 and 157.50 ($ Mg$^{-1}$), respectively.

‡ Within a column for a given dependent variable, treatment means followed by the same letter are not significantly different ($\alpha = 0.05$)

Table 6. Parameter estimates, $R^2$ values, and model significance values for regression models of the 3-yr planting date and plant density study.

| | | Parameter estimates† | | | | | |
|---|---|---|---|---|---|---|---|
| Dependent variable | Regression model | $\hat{\beta}_0$ | $\hat{\beta}_1$ | $\hat{\beta}_2$ | $X_0$ | $R^2$ | Model significance |
| | | | | | plants $ha^{-1}$ | | $P > F$ |
| Stalk diameter (mm) | Quadratic (Q) | 34.025 | -0.2273 | 0.0010 | - | 0.52 | <0.001 |
| IPAR (%)‡ | Q + plateau (QP) | 68.185 | 0.5982 | -0.0030 | 98,600 | 0.54 | <0.001 |
| LAI ($m^2$ $m^{-2}$)§ | Linear (L) | 2.8406 | 0.0400 | - | - | 0.85 | <0.001 |
| Grain yield (Mg $ha^{-1}$) | QP | 3.3670 | 0.2235 | -0.0014 | 81,700 | 0.27 | <0.001 |
| Kernel weight (mg) | Q | 452.91 | -3.2323 | 0.0146 | - | 0.88 | <0.001 |
| Kernels $m^{-2}$ | Q | 488.98 | 75.953 | -0.3542 | - | 0.71 | <0.001 |
| High S low G (\$ $ha^{-1}$)¶ | Q | 655.10 | 18.935 | -0.1188 | - | 0.75 | <0.001 |
| Low S low G (\$ $ha^{-1}$) | Q | 782.88 | 15.933 | -0.1009 | - | 0.76 | <0.001 |
| High S high G (\$ $ha^{-1}$) | Q | 1054.51 | 31.676 | -0.1872 | - | 0.76 | <0.001 |
| Low S high G (\$ $ha^{-1}$) | Q | 1054.51 | 32.332 | -0.1872 | - | 0.76 | <0.001 |

† Parameter estimates expressed as plants $ha^{-1}$/1,000.

‡ Intercepted photosynthetically active radiation (IPAR) measurements when after the last planting date was at the silking stage.

§ Leaf area index (LAI) measurements when after the last planting date was at the silking stage.

¶ Net return to seed costs (S) and grain prices (G) based on a partial budget analyses for both a high and low S of 275 and 225 (\$ 80,000 $seeds^{-1}$), respectively, and a high and low G of 236.25 and 157.50 (\$ $Mg^{-1}$), respectively.

Table 7. Observed means for stalk diameter, intercepted photosynthetically active radiation (IPAR), leaf area index (LAI)†, along with corresponding predicted values from regression models relating these dependent variables to plant density, across planting dates.

| | Stalk diameter | | IPAR | | LAI | |
|---|---|---|---|---|---|---|
| Plant density | Observed mean | Predicted mean | Observed mean | Predicted mean | Observed mean | Predicted mean |
| plants ha$^{-1}$ | mm | | % | | m$^2$ m$^{-2}$ | |
| 38,400 | 27.3 | 26.8 | 87.2 | 87.4 | 4.21 | 4.37 |
| 52,300 | 25.2 | 24.8 | 91.3 | 91.5 | 4.86 | 4.93 |
| 66,200 | 23.7 | 23.3 | 94.9 | 94.5 | 5.77 | 5.49 |
| 80,100 | 22.7 | 22.2 | 96.4 | 96.6 | 6.11 | 6.04 |
| 94,000 | 21.9 | 21.4 | 97.5 | 97.6 | 6.71 | 6.60 |
| 107,900 | 21.2 | 21.0 | 97.9 | 97.7 | 6.97 | 7.15 |

† IPAR and LAI measurements taken when the last planting date was at the silking stage.

Table 8. Observed means for grain yield, kernel weight, and kernels m$^{-2}$, along with corresponding predicted values from regression models relating these dependent variables to plant density, across planting dates.

| | Grain yield | | Kernel weight | | Kernels m$^{-2}$ | |
|---|---|---|---|---|---|---|
| Plant density | Observed mean | Predicted mean | Observed mean | Predicted mean | Observed mean | Predicted mean |
| plants ha$^{-1}$ | —— Mg ha$^{-1}$ —— | | ——— mg ——— | | | |
| 38,400 | 9.9 | 9.9 | 349 | 350 | 2870 | 2880 |
| 52,300 | 11.4 | 11.3 | 328 | 324 | 3510 | 3490 |
| 66,200 | 12.0 | 12.2 | 301 | 303 | 3980 | 3970 |
| 80,100 | 12.3 | 12.5 | 285 | 288 | 4270 | 4300 |
| 94,000 | 12.5 | 12.5 | 280 | 278 | 4500 | 4500 |
| 107,900 | 12.5 | 12.5 | 274 | 274 | 4560 | 4560 |

Table 9. Observed means for net return to seed cost based on partial budget analysis for both a high and low seed cost (S) and grain price (G)†, along with corresponding predicted values from regression models relating these dependent variables to plant density, across planting dates.

| | High S low G | | Low S low G | | High S high G | | Low S high G | |
|---|---|---|---|---|---|---|---|---|
| Seeding rate | Observed mean | Predicted mean | Observed mean | Predicted mean | Observed mean | Predicted mean | Observed mean | Predicted mean |
| seeds ha$^{-1}$ | | | | $ ha$^{-1}$ | | | | |
| 38,400 | 1186 | 1207 | 1212 | 1246 | 1964 | 1995 | 1989 | 2020 |
| 52,300 | 1358 | 1320 | 1392 | 1340 | 2257 | 2199 | 2291 | 2233 |
| 66,200 | 1398 | 1388 | 1442 | 1395 | 2345 | 2331 | 2388 | 2374 |
| 80,100 | 1394 | 1410 | 1447 | 1412 | 2366 | 2391 | 2418 | 2443 |
| 94,000 | 1369 | 1385 | 1430 | 1389 | 2353 | 2378 | 2414 | 2440 |
| 107,900 | 1332 | 1315 | 1403 | 1327 | 2320 | 2293 | 2391 | 2364 |

† High and low S were 275 and 225 ($ 80,000 seeds$^{-1}$), respectively. High and low G were 236.25 and 157.50 ($ Mg$^{-1}$), respectively.

Table 10. Seeding rate at maximum net return to seed cost and seeding rates within \$2.50 ha$^{-1}$ of maximum net return to seed cost from regression models for net return to seed cost based on partial budget analysis for both a high and low seed cost (S) and grain price (G),† across planting dates.

| Economic scenario | Seeding rate at maximum net return | Seeding rates ±\$2.50 ha$^{-1}$ of maximum net return to seed cost |
|---|---|---|
| | seeds ha$^{-1}$ | |
| High S low G | 79,700 | 75,100 to 84,300 |
| Low S low G | 79,000 | 74,000 to 83,900 |
| High S high G | 84,600 | 80,800 to 88,300 |
| Low S high G | 86,400 | 82,700 to 90,000 |

† High and low S were 275 and 225 (\$ 80,000 seeds$^{-1}$), respectively. High and low G were 236.25 and 157.50 (\$ Mg$^{-1}$), respectively.

# CHAPTER 3

# Agronomic Responses of Corn Hybrids to Row Width and Plant Density

## MATERIALS AND METHODS

From 2009 to 2010, field experiments were conducted near Lamberton (44°14’ N, 95°19’ W) and Waseca, MN (44°04’ N, 93°32’ W) at University of Minnesota research and outreach centers. For each site-year, a split plot arrangement in a randomized complete block with four replications was the experimental design. Main plots were a factorial arrangement of two row widths and three hybrids. Split plots were six final plant densities ranging from 41,700 to 108,700 plants ha$^{-1}$ on intervals spaced at 13,600 plants ha$^{-1}$ and were four 76-cm rows (3.0 m) or five 51-cm rows (2.6 m) wide by 9.7 m long. To achieve the proper final plant densities, plots were over-planted at 128,500 plants ha$^{-1}$ and hand-thinned to a uniform stand with approximately uniform within-row interplant spacing at the fifth leaf collar stage (Ritchie et al., 1993).

The previous crop was corn in all experiments. Soil types were Normania loam (fine-loamy, mixed, mesic Aquic Haplustolls) and Webster silty clay loam (fine-loamy, mixed, mesic Typic Haplaquolls) at Lamberton and Waseca, respectively. Recommendations from Rehm et al. (2006) were used to maintain soil P, K, and pH levels. Each year, 179 kg N ha$^{-1}$ as anhydrous ammonia was injected 15 cm deep in the spring prior to seedbed preparation. Fall tillage consisted stalk chopping followed by disk-chiseling to a depth of 25 cm and two passes of field cultivation at a depth of 9 cm following the N application. A preemergence herbicide, followed by postemergence herbicide applications as needed were used to control weeds. Corn was planted in all experiments using a customized Almaco cone-type planter (Almaco, Nevada, IA) capable of planting either four 76- or five 51-cm rows. The hybrids used in all experiments were Pioneer (Pioneer Hi-Bred Int., Johnston, IA) '38P43', '37N68', and '35F44', with relative maturity ratings of 95-, 101-, and 105-d, respectively. Hybrids chosen were similar in all agronomic characteristics except for relative maturity. All hybrids contained transgenic resistance to glyphosate, glufosinate, European corn borer [(*Ostrinia nubilalis* (*Hübner*)], corn rootworm (*Diabrotica* spp.). The planting date in 2009 was 24 April at both locations and in 2010 it was 29 April at Lamberton and 20 April at Waseca.

An AccuPAR LP-80 (Decagon Devices, Pullman, WA) was used to measure IPAR and LAI. Measurements were taken between 1130 and 1430 h on clear and calm days from all plots when the 105-d relative maturity hybrid was at the silking stage (Ritchie et al., 1993). The 0.8 m-long sensor bar was placed diagonally across the center two 76-cm rows or across two of the center three 51-cm rows. Four independent measurements were taken from the center portion of the plot while the external sensor was simultaneously held level and above the top of the canopy. An electronic caliper was used to measure stalk diameter on the internode directly above the brace roots when the 105-d relative maturity hybrid was at the silking stage. Stalk diameter was measured on ten plants from the center two or three rows that were at least 1 m from the end of the plot. Just prior to harvest, lodging notes were taken from the center two or three rows of each plot, ignoring the first and last three plants in the row. Plants were considered root lodged if the stalk was angled >45° from vertical and stalk lodged if the stalk was broken below the ear.

Corn grain yield and moisture content were measured by using a plot combine to harvest the entire length of the center two 76-cm rows or center three 51-cm rows of each plot, resulting in the same harvest area for each row width. Separate two- and three-row combine headers that were built for these row widths were used to harvest the 76- and 51-cm rows, respectively. Yield was adjusted to 150 g $kg^{-1}$ moisture content. Grain samples from each plot were collected with the combine at harvest. Grain samples from each plot were air dried in a forced-air drier at 60ºC until constant moisture, and kernel weight was determined by weighing a sample of 300 kernels. Kernels per square meter was determined by adjusting plot yields to 0 g $kg^{-1}$ moisture content, and then dividing by kernel weight.

Partial budget analyses including only those costs and revenues that changed with the treatments were used to determine economic return which was calculated as gross revenue less production costs. Due to volatile grain prices, gross revenue is the product of grain yield and a high and low corn grain price, based on the range of quotes from local grain elevators at the time of this experiment, minus dockage. Production costs included drying, dryer bin rental, and handling costs, hauling to farm and market, storage, and a high and low seed cost, based on the range of quotes from local seed dealers at the time of this experiment (Table 2). By assuming half the crop was sold immediately, 25% was sold 90 d later, and 25% was sold 180 d later, storage costs were estimated. All variables were considered constant across both years and both locations. Half of the grain yield was used to calculate dockage, drying, dryer bin rental, handling, and hauling to the farm. By assuming 5% over-seeding from the final plant density, seed costs were estimated to account for losses in stand establishment (Carter et al., 2007). Crop production costs were assumed to be similar for both row widths since crop production costs reported by growers in southwest and south-central Minnesota from 1993 to 2009 showed that production and machinery costs were within \$25 $ha^{-1}$ on average for 48 to 64 cm and 66 to 81 cm row widths (Center for Farm Financial Management, 2011).

To analyze the data, the MIXED procedure of SAS (SAS Institute, 2003) was used. Hybrid, row width, plant density and all interactions with these effects were considered fixed effects. Location, year, block (nested within location and year), and all interactions with these effects were considered random. Mean comparisons were made using Fisher’s protected LSD test ($\alpha = 0.05$) when the effect of hybrid was significant at $\alpha = 0.05$. When the response of the dependent variables to plant density was significant at $\alpha = 0.05$, regression equations were developed. The MIXED procedure of SAS was used to develop linear and quadratic regression models were appropriate to describe the response of IPAR, LAI, kernel weight, and kernels per square meter to plant density. The NLIN procedure of SAS which is defined by the following equations:

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X + \hat{\beta}_2 X^2 \ if \ X < X_0$$

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X_0 + \hat{\beta}_2 {X_0}^2 \ if \ X \geq X_0$$

where $\hat{Y}$ is the predicted value, $X$ is the plant density, $\hat{\beta}_0$ is the intercept, $\hat{\beta}_1$ is the linear coefficient, $\hat{\beta}_2$ is the quadratic coefficient, and $X_0$ is the plant density at the intersection of the quadratic response and plateau line was used were appropriate to develop non-linear quadratic-plateau regression models to describe the response of grain yield to plant density. Model-fit residuals and scatterplots of model-fit residuals vs. predicted values were used to determine which regression model was most appropriate.

## RESULTS AND DISCUSSION

Monthly average rainfall and air temperature varied less between locations than years (Table 3). The 2009 growing season averaged 2.1ºC cooler than the 30-yr average for both locations from May to August. However, the month of September was 1.8ºC warmer than the 30-yr average at both locations. Rainfall in 2009 was below the 30-yr average at both locations, averaging 24 and 54 mm less per month from May to September at Lamberton and Waseca, respectively. During the 2010 growing season, the month of August averaged 12% warmer than the 30-yr average while all the other months had air temperatures within -0.7 to 1.3ºC of the average. Rainfall during the 2010 growing season was excessive during June and September, with totals measuring 54 and 129 mm, and 193 and 234 mm above the 30-yr average at Lamberton and Waseca, respectively.

## Grain Yield and Yield Components

Grain yield was affected by hybrid and plant density, but not by row width or any of the interactions among the fixed effects (Table 11). When averaged across three hybrids and six plant densities, row width had a non-significant effect on grain yield, harvest moisture, kernel weight, and kernels per square meter ($P \geq 0.527$). These results contradict previous work from southern Minnesota where a 7% grain yield advantage was reported with 25- and 51-cm row widths compared with a 76 cm row width (Porter et al., 1997). It is likely that as breeders have modified corn hybrids to withstand increased plant density stresses (Tollenaar and Lee, 2002), they have also indirectly been breeding corn for increased performance in 76-cm rows through improved tolerance to crowding stress, as within-row interplant spacing is less in 76-cm rows than in 51-cm rows for a given plant density. The main effect of environment and year accounted for 23 and 42% of the total random variability in corn grain yield, respectively, as indicated by the covariance parameter estimates. The interaction of environment and year accounted for 5% and the sum of the interactions of hybrid and/or row width and/or density with environment and/or year accounted for 9% of the total random variability in corn grain yield. This indicates that differences in years and environments influenced the random variability of grain yield but were consistent for all the treatments.

There was no interaction between row width and plant density, or between row width and hybrid for any of the measured variables (Table 11). This indicates that corn grown in 51-cm or 76-cm rows will respond similarly to changes in plant density and to hybrids of differing relative maturity within an adapted range. The lack of interaction between row width and plant density for corn grain yield agrees with previous research from Minnesota (Porter et al., 1997), New York (Cox et al., 1998), and Iowa (Farnham, 2001). Also in agreement with these results, no interaction between row width and hybrid was observed for grain yield by Porter et al. (1997) or for silage yield by Cox et al. (1998; 2006). However, out of six hybrids, Farnham (2001) reported that one early-maturity hybrid yielded 5% more in 76-cm rows than in 38-cm rows, and that one late-maturity hybrid yielded 2% more in 38-cm rows than in 76-cm rows. It is possible that certain hybrids may respond better to narrow rows for reasons other than relative maturity.

One hybrid characteristic commonly discussed but not well understood within the seed corn industry is ear flex, also known as reproductive plasticity. The Pioneer Hi-Bred Int. corn seed guide defines ear flex as “the ability of a hybrid to flex ear size as plant density is reduced or as growing conditions improve” (Pioneer Hi-Bred Int., 2010). The hybrids chosen in this study were given ear flex ratings of 5, 4, and 5 for the 95-, 101-, and 105-d hybrids, respectively, with a 9 being excellent flex and a 1 being very little flex or fixed ear types. The range of ear flex ratings for hybrids available from Pioneer Hi-Bred Int. in 2010 was from 4 to 8 for hybrids with maturity ratings from 83- to 110-d (Pioneer Hi-Bred Int., 2009). Research from Argentina found that uneven within-row interplant spacing can cause a greater reduction in corn grain yield for fixed ear type hybrids compared with flex ear type hybrids (Andrade and Abbate, 2005). It is possible that flex ear type hybrids may respond more positively to the increase in within-row interplant spacing experienced with a reduction from a 76- to 51-cm row width compared with fixed ear type hybrids.

When averaged across two row widths and six plant densities, grain yield increased with increasing hybrid relative maturity, and the 105-d hybrid yielded 13% more than the 95-d hybrid (Table 12). These results are in agreement with Farnham (2001) and Lauer et al. (1999) when averaged across row widths and early planting dates, respectively. Kernel weight and kernels per square meter were also both affected by hybrid (Table 11). Kernel weight was similar for the 95- and 101-d hybrid, which averaged 7% more than the 105-d hybrid (Table 12). However, the 105-d hybrid had the greatest number of kernels per square meter, which contributed to it having the highest yield. These results demonstrate how late-maturity hybrids can have the potential for higher yields (Lauer et al., 1999; Farnham, 2001). If more favorable late-season growing conditions occurred and kernel weight of the 105-d hybrid would have increased to the levels of the 95- and 101-d hybrids, estimated total grain yield of the 105-d hybrid would have been 7% higher. However, only one hybrid of each relative maturity was studied and it is likely that factors besides relative maturity, but also genetics affect the potential kernel weight and kernel number of a given hybrid. The covariance parameter estimates indicate that the main effect of year accounted for 52% of the random variability with kernel weight while no other single effect accounted for greater than 18% of the variability with kernel weight or kernels per square meter. The differences in weather patterns between years was most likely the contributor to the large amount of random variability due to year with kernel weight (Table 3), and similar results were found in the planting date and plant density study described in Chapter 2.

When averaged across three hybrids and two row widths, there was a quadratic-plateau response of corn grain yield response to plant density. An estimated maximum grain yield of 10.9 Mg ha$^{-1}$ occurred at 84,500 to 108,700 plants ha$^{-1}$ (Tables 13 and 15). Kernel weight decreased by 6% as plant density increased from 81,500 to 108,700 plants ha$^{-1}$, but grain yield did not differ (*P* = 0.862), most likely due to a 5% increase in kernels per square meter (Table 15). Previous research in southern Minnesota found that in two of three yr at Lamberton and one yr at Waseca, corn grain yield was maximized with plant densities ranging from 86,500 to 101,300 plants ha$^{-1}$ (Porter et al., 1997). The results from this study indicate that a similar response of grain yield to plant density was observed. In comparison, recent work from Wisconsin with transgenic hybrids with Bt resistance to European corn borer found a quadratic response of grain yield to plant density, with an estimated maximum yield of 12.8 Mg $ha^{-1}$ at 104,500 plants $ha^{-1}$ and 95% of the maximum yield at 72,100 plants $ha^{-1}$ (Stanger and Lauer, 2006). Although there was a quadratic-plateau response of corn grain yield to plant density in this study, the plant density at the maximum and 95% of the maximum grain yield were similar between the studies.

## Phenotypic Characteristics

Stalk diameter, stalk lodging, and root lodging were not affected by hybrid, row width, plant density, or their interactions (Table 11). Both stalk and root lodging was very rare in all experiments and is likely the reason why no significance was found. Covariance parameter estimates indicate that 48% of the total random variability of stalk diameter was accounted for by environment, year, and their interaction. Smaller differences in stalk diameter among plant densities, compared with the differences observed in the planting date and plant density study described in Chapter 2, may have contributed to the lack of significance observed for stalk diameter. Intercepted photosynthetically active radiation and LAI were both affected by hybrid and plant density, but not by row width or any of the interactions among the fixed effects. These results agree with Andrade et al. (2002) and Maddonni et al. (2006), who reported that when corn in 76-cm rows can achieve IPAR and LAI values similar to that in narrower row widths, corn grain yield was similar. The lack of a significant interaction between hybrid and row width for both IPAR and LAI indicate that the relative maturity differences between these regionally adapted hybrids were not large enough for the early-maturity hybrid to response differently to row width. Similarly, the lack of a significant interaction between plant density and row width for both IPAR and LAI indicates that corn in either high or low plant densities in 51-cm rows did not intercept more radiation or produce greater leaf area than corn in 76-cm rows.

When averaged across two row widths and three hybrids, there was a quadratic response of IPAR to plant density, with an estimated maximum IPAR of 96% at 108,700 plants ha$^{-1}$, which was the highest plant density tested (Tables 13 and 14). When averaged across row widths and hybrids, the response of LAI to plant density was linear (Table 13). Maximum corn grain yield across row widths and hybrids was estimated to occur at 84,500 to 108,700 plants ha$^{-1}$ with ≥94.0% IPAR and LAI values ≥5.9 (Table 13). Maximum corn grain yield in the planting date and plant density study described in Chapter 2 was estimated to occur at 81,700 to 107,900 plants ha$^{-1}$ with ≥97.0% IPAR and LAI values ≥6.1 (Table 6). These differences may be related to having lower yield levels in this study and corn versus soybean as a previous crop. When averaged across row widths and plant densities, IPAR and LAI did not differ between the 105- and 101-d hybrids, but averaged 3 and 11% less with the 95-d hybrid, respectively (Table 12). The covariance parameter estimates indicate that the main effect of year accounted for 25% of the random variability, likely due to differences in weather patterns (Table 3), with IPAR while no other single effect accounted for greater than 12% of the variability with IPAR or LAI.

One visual observation that was noted for corn in the 51-cm rows was a more random leaf arrangement compared with the 76-cm rows, especially at the low plant densities from 40,700 to 67,900 plants ha$^{-1}$. Both low plant densities and 51-cm rows have large distances between plants within the row which can inhibit the ability of a plant to sense neighboring plants and orient its leaves perpendicular to the row direction (Girardin and Tollenaar, 1994). This discrepancy was not as evident at the higher plant densities, but there was no significant effect of row width or the interaction existed row width and plant density for IPAR in this study (Table 11).

## Economic Return

All four economic scenarios responded similarly to the treatments and were not affected by hybrid, row width, plant density, or any of their interactions (Table 11). The average yield in this study was 10.4 Mg ha$^{-1}$, which was 5% lower than the 5-yr county average from 2003 to 2008 at these locations (USDA-National Agricultural Statistics Service, 2011). The lower yields observed in this study were likely related to possible above normal N losses in 2010 due to rainfall which averaged 67% greater than the 30-yr average at both locations, or because of having corn as a previous crop. For example, previous research from Iowa and Wisconsin found that corn grain yield was 13 to 14%

lower when following corn rather than soybean (Pedersen and Lauer, 2003; Al-Kaisi et al., 2008). The lower yields may have contributed to the lack of a significant response of economic return to plant density, which is most likely due to a weak response of corn grain yield to plant density, as indicated by the smaller $\hat{\beta}_1$ parameter estimate for this study (Table 13) when compared with the $\hat{\beta}_1$ parameter estimate in the previous planting date and plant density study described in Chapter 2 (Table 6). Additionally, the effect of hybrid did not significantly influence the response of economic return and was likely partially due to the grain yield advantage of the late-maturity hybrid being offset by higher harvest grain moisture content and thus, drying costs.

## CONCLUSIONS

Over two yr at two locations in southern Minnesota, there were no significant interactions between two row widths, three hybrids, and six plant densities for any of the variables measured in this study. Grain yield, IPAR, LAI, and economic return did not differ between 51- and 76-cm row widths. The 105-d hybrid yielded 1.3 Mg $ha^{-1}$ more than the 95-d hybrid. The 101- and 105-d hybrids had similar IPAR, which was 3% greater than that with the 95-d hybrid. The 101- and 95-d hybrids had similar kernel weight and kernels per square meter, which were 22 mg $kernel^{-1}$ higher and 643 kernels $m^{-2}$ lower than with the 105-d hybrid, respectively. The plant densities that maximized yield in this study were 84,500 to 108,700 plants $ha^{-1}$. Economic return was not significantly affected by plant density and indicates that seeding rates from 42,700 to 114,100 seeds ha$^{-1}$ will optimize economic return. Growers in southern Minnesota producing corn in 51-cm rows should plant the same hybrids and plant densities as those recommended for 76-cms rows, and will likely not get higher yields with the narrower row width. Since the average final plant density for Minnesota in 2009 was 75,600 plants ha$^{-1}$ (USDA-National Agricultural Statistics Service, 2009), growers currently growing corn following corn at plant density levels near the average may see a slight yield increase with higher plant densities.

Evaluation of a greater number of hybrids with differing relative maturity would be useful to confirm that the responses to hybrid in this study are truly due to maturity differences and not simply differences in the hybrids themselves. Since the response of corn grain yield to row width in this study differs from that in previous research conducted in corn following soybean cropping systems in southern Minnesota, it should be further evaluated the future. In addition, all agronomic practices should be re-evaluated periodically due to the potential changes in environments and the response of improved hybrids to these practices.

Table 1. Values used to determine net return to seed cost for the 2-yr row width, hybrid, and plant density study.

| Variable | Value |
|---|---|
| Seed cost | |
| High seed cost ($ 80,000 seeds$^{-1}$) | 275.00 |
| Low seed cost ($ 80,000 seeds$^{-1}$) | 225.00 |
| Grain price | |
| High grain price ($ Mg$^{-1}$) | 236.25 |
| Low grain price ($ Mg$^{-1}$) | 157.50 |
| Dockage ($ Mg$^{-1}$ for each 10 g kg$^{-1}$ > 105 g kg$^{-1}$) | 3.15 |
| Harvest, storage, and transportation costs† | |
| Drying ($ Mg$^{-1}$ for each 10 g kg$^{-1}$ > 105 g kg$^{-1}$) | 1.97 |
| Dryer bin rental ($ Mg$^{-1}$) | 2.91 |
| Handling by auger ($ Mg$^{-1}$) | 2.60 |
| Hauling to farm storage ($ Mg$^{-1}$) | 2.40 |
| Hauling to market, assuming 40 km one-way ($ Mg$^{-1}$) | 5.79 |
| On-farm storage ($ Mg$^{-1}$ for 30 d) | 0.91 |

† Edwards and Johanns (2010).

Table 2. Monthly rainfall and average air temperature during the 2009 to 2010 growing seasons at Lamberton and Waseca, MN. Departures from the 30-yr (1979-2008) mean are shown in parentheses.

| Location | Year | May | June | July | August | September |
|---|---|---|---|---|---|---|
| | | ——— Monthly rainfall, mm ——— | | | | |
| Lamberton | 2009 | 41 (-46) | 102 (-4) | 42 (-52) | 87 (-15) | 71 (-4) |
| | 2010 | 51 (-36) | 159 (53) | 96 (2) | 122 (25) | 269 (194) |
| Waseca | 2009 | 49 (-51) | 70 (-46) | 38 (-77) | 85 (-45) | 38 (-48) |
| | 2010 | 83 (-17) | 244 (128) | 168 (53) | 59 (-71) | 322 (236) |
| | | ——— Monthly average air temperature, °C ——— | | | | |
| Lamberton | 2009 | 14.6 (-0) | 19.0 (-1.2) | 19.4 (-2.8) | 19.8 (-0.8) | 17.8 (1.9) |
| | 2010 | 14.6 (-0) | 20.9 (0.7) | 23.6 (1.4) | 23.3 (2.7) | 15.1 (-0.8) |
| Waseca | 2009 | 14.4 (-0.2) | 18.8 (-1.3) | 19.0 (-3.1) | 19.1 (-1.6) | 17.8 (1.8) |
| | 2010 | 15.1 (0.5) | 19.4 (-0.7) | 22.6 (0.5) | 22.8 (2.1) | 14.9 (-1.1) |

Table 3. Significance of *F*-values for fixed sources of variation from statistical analyses of the 2-yr row width, hybrid, and plant density study.

| | Fixed source of variation | | | | | | |
|---|---|---|---|---|---|---|---|
| Dependent variable | Hybrid (H) | Row width (R) | Plant density (D) | H × R | H × D | R × D | H × R × D |
| | | | | $P > F$ | | | |
| Stalk diameter | 0.208 | 0.788 | 0.070 | 0.432 | 0.154 | 0.541 | 0.909 |
| IPAR† | 0.043 | 0.649 | 0.005 | 0.889 | 0.082 | 0.910 | 0.823 |
| LAI‡ | 0.043 | 0.989 | <0.001 | 0.739 | 0.406 | 0.715 | 0.251 |
| Root lodging | 0.540 | 0.425 | 0.615 | 0.549 | 0.533 | 0.641 | 0.469 |
| Stalk lodging | 0.582 | 0.414 | 0.465 | 0.536 | 0.517 | 0.913 | 0.970 |
| Grain yield | 0.048 | 0.586 | 0.016 | 0.903 | 0.862 | 0.731 | 0.756 |
| Grain moisture | 0.166 | 0.752 | 0.092 | 0.564 | 0.494 | 0.792 | 0.782 |
| Kernel weight | 0.014 | 0.849 | <0.001 | 0.946 | 0.739 | 0.637 | 0.434 |
| Kernels $m^{-2}$ | 0.017 | 0.527 | 0.001 | 0.847 | 0.574 | 0.934 | 0.960 |
| High S, low G§ | 0.125 | 0.655 | 0.292 | 0.854 | 0.721 | 0.803 | 0.789 |
| Low S, low G | 0.125 | 0.655 | 0.249 | 0.854 | 0.721 | 0.803 | 0.789 |
| High S, high G | 0.076 | 0.649 | 0.157 | 0.873 | 0.787 | 0.780 | 0.787 |
| Low S, high G | 0.076 | 0.649 | 0.112 | 0.873 | 0.787 | 0.780 | 0.787 |

† Intercepted photosynthetically active radiation (IPAR) measurements taken when the late-maturity hybrid was at the silking stage.

‡ Leaf area index (LAI) measurements taken when the late-maturity hybrid was at the silking stage.

§ Net return to seed costs (S) and grain prices (G) based on a partial budget analyses for both a high and low S of 275 and 225 (\$ 80,000 seeds$^{-1}$), respectively, and a high and low G of 236.25 and 157.50 (\$ Mg$^{-1}$), respectively.

Table 4. Intercepted photosynthetically active radiation (IPAR), leaf area index (LAI)†, grain yield, kernel weight, and kernels m$^{-2}$, as affected by hybrid, across row widths and plant densities.

| Hybrid relative maturity | IPAR | LAI | Grain yield | Kernel weight | Kernels m$^{-2}$ |
|---|---|---|---|---|---|
| days | % | m$^{2}$ m$^{-2}$ | Mg ha$^{-1}$ | mg kernel$^{-1}$ | |
| 95 | 89.9 b‡ | 5.1 b | 9.7 b | 293 a | 3332 b |
| 101 | 92.4 a | 5.7 a | 10.4 ab | 302 a | 3445 b |
| 105 | 92.7 a | 5.8 a | 11.0 a | 276 b | 4031 a |

† IPAR and LAI measurements taken when the late-maturity hybrid was at the silking stage.

‡ Within a column for a given dependent variable, treatment means followed by the same letter are not significantly different ($\alpha = 0.05$).

Table 5. Parameter estimates, $R^2$ values, and model significance values for regression models relating plant density to intercepted photosynthetically active radiation (IPAR), leaf area index (LAI)†, grain yield, kernel weight, and kernels $m^{-2}$, across hybrids and row widths.

| | | Parameter estimates‡ | | | | | |
|---|---|---|---|---|---|---|---|
| Dependent variable | Regression model | $\hat{\beta}_0$ | $\hat{\beta}_1$ | $\hat{\beta}_2$ | $X_0$ | $R^2$ | Model significance |
| | | | | | plants $ha^{-1}$ | | $P > F$ |
| IPAR (%) | Quadratic | 68.836 | 0.4754 | -0.0021 | - | 0.47 | <0.001 |
| LAI ($m^2$ $m^{-2}$) | Linear | 3.0120 | 0.0338 | - | - | 0.45 | <0.001 |
| Grain yield (Mg $ha^{-1}$) | Quadratic-plateau | 3.0096 | 0.1878 | -0.0011 | 84,500 | 0.20 | <0.001 |
| Kernel weight (mg) | Quadratic | 874.78 | 57.831 | -0.2603 | - | 0.49 | <0.001 |
| Kernels $m^{-2}$ | Linear | 344.45 | -0.7255 | - | - | 0.71 | <0.001 |

† IPAR and LAI measurements taken when the late-maturity hybrid was at the silking stage.

‡ Parameter estimates expressed as plants $ha^{-1}$/1,000.

Table 6. Observed means for grain yield, kernels m$^{-2}$, and kernel weight, along with corresponding predicted values from regression models relating these dependent variables to plant density, across hybrids and row widths.

| | Grain yield | | Kernels m$^{-2}$ | | Kernel weight | |
|---|---|---|---|---|---|---|
| Plant density | Observed mean | Predicted mean | Observed mean | Predicted mean | Observed mean | Predicted mean |
| plants ha$^{-1}$ | — Mg ha$^{-1}$ — | | | | — mg — | |
| 40,700 | 8.8 | 8.8 | 2800 | 2800 | 314 | 315 |
| 54,300 | 10.0 | 9.9 | 3240 | 3250 | 307 | 305 |
| 67,900 | 10.6 | 10.6 | 3590 | 3600 | 295 | 295 |
| 81,500 | 11.0 | 10.9 | 3880 | 3860 | 283 | 285 |
| 95,100 | 11.0 | 10.9 | 4010 | 4020 | 275 | 275 |
| 108,700 | 10.9 | 10.9 | 4090 | 4090 | 267 | 266 |

Table 7. Observed means for intercepted photosynthetically active radiation (IPAR), and leaf area index (LAI)†, along with corresponding predicted values from regression models relating these dependent variables to plant density, across hybrids and row widths.

| | IPAR | | LAI | |
|---|---|---|---|---|
| Plant density | Observed mean | Predicted mean | Observed mean | Predicted mean |
| plants ha$^{-1}$ | —— % —— | | — m$^2$ m$^{-2}$ — | |
| 40,700 | 84.6 | 84.7 | 4.3 | 4.4 |
| 54,300 | 88.8 | 88.5 | 4.9 | 4.8 |
| 67,900 | 91.5 | 91.5 | 5.4 | 5.3 |
| 81,500 | 93.8 | 93.8 | 5.9 | 5.8 |
| 95,100 | 95.1 | 95.2 | 6.3 | 6.2 |
| 108,700 | 96.1 | 95.9 | 6.5 | 6.7 |

† IPAR and LAI measurements taken when the late-maturity hybrid was at the silking stage.

# CHAPTER 4

## Agronomic Responses to Planting Date, Hybrid, Row Width, and Plant Density: A Summary

Over three yr at two locations in southern Minnesota, it was found that corn grain yield responded similarly to plant density across planting dates ranging from late April to late May. It was also found that corn planting dates ranging from late April until mid-May produced higher grain yields than a late May planting date. If planting takes place in late May, yield reductions can be near 15%. If adverse spring soil conditions occur, striving to have all corn planted by mid-May will help maintain yield potential near the maximum. Knowledge of when yield penalty for delayed planting begins will help growers increase overall grain production by limiting yield losses due to delayed planting. Future research should focus on examining the response of grain yield to planting dates at other locations to determine when yield penalties begin to occur with delayed planting in different environments.

Research on the response of corn grain yield to row width and plant density found that responses were similar across three hybrids of differing maturity over two yr in southern Minnesota. Research also revealed that the late-maturity hybrid had 13% higher grain yield than the early-maturity hybrid. The higher yield of the late-maturity hybrid was due to an increase in kernels per square meter. The late-maturity hybrid had the most kernels per square meter but the lowest kernel weight, yet it still had the highest grain yield. This indicates a possible higher yield potential of late-maturity hybrids. If more favorable late season growing conditions had occurred and kernel weight of the late-maturity hybrid would have increased to the levels of the early- and mid-maturity hybrids, grain yields could have been approximately 7% higher. Thus, growers may be able to increase grain production totals by limiting the hectarage on which early-maturity hybrids are grown. However, other constraints such as harvest timing and grain drying capacity exist, which can favor the use of early-maturity hybrids. Future research is needed to verify that the response of grain yield, kernel weight, and kernels per square meter to hybrid maturity remains the same with a larger set of hybrids of differing maturity.

Over two yr at two locations in southern Minnesota, it was found that corn grain yield and the response of corn grain yield to plant density was similar in both 51- and 76-cm row widths. This is contradictory to previous research from the same two locations where a 7% grain yield advantage occurred with 25- and 51-cm row widths compared with a 76-cm row width (Porter et al., 1997). This discrepancy might be due to the use of improved hybrids which can now better tolerate the reduced within-row interplant spacing associated with 76-cm rows. Growers should choose the row width that best fits their operation and maximizes their economic return. For example, soybean can have yield increases from 5 to 7% in row widths <76 cm in Iowa and Minnesota (Naeve et al., 2004; De Bruin and Pedersen, 2008). However, more research is needed to determine if other hybrids with different characteristics, like higher ear flex ratings, will have higher grain yields when grown in row widths narrower than 76 cm.

Research from southern Minnesota over two to three yr at two locations found that corn grain yield can be maximized with plant densities ranging from 84,500 to 108,700 plants $ha^{-1}$ when grown following corn, and from 81,700 to 107,900 plants $ha^{-1}$ when grown following soybean. When corn was grown following soybean, the economically optimum seeding rate ranged from 79,000 to 86,400 seeds $ha^{-1}$ based on four different seed cost and grain price scenarios, assuming 5% over-seeding. These economically optimum plant densities are less than those reported from previous research at the same locations. For example, Porter et al. (1997) found that maximum grower return would be obtained with a final plant density of 86,500 plants $ha^{-1}$. Although the response of corn grain yield to plant density was analogous between the two studies, the seed costs and grain prices were dissimilar and resulted in a different economically optimum seeding rate. These results indicate that while hybrids have changed over time and yields have improved, the response of corn grain yield to plant density has remained relatively similar from 1992 to 2010. Future research should examine the response of grain yield to plant density at different locations with different hybrids to determine which factors have the greatest influence on the response to plant density.

Altering corn production practices such as planting date, row width, and plant density have contributed to the increased corn yields over the past 80 yr. The results from the research presented in this thesis indicate that these agronomic practices should be managed to avoid grain yield losses, and that there is relatively little potential for altering these practices to achieve even higher yields. There is a need for future work to identify ways to improve grain yields in ways beyond the agronomic practices examined in this thesis. Corn grain yield was highest in the study where corn followed soybean and lowest when corn followed corn. Future research could examine other crop rotations for the potential to increase corn grain yield, and for ways to increase grain yield when corn follows corn. Additionally, before external agronomic inputs become cost prohibited or source limited, research should examine ways in which yield levels can be maintained in low-external-input cropping systems. An example of this could include research to evaluate the response of grain yield to row width and plant density in N-limiting environments. As the demand for corn grain increases and realized yields continue to approach the theorized potential maximum yield (Alston et al., 2010a), there is a need to find new ways to increase the amount of corn grain produced. This can be accomplished through new practices that raise corn grain yield potential and through management of agronomic practices, such as those presented in this thesis, to minimize yield losses and raise grain production overall.

# LITERATURE CITED

Al-Kaisi, M., R. Elmore, A. Mallarino, P. Pedersen, A. Robertson, J. Sawyer, and J. Tollefson. 2008. Corn following corn in 2008. Available at http://www.agronext.iastate.edu/corn/production/management/cropping/cornfollowcorn.html (posted 3 Jul. 208, cited 24 Jan. 2011, verified 24 Jan. 2011). Iowa State Univ., Ames.

Alston, J.M., B. Babcock and P.G. Pardey. 2010a. Introduction and overview. p. 1-6. *In* J.M. Alston et al. (ed.) The shifting patterns of agricultural production and productivity worldwide. Iowa State Univ., Ames.

Alston, J.M., J.M. Beddow and P.G. Pardey. 2010b. Global patterns of crop yields and other partial productivity measures and prices. p. 39-61. *In* J.M. Alston et al. (ed.) The shifting patterns of agricultural production and productivity worldwide. Iowa State Univ., Ames.

Andrade, F.H. and P.E. Abbate. 2005. Response of maize and soybean to variability in stand uniformity. Agron. J. 97:1263-1269.

Andrade, F.H., P. Calvino, A. Cirilo, and P. Barbieri. 2002. Yield response to narrow rows depend on increased radiation interception. Agron. J. 94:975-980.

Andrade, F.H., S.A. Uhart, and M.I. Frugone. 1993. Intercepted radiation at flowering and kernel number in maize: Shade versus plant density effects. Crop Sci. 33:482-485.

Barbieri, P.A., H.R. Sainz Rozas, F.H. Andrade, and H.E. Echeverria. 2000. Row spacing effects at different levels of nitrogen availability in maize. Agron. J. 92:283-288.

Beddow J.M., P.G. Pardey, J. Koo, and S. Wood. 2010. The changing landscape of global agriculture. p. 7-38. *In* J.M. Alston et al. (ed.) The shifting patterns of agricultural production and productivity worldwide. Iowa State Univ., Ames.

Boomsma C.R., J.B. Santini, M. Tollenaar, and T.J. Vyn. 2009. Maize morphophysiological responses to intense crowding and low nitrogen availability: An analysis and review. Agron. J. 101:1426-1452.

Borras, L., M.E. Westgate, J.P. Astini, and L. Echarte. 2007. Coupling time to silking with plant growth rate in maize. Field Crops Res. 86:131-146.

Butzen, S. and S. Paszkiewicz. 2008. Narrow-row corn production: When does it increase yields? Crop Insights. 18(15):1-5. Pioneer Hi-Bred Int., Johnston, IA.

Campos, H., M. Cooper, J.E. Habben, G.O. Edmeades, and J.R. Schussler. 2004. Improving drought tolerance in maize: A view from industry. Field Crops Res. 90:19-34.

Cardwell, V.B. 1982. Fifty years of Minnesota corn production: Sources of yield increase. Agron. J. 74:984-990.

Carter, P., T. Doerge, M. Jeschke, S. Butzen, S. Paszkiewicz, D. Ellerman, et al. 2007. Corn hybrid response to plant population. p. 18-22. *In* S. Butzen and M. Jeschke (ed.) Agronomy sciences research summary – central and eastern U.S. Pioneer Hi-Bred Int., Johnston, IA.

Center for Farm Financial Management. 2011. FINBIN farm financial database. Available at http://www.finbin.umn.edu (posted 11 Jan. 2011, cited 11 Jan. 2011, verified 20 Jan. 2011). Univ. of Minnesota, St. Paul.

Cirilo, A.G. and F.H. Andrade. 1994. Sowing date and maize productivity: I. Crop growth and dry matter partitioning. Crop Sci. 34:1039-1043.

Cox, W.J., J.J. Hanchar, W.A. Knoblauch, and J.H. Cherney. 2006. Growth, yield, quality, and economics of corn silage under different row spacings. Agron. J. 98:163-167.

Cox, W.J., D.J.R. Cherney, and J.J. Janchar. 1998. Row spacing, hybrid, and plant density effects on corn silage yield and quality. J. Prod. Agric. 11:128-134.

Cox, W.J. 1997. Corn silage and grain yield responses to plant densities. J. Prod. Agric. 10:405-410.

Coulter, J. 2010. Plan now for successful corn planting. Available at http://blog.lib.umn.edu/efans/cropnews/2010/03/plan-now-for-successful-corn-p.html (posted 20 Mar. 2010, cited 9 Sept. 2010, verified 20 Jan. 2011). Univ. of Minnesota, St. Paul.

Coulter, J.A., E.D. Nafziger, M.R. Janssen, and P. Pedersen. 2010. Response of Bt and near-isoline corn hybrids to plant density. Agron J. 102:103-111.

Coulter, J.A. 2009. Optimum plant population for corn in Minnesota. Available at http://www.extension.umn.edu/distribution/cropsystems/M1244.html (posted 2009, cited 9 Sept. 2010, verified 20 Jan. 2011). Univ. of Minnesota, St. Paul.

De Bruin, J.L. and P. Pedersen. 2008. Effect of row spacing and seeding rate on soybean yield. Agron. J. 100:704-710.

Duvick, D.N. 2005. The contribution of breeding to yield advances in maize (*Zea mays* L.). Adv. Agron. 86:84-145.

Duvick, D.N. and K.G. Cassman. 1999. Post-green revolution trends in yield potential of temperate maize in the North-Central United States. Crop Sci. 39:1622-1630.

Edwards, W. and A. Johanns. 2010. 2010 Iowa farm custom rate survey. Available at http://www.extension.iastate.edu/publications/fm1698.pdf (posted 2010, cited 15 Dec. 2010, verified 25 Jan. 2011). Iowa State Univ., Ames.

Edwards J.T., L.C. Purcell, and E.D. Vories. 2005. Light interception and yield potential of short-season maize hybrids in the Midsouth. Agron. J. 97:225-234.

Farnham, D.E. 2001. Row spacing, plant density, and hybrid effects on corn grain yield and moisture. Agron. J. 93:1049-1053.

Girardin, Ph. And M. Tollenaar. 1994. Effects of intraspecific interference on maize leaf azimuth. Crop Sci. 34:151-155.

Gupta, S.C. 1985. Predicting corn planting dates for moldboard and no-tillage systems in the Corn Belt. Agron. J. 77:446-455.

Hammer, G.L, Z. Dong, G. McLean, A. Doherty, C. Messina, J. Schussler, C. Zinselmeier, S. Paszkiewicz, and M. Cooper. 2009. Can changes in canopy and/or root system architecture explain historical maize yield trends in the U.S. corn belt? Crop Sci. 49:299-312.

Harris, K.E., R.H. Moll, and C.W. Stuber. 1976. Control and inheritance of prolificacy in maize. Crop Sci. 16:843-850.

Hashemi, A.M., S.J. Herbert, and D.H. Putnam. 2005. Yield response of corn to crowding stress. Agron. J. 97:839-846.

Kiniry, J.R., and D.P. Knievel. 1995. Response of maize seed number to solar radiation intercepted soon after anthesis. Agron. J. 87:228-234.

Kucharik, C.J. 2008. Contribution of planting date trends to increased maize yields in the central United States. Agron. J. 100:328-336.

Kucharik, C.J. 2006. A multidecadal trend of earlier corn planting in the central USA. Agron. J. 98:1544–1550.

Lauer, J.G., P.R. Carter, T.M. Wood, G. Diezel, D.W. Wiersma, R.E. Rand, and M.J. Mlynarek. 1999. Corn hybrid response to planting date in the northern Corn Belt. Agron. J. 91:834-839.

Lee, C.D. 2006. Reducing row widths to increase yield: Why it does not always work. Available at http://www.plantmanagementnetwork.com/cm/. Crop Manage. doi:10.1094/CM-2006-0227-04-RV.

Maddonni, G.A., A.G. Cirilo, and M.E. Otegui. 2006. Row width and maize grain yield. Agron. J. 98:1532-1543.

Naeve, S.L., S.R. Quiring, T.A. O’Neill, J.E. Kurle. 2004. Influence of soybean row spacing and plant population on development and yield across planting dates in Minnesota. Available at http://www.soybean.umn.edu/pdfs/2004asaposter_1_spacingplanting_screen.pdf (posted 2004, cited18 Jan. 2011, verified 25 Jan. 2011). Univ. of Minnesota, St. Paul.

Nafziger, E.D. 2009. Corn production. p. 13-26. *In* R.G. Hoeft and E.D. Nafziger (ed.) Illinois agronomy handbook. 24th ed. Univ. of Illinois, Urbana.

Nafziger, E.D. 1994. Corn planting date and plant population. J. Prod. Agric. 7:59-62.

Nielsen, R.L., P.R. Thomison, G.A. Brown, A.L. Halter, J. Wells, and K.L. Wuethrich. 2002. Delayed planting effects on flowering and grain maturation of dent corn. Agron. J. 94:549-558.

Nielsen, R.L. 1988. Influence of hybrids and plant density on grain yield and stalk breakage in corn grown in 38 cm row width. J. Prod. Agric. 1:190-195.

Olson, R.A., and D.H. Sander. 1988. Corn production. P. 639-686. *In* G.F. Sprague and J.W. Dudley (ed.) Corn and corn improvement. ASA, CSSA, and SSSA, Madison, WI.

Ottman M.J. and L.F. Welch. 1989. Planting pattern and radiation interception, plant nutrient concentration, and yield in corn. Agron. J. 81:167-174.

Paszkiewicz, S. and S. Butzen. 2007. Corn hybrid response to plant population. Crop Insights 17(16):1-4. Pioneer Hi-Bred Int., Johnston, IA.

Pedersen, P. and J.G. Lauer. 2003. Corn and soybean response to rotation sequence, row spacing, and tillage system. Agron. J. 95:965-971.

Pedersen, P. and J.G. Lauer. 2002. Influence of rotation sequence on the optimum corn and soybean plant population. Agron. J. 94:968-974.

Pioneer Hi-Bred Int. 2010. Characteristics and suitability ratings. Available at http://www.pioneer.com/home/site/ca/template.CONTENT/products/corn/corn-trait-technology-chart/guid.28C69A1A-A286-BE3A-C09E-5C7483C1B2BD (posted 2011, cited 11 Jan. 2011, verified 20 Jan. 2011). Pioneer Hi-Bred Int., Johnston, IA.

Pioneer Hi-Bred Int. 2009. Pioneer brand products 2010. Pioneer Hi-Bred Int., Johnston, IA.

Porter, P.M., D.R. Hicks, W.E. Lueschen, J.H. Ford, D.D. Warnes, and T.R. Hoverstad. 1997. Corn response to row width and plant density in the northern Corn Belt. J. Prod. Agric. 10:293-300.

Rehm, G., G. Randall, J. Lamb, and R. Eliason. 2006. Fertilizing corn in Minnesota. Publ. FO-03790 Univ. of Minnesota Ext., St. Paul.

Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1993. How a corn plant develops. Rep. 48. Iowa State Coop. Ext., Iowa State Univ., Ames.

Sangoi, L., M.A. Gracietti, C. Rampazzo, and P. Bianchetti. 2002. Response of Brazilian maize hybrids from different eras to changes in plant density. Field Crops Res. 79:39-51.

Sarlangue, T., F.H. Andrade, P.A. Calvino, and L.C. Purcell. 2007. Why do maize hybrids respond differently to variations in plant density? Agron. J. 99:984-991.

SAS Institute. 2003. The SAS system for windows. Version 9.1. SAS Institute Inc., Cary, NC.

Sharratt, B.S., and D.A. McWilliams. 2005. Microclimate and rooting characteristics of narrow-row versus conventional-row corn. Agron. J. 97:1129-1135.

Staggenborg. S.A., W.B. Gordon, V.L. Martin, D.L. Fjell, T. Dumler, G. Kilgore, and R.K. Taylor. 2001. Narrow row corn production in Kansas. MF-2516. Kansas State Univ., Manhattan.

Stanger, T.F., and J.G. Lauer. 2007. Corn stalk response to plant population and the Bt-European corn borer trait. Agron. J. 99:657-664.

Stanger, T.F., and J.G. Lauer. 2006. Optimum plant population of Bt and Non-Bt corn in Wisconsin. Agron. J. 98:914-921.

Tetio-Kagho, F., and F.P. Gardner. 1988. Responses of maize to plant population density. II. Reproductive development, yield, and yield adjustments. Agron. J. 80:935-940.

Thelen, K.D. 2006. Interaction between row spacing and yield: Why it works. Available at http://www.plantmanagementnetwork.com/cm/. Crop Manage. doi:10.1094/CM-2006-0227-03-RV.

Tollenaar, M., and E.A. Lee. 2002. Yield potential, yield stability and stress tolerance in maize. Field Crops Res. 75:161-169.

Tollenaar, M. 1991. Physiological basis of genetic improvement of maize hybrid in Ontario from 1959 to 1988. Crop Sci. 31:119-124.

Tollenaar, M. 1989. Genetic improvement in grain yield of commercial maize hybrids grown in Ontario from 1959 to 1988. Crop Sci. 29:1365-1371.

USDA-National Agricultural Statistics Service. 2011. Statistics by state. USDA-NASS, Washington, DC.

USDA-National Agricultural Statistics Service. 2009. AV-21-09. Agri-view. USDA-NASS, Washington, DC.

US Census Bureau. 2010. International data base. Available at http://www.census.gov/ipc/www/idb/worldpopinfo.php (posted 2010, cited 9 Sept 2010, verified 20 Jan. 2011). US Census Bureau, Washington DC.

Valentinuz, O.R. and M. Tollenaar. 2004. Vertical profile of leaf senescence during the grain-filling period in older and newer maize hybrids. Crop Sci. 44:827-834.

Westgate, M.E., F. Forcella, D.C. Reicosky, and J. Somsen. 1997. Rapid canopy closure for maize production in the northern US corn belt: Radiation-use efficiency and grain yield. Field Crops Res. 49:249-258.

Widdicombe, W.D., and K.D. Thelen. 2002. Row width and plant density effects on corn grain production in the northern Corn Belt. Agron. J. 94:1020-1023.

Zinselmeier, C., B.-R. Jeong, and J.S. Boyer. 1999. Starch and the control of kernel number in maize at low water potentials. Plant Physiol. 121:25-36.