EFFECT OF DELAYED PLANTING ON CORN IN CENTRAL KANSAS

by

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Abstract

Interest has grown regarding management options to improve and stabilize dryland corn production (*Zea mays* L.) in challenging environments. Grain sorghum (*Sorghum bicolor* L.) has been documented to produce more consistent grain yields than corn in dryland production in Kansas. In periods of reduced water availability, sorghum can delay growth and development, allowing the plant to capture water later in the season for flowering and grainfill. Delaying planting in corn can serve a similar purpose. In central Kansas, planting corn earlier so pollination occurs before periods of extreme stress has been successful, but little research has investigated delayed planting or its long-term effect. The objectives of this study were to evaluate plant growth and yield response to delayed planting through field research and to quantify its long-term effects through crop model simulations. Field trials with delayed planting dates and hybrids of varying maturity revealed that yield at Manhattan, KS, did not decrease significantly until the final planting date in 2007 and did not decrease at all with delayed planting in 2008. At Belleville, yield increased with later planting in 2007 and was not affected by planting date in 2008. At Hutchinson, yield decreased significantly with each planting date until the third in 2007. However, in 2008, yield increased significantly from the second to fourth planting dates. Simulations in CERES-Maize over 51 years revealed no difference in yield between planting dates at Manhattan and Belleville, but showed a significant decrease between the first planting date and the third and fourth planting dates at Hutchinson. Chi-squared tests indicated that all planting date x hybrid combinations at Manhattan and Belleville produced economically profitable yields at frequencies significantly greater than 0.5. At Hutchinson, all but two of the twelve planting date x hybrid combinations produced profitable yields at frequencies significantly less than 0.5. The two remaining combinations produced profitable

yields at frequencies that were not different than 0.5. One of these combinations was observed at the fourth planting date. These results suggest that the economical viability of delayed planting of corn is heavily dependent on location.

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CHAPTER 1 - Literature Review

Physiological Responses to Environmental Conditions

Several factors including planting date, plant population, water and nutrient availability, soil and air temperature, and genetics contribute to the yield potential of a grain crop. These factors can influence light interception, radiation use efficiency, and photoassimilate partitioning, all of which influence plant growth and development at the most basic level (Gifford et al., 1984). Management of planting dates in grain crops can influence the timing of environmental factors such as water and nutrient availability and soil and air temperatures, affecting both dry matter and grain production. Inaccurate planting dates can cause important stages of plant growth and development to occur during periods of peak environmental stress, potentially limiting damage or terminating growth and development.

The amount of radiation intercepted directly influences crop growth rate (Tollenaar and Bruulsema, 1988). Wilhelm et al. (1987) found that the size and longevity of the crop canopy contribute to the determination of yield potential. Muchow et al. (1990) found that under favorable conditions, biomass accumulation is directly proportional to the amount of radiation intercepted and that grain yield is directly proportional to biomass. They indicated that lower temperature increases the length of time that the crop can intercept radiation. Simmons and Jones (1985) showed that the upper leaves in the corn (*Zea mays* L.) canopy are the major contributors of photosynthesis to the ear during the grain filling period, suggesting that the relative timing of canopy development and peak radiation is important to grain production.

Temperature affects the efficiency of crop growth and partitioning. Temperatures outside the optimum range slow growth and development (Warington and Kanemasu, 1983).

Temperature also affects the duration of crop growth (Allison and Daynard, 1979) and the maximum time that radiation can be intercepted (Muchow et al. 1990), in particular during grain fill. It has been shown that the length of grain filling is reduced with increasing temperatures and that a shorter grain filling period is often associated with lower grain yield (Hunter et al., 1977; Badu-Apraku et al., 1983). However, Muchow (1990) observed that, although the length of grain filling was shorter at higher temperatures, grain yield was unchanged due to greater radiation at higher temperatures. Duncan et al. (1973) observed greater grain yields of the same corn hybrid in Davis, CA than at Greenfield and Lexington, KY, because Davis received greater solar radiation and Lexington received higher temperatures. Findings by Muchow et al. (1990) support these results, because they observed that the duration of solar radiation interception is negatively associated with higher temperatures. Although high temperatures are well documented to affect dry matter production and partitioning, low temperatures can have a similar impact. Bollero et al. (1996) observed that grain yield in corn decreased linearly with decreasing soil temperatures.

Dry matter production and partitioning also can be susceptible to limited water conditions. Denmead and Shaw (1960) reported that stem elongation, leaf area, and cob length were all decreased when water was limited. They also noted that growth rates returned to near normal within days after the stress was removed. Grain yield was reduced due to moisture stress in the vegetative, silking, and grainfill stages by 25%, 50%, and 21%, respectively, illustrating the greater importance of adequate moisture at silking.

Several yield components can be affected by environmental stress. Earley et al. (1974) reported that, although the number of silking ears is genetically controlled, environmental conditions, including temperature and water availability, are also critical factors in determining ear number. Application of environmental stress at important physiological stages can have a negative effect on kernel number and kernel density. Frey (1981) noted that the most critical period for determining corn yield occurs between 50% silking and 2 to 3 weeks after silking in terms of environmental stress. He observed that after kernel number was set, assimilate supply had little effect on linear kernel dry matter accumulation rates for kernels located at the base and middle of the ear. Ritchie et al. (1993) stated that the largest yield reductions result from environmental stresses at silking, with smaller reductions when the stress occurs further away from silking. Herrero and Johnson (1981) observed that drought stress during flowering increased the interval between pollen shed and initial silking. In another study, Herrero and Johnson (1980) observed that extreme drought stress led to decreased pollen viability. Claassen and Shaw (1970) found that kernel number reductions were greatest due to moisture stress in the silking and early grain fill stages, and stress during the grain fill stage led to decreased kernel density. Collins and Russell (1965) reported that the inability of a secondary ear to compete with the primary ear was closely related to a 2- to 3-day period prior to silking, because elongation of the primary ear was two times greater than the secondary ear during that period. Nishikawa and Kudo (1973) observed that 60% of eventually barren plants had normal ear development until silk emergence. If drought conditions are severe, silking may be delayed (Kiesselbach, 1950), acting as a stress avoidance mechanism. However, the introduction of newer hybrids with improved water use efficiency (Castleberry et al., 1984) and improved radiation use efficiency (Tollenaar and Aguilera, 1992) has improved the potential for growing corn in areas where water and radiation deficiencies may exist.

Hybrid Selection and Optimum Planting Date

There are various ways to match hybrid maturity with the available growing season. One tool is the relative-maturity (RM) method, which estimates the number of calendar days required for a specific hybrid to reach physiological maturity, also known as black-layer (BL) formation (Gilmore and Rogers, 1958; Daynard and Duncan, 1969). This method can be useful in scenarios where a full growing season is available and season length is not an issue. While this system is the most simplistic, it also can be faulted as the least accurate, because it assumes an optimal growing season. The system does not account for various environmental stresses than can affect the phenology of the plant. The system is not recommended in areas where the probability of an early-killing frost is high, because it relies on calendar time, a variable that is independent from the physiological processes of the plant. Another tool for matching the available growing season with proper hybrid maturity is the growing degree day (GDD) rating system (Dwyer et al., 1999).

$$GDD = \frac{Temp_{MAX} + Temp_{MIN}}{2} - Temp_{BASE} \qquad [1.1]$$

This system is based on the close relationship between corn phenology and thermal time (Nielsen et al., 1994), and is better adapted for situations when growing season length has been shortened because it uses the GDD ratings of hybrids and the estimated GDDs remaining until the average date of a killing fall freeze (Nielsen et al., 2002). This system utilizes thermal time rather than calendar time to more accurately predict physiological maturity. The GDD system can provide a more accurate determination of plant maturity than attainable with the RM method because it accounts for changes in the accumulation of thermal units that occur throughout the growing season.

Although the GDD system is superior to the RM method, there are still issues that require consideration. Daynard (1972) observed difficulty determining date of black layer formation due to high plant-to-plant variability. Sutton and Stucker (1974) found great variability in the amount of time required to reach physiological maturity unless researchers used highly standardized weather data to rate specific hybrids. Roth and Yocum (1997) found that most hybrids they tested in field studies reached 50% silking within 60 GDD with non-water-limiting conditions. However with water stress, GDD accumulation ranged from 500 GDD less than reported ratings to 235 GDD more, suggesting that environmental conditions significantly influence plant growth and development. In response to these issues, Stewart et al. (1998) suggested the incorporation of actual temperature response functions into the current system, which assumes that phenological development is constant per degree of temperature between a base temperature and an upper threshold temperature. They contended that these response functions would provide a more dependable estimate of thermal time required for vegetative growth because more variability was observed during vegetative growth than during other developmental stages.

The GDD system can better describe trends that are being observed in the field compared with traditional calendar days. Nielsen et al. (2002) used the GDD system to show that the timing of flowering and grain maturation of corn was affected by later planting dates. They observed that delaying planting from 3 May to 11 June decreased calendar time from planting to silking (R1), defined as the date when 50% or more plants showed silks (Ritchie et al., 1993), by about 14 days and thermal time by an average of 34 GDDs. Delayed planting reduced the grain-fill period (R1 to R6) by 100 GDDs in thermal time. In that environment, later planting reduced the time required for maturation by an average of 3.8 GDDs per day of delayed planting. Cirilo and Andrade (1994a) observed that later planting dates increased the growth rate during vegetative growth due to high radiation interception and radiation use efficiency and more rapid canopy development, but later planting decreased interception and efficiency during the reproductive period. Delaying planting date decreased the number of kernels per ear and kernel weight due to a shortage in assimilate supply after flowering (Cirilo and Andrade, 1994b). They also reported a,positive correlation between kernels per ear and crop growth rate during a 2-week period following silking.

Hybrid selection and planting dates are two management factors that require insightful deliberation in areas of potential water limitations. Central Kansas has shown an increase in harvested dryland corn from 23,470 hectares in 1972 to 114,120 hectares in 2007 (NASS, 2008). However, annual precipitation and temperature variability in the region have caused average annual yields to range from 1.50 to 7.33 mg ha^{-1} during this same period. The current recommendation is that dryland corn should be planted early to capture a greater amount of solar radiation and allow pollination to occur before high midsummer temperatures (Roozeboom et. al, 2007). Staggenborg et al. (1999) reported an approximate optimal planting date of 1 May for north central KS, observing an increase of 3.5 mg ha^{-1} when delaying planting from early April until early May and a decrease of 3.4 mg ha^{-1} by delaying planting from early May until early June. Swanson and Wilhelm (1996) reported similar results, determining that the optimal planting date for Lincoln, NE was approximately 12 May, with a reduction of an average of 3.07 mg ha^{-1} when delaying planting until early June. Nafziger (1994) reported an optimum planting date of 24 April for Dekalb, IL, with increasing yield losses the further planting is moved before or after this date.

Research also has been conducted regarding hybrid response to delayed planting. Staggenborg et al. (1999) found that a short-season hybrid (102 RM) produced an average of 1.38 mg ha^{-1} more than the full season-hybrid (113 RM) in half of the location-years when planting was delayed until May. In the remaining location-years, short-season hybrids yielded 0.25 mg ha^{-1} more than the full-season hybrids, suggesting that short-season hybrids should be used when planting is delayed until June because short-season hybrids will utilize their entire grain filling period and mature before cooler temperatures occur in the fall. Full-season hybrids planted late may not be able to reach physiological maturity before a killing frost.

Potential Consequences of Delayed Planting

Several researchers have observed yield reductions when planting occurred before or after an optimum time (Benson, 1990; Imholte and Carter, 1987; Lauer et al., 1999; Nafziger, 1994; Nielsen et al., 2002; Swanson and Wilhelm, 1996). Lauer et al. (1999) observed that corn planted in late May yielded at least 30% less than corn planted in early May. Swanson and Wilhelm (1996) observed that kernels per ear and kernels per plant showed a quadratic response to planting date and were maximized when corn was planted at the optimum date of approximately 10 May in Lincoln, NE. Bauer and Carter (1986) found that delayed planting caused pollination and grain filling to occur later in the growing season, contributing to an increase in susceptibility to kernel breakage. This susceptibility was likely caused by kernel development occurring during periods of greater physiological stress. Benson (1990) noted that in addition to potential physiological stresses, late-planted corn can be exposed to increased weed competition and greater insect populations and occurrence of disease. Anderson (1994) supported this conclusion, showing that weed community emergence was greatest in the interval from mid-May to mid-June.

Although delayed planting has been well documented to result in lower yields in several environments, evidence for reduced yields also exists for early planting dates. Norwood (2001a) observed a general pattern of greater yields in planting dates in mid-May compared to mid-April in western Kansas, noting cooler temperatures as the probable cause for lower yields in April. Norwood (2001b) also found that water use efficiency (WUE) increased when planting was delayed from 16 April until 8 May. This suggests delayed planting may be a viable option and warrants further research.

Crop Modeling

Biomass and grain yields provide evidence of the plant's response to environmental conditions. Quantifying these yield responses occurs in three ways: (i) basic calculations from components of yield and radiation use efficiency, (ii) measurements in highly-controlled, small experiments with ideal growing conditions, and (iii) estimation by crop simulation models (Doberman et al., 2003). Whisler et al. (1986) summarized reasons for using crop models into three categories: (i) to aid in interpreting experimental results, (ii) as agronomic research tools, or (iii) as agronomic grower tools. Historically, long-term research regarding cropping systems required large investments of time, labor, and money, as evident in studies by Norwood et al. (1990), who conducted trials for 14 years to study crop sequence and tillage effects on soil water, Kolberg et al. (1996), who studied nitrogen efficiency in wheat rotations for six years, and Varvel (2000), who analyzed 16 years of yield data to investigate the long-term effects of nitrogen rates and rotations on corn yields. The introduction of crop modeling has allowed researchers to simulate long-term experiments in a much shorter period of time, while conserving labor and money.

Crop models can be defined as quantitative schemes for predicting growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables (Monteith, 1996). The most simplistic crop models appeared near the conclusion of World War II (Sinclair and Seligman, 1996), and have become more complex and potentially useful as they have been refined over time. Early crop models were developed to estimate light interception in crop canopies (Loomis and Williams, 1963; Duncan et al., 1967).

Crop models are grouped as empirical or mechanistic. Empirical models describe relationships between variables without referring to any biological or physical process that may exist between the two variables (Whisler et al., 1986). Empirical models have been found to fit better when research objectives are very narrow or are related to a single component, such as water use (Asare et al., 1992). Conversely, Whisler et al. (1986) stated that mechanistic models use mathematical functions to represent the known or hypothesized mechanisms that connect the input and output variables and explain the observed behavior. The addition of these variables and functions increases the complexity of the model. Boote et al. (1996) stated that mechanistic crop models are generally based on physiological and physical processes. Although empirical and mechanistic approaches differ dramatically in approach, most models use a combination of the two types. Even highly mechanistic models use empirical processes at the cellular or biochemical level (Boote et al., 1996).

With the development of mechanistic models, modeling has been used to predict agronomic responses in various crops, environments, and management situations, including planting date effects. Several studies regarding yield potential have been conducted. Hodges et al. (1987) evaluated yield potential in 14 states in the Cornbelt. Xie et al. (2001) used CERES-Maize, Almanac, and SORKAM to assess corn and sorghum production in water-limiting environments. Anapalli et al. (2005) used CERES-Maize and SORKAM to evaluate the implications of delayed planting and hybrid selection in northeastern Colorado. Fritz et al. (1997) used SORKAM to predict dry matter production in forage sorghum (*Sorghum bicolor* L. [Moench]). Heiniger et al. (1997) used SORKAM to develop replanting recommendations in sorghum in Kansas.

Crop models have been used to observe climatic effects and physiological responses in various crops. Egli and Bruening, (1992) used SOYGRO to investigate the effects of delayed planting in soybeans (*Glycine max*) in two different moisture regimes to determine date of planting recommendations. Aggarwal and Kalra (1994) analyzed limitations set by climatic factors in wheat (*Triticum aestivum*). Manrique and Hodges (1991) used CERES-Maize to simulate the effects of daylength and temperature in corn on leaf area, development, and yield in a tropical environment. Asare et al. (1992) used COTTAM, GOSSYM, and IRRSCH to approximate crop water stress in cotton (*Gossypium spp.*) in different irrigation regimes. Staggenborg et al. (1996) used GOSSYM to predict crop water use in cotton for irrigation scheduling purposes.

Modeling also has been used to evaluate other management practices. Boote et al. (1996) used CROPGRO to evaluate yield response to plant population and row spacing in soybean. Staggenborg and Vanderlip (2005) evaluated rotational effects on wheat, soybean, and sorghum using DSSAT, an interface that utilizes CERES-Maize, CERES-Wheat, CERES-Sorghum, and CROPGRO, among others, for corn, wheat, sorghum, and soybean predictions, respectively, and accounts for preceding crop effects in multi-year simulations (Jones and Kiniry, 1986). Pang et al. (1997) used CERES-Maize to predict nitrogen uptake in corn to determine if modeling could be used as a tool for nitrogen management. Miao et al. (2006) used CERES-Maize to predict optimal nitrogen rates for delineated management zones. Retta et al. (1991) used two corn growth models, CERES-Maize, and CORNF, to predict the effects of weed infestations to aid pesticide application management. Dogan et al. (2006) used CERES-Maize to predict if an irrigation scheduling program in Kansas could successfully be implemented without substantial yield losses.

CERES-Maize

Crop-Environment Resource Synthesis (CERES)-Maize is a management level model of corn growth and development (Jones and Kiniry, 1986). The model simulates the effect of genotype, weather, and soil properties on corn development (Paoli, 1997). CERES-Maize uses a daily-time step model that simulates phenology, biomass accumulation, carbon and nitrogen pools, soil water, soil nitrogen, yield components, and yield (Paoli, 1997; Pachta, 2007). Several studies have been developed to test the validity of CERES-Maize and other crop models. Kiniry et al. (1997) tested the accuracy of CERES-Maize and ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) in dryland production for locations in nine states. They determined that mean simulated grain yields for both models were within 5% of the grain yields reported by the National Agricultural Statistical Service (NASS). However, CERES-Maize produced greater r^2 values at more locations when measured yield and simulated yield were compared. Xie et al. (2001) compared prediction accuracy of CERES-Maize and ALMANAC. In dryland corn, mean simulated yield error,

$$\frac{simulated - measured}{measured} x100 , \qquad [1.2]$$

was found to be -2.2% for CERES-Maize and 6.2% for ALMANAC. They noted that the underestimated yields were the result of drought stress occurring mainly during grainfill, resulting in low simulated kernels mass due to an increased degree of sensitivity to drought stress by CERES-Maize. However, the authors explained that CERES-Maize was still suitable for these conditions due to its ability to accurately simulate phenology and yield components.

Anapalli et al. (2005) compared CERES-Maize to the Root Zone Water Quality Model (RZWQM) in a delayed planting study and found that CERES-Maize predicted yields more accurately at the final planting date (13% underpredicted) compared with RZWQM (50% overpredicted). They also found that late-maturing corn hybrids had higher rates of yield loss compared with early-maturing hybrids when planting was delayed.

Xevi et al. (1996) compared CERES-Maize with the SWATER-SUCROS (Soil Water and Actual Transpiration Rate) model. They found that SWATER-SUCROS better predicted dry matter and leaf area index, but CERES-Maize was still within the 95% confidence limit and was far superior for predicting grain water content.

Several studies have been conducted to evaluate the potential for using CERES-Maize at different scales, ranging from nine sites in Texas by Kiniry and Bockholdt (1998) to fourteen states by Hodges et al. (1987). Kiniry and Bockholt (1998) used nine sites (four irrigated, five dryland) in Texas to study the year-to-year yield variability of CERES-Maize and ALMANAC over a five-year period. CERES-Maize simulated mean yields within 10% of the measured yields at eight of the nine sites. The authors hypothesized that the site that was not within the 10% threshold was affected by drought conditions causing greater errors in yield component estimates when simulated by a harvest index approach. Hodges et al. (1987) used CERES-Maize to estimate corn production in 14 states in the Cornbelt, which account for 85% of the U.S. corn production. They found that for 1982 (the calibration year), 1983, 1984, and 1985, the model production estimates were 92, 97, 98, and 101%, respectively, of the yields reported by the NASS. The results reported in these studies support the conclusion that CERES-Maize is suitable for simulations across a wide range of scales where adequate temperature and precipitation data is available.

Research Question and Justification

Recent trends show dryland corn production increasing throughout the state of Kansas (NASS, 2008). Harvested corn area in central Kansas has increased from 23,470 hectares in 1972 to 114,120 hectares in 2007 for several reasons, including increasing commodity prices, greater energy and livestock demands, and genetic advancements. However, the possibility of high temperatures and low precipitation during the critical period surrounding silking creates a large amount of risk associated with planting corn in this region.

Typical management recommendations for central Kansas are to plant corn near an optimal range from early April in the south to late April in the north in order to capture the greatest amount of solar radiation (Roozeboom et al., 2007). The intent of the current recommended range is to allow key periods of development, including silking, to occur prior to periods of heat and water stress. However, this strategy can have limited success, because cool soil temperatures can limit plant growth initially, lengthening the time required for vegetative growth (Walker, 1970; Swanson and Wilhelm, 1996). Little research has been conducted regarding the effects of shifting planting dates later in the season. Although decreases in yield would be expected due to a shortened grain fill period and reduced utilization of solar radiation, the potential benefit of this type of management would be that the probability of silking occurring during stressful periods are decreased with of the possibility of capturing rains occurring later in the season, which could aid in the stabilization of yields.

The goal of this project was to explore delayed planting as an option for stabilizing dryland corn production in central Kansas. Field research investigated yields and key stages of physiological development at three locations in two years. Crop simulations used the short-term field responses to predict long-term physiological and yield data based on biotic and abiotic factors. Traditional cropping systems research requires a large investment in time, labor, and capital. Crop modeling was used to analyze the effect of delayed planting for a large area and for multiple years using historical weather information with a relatively small investment of time, labor, and other resources.

Therefore, the objectives of the research were to:

i.) evaluate the effects of delayed planting on physiological growth and grain yield in corn in central Kansas in six location-years through field research, and

ii.) evaluate the long-term effects of delayed planting on grain yield through the use of CERES-Maize and the aid of short-term field data.

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CHAPTER 2 - Effect of Delayed Planting on Growth and Yield in Central Kansas

Abstract

With the increased value of corn (*Zea mays* L.) grain, interest has grown regarding management options to improve and stabilize production in challenging environments. In central Kansas, grain sorghum (*Sorghum bicolor* L.[Moench]) has been documented to have more consistent grain yields than corn in dryland production. In periods of reduced water availability, sorghum exhibits drought avoidance by delaying pre-flowering growth and development, allowing the plant to capture water later in the season for flowering and grainfill. Although corn does not exhibit this ability, delaying planting can serve a similar purpose. In central Kansas, planting corn earlier so silking occurs before periods of extreme stress has been successful, but little research has been conducted regarding delayed planting and its impact. A study evaluating plant growth and yield response to delayed planting was conducted to evaluate the feasibility of delayed planting in central Kansas. Three hybrids with relative maturities ranging from 100-d to 113-d were planted at Manhattan, KS, Hutchinson, KS, and Belleville, KS, at four dates ranging from an optimal period in early April until late June. In 2007, no difference in leaf area at tasseling between the first three planting dates was detected at Manhattan and Hutchinson. Yield was not different for the first three dates at Manhattan, but declined with each later planting date at Hutchinson, and increased between the second and third plating dates at Belleville. In 2008, leaf area did not decrease until the final planting date at Manhattan or in H1 at Hutchinson and increased significantly between the third and fourth planting dates at Belleville. No difference in yield was observed among planting dates at Manhattan and Belleville. These results suggest that

later planting may be a viable alternative for maintaining dryland corn yields in some environments.

Introduction

Dryland corn production in central Kansas historically has been highly variable due to the common occurrence of heat and water stress during key periods of plant growth and development (Norwood, 2001a; Staggenborg et al., 2008). Although yields have been unstable, harvested dryland corn acres in central Kansas have increased from 23 500 ha in 1972 to 114 000 ha in 2007 (NASS, 2008) for several reasons, including improved hybrid performance, implementation of reduced- or no-till systems, and recent increases in value of the grain (Norwood, 2001b).

Several studies have attempted to identify an optimal date or period for planting corn and quantified yield reductions based on deviations from this optimum. However, little research has been conducted regarding the effect of planting substantially later than the optimal period. Staggenborg et al. (1999) reported an approximate optimal planting date of 1 May for north central KS, observing an increase of 3.5 Mg ha^{-1} when planting was delayed from early April until early May and a decrease of 3.4 Mg ha^{-1} by delaying planting from early May until early June. Swanson and Wilhelm (1996) reported an optimal date of 12 May for eastern Nebraska, with a yield reduction of 2.9 Mg ha^{-1} from delaying planting until early June. Nafziger (1994) reported an optimum planting date of 24 April for Dekalb, IL, with increasing yield losses as planting moved farther away from the optimal planting date.

Ample research supports optimal planting dates from late-April to early-May, but the potential for silking and pollination to occur during periods of peak stress is realistic. Although later planting dates may have lower yield potential, they may have certain physiological advantages. Norwood (2001b) observed a pattern of greater yields for planting dates in mid-May compared to mid-April in western Kansas due to warmer soil temperatures in May. Cirilo and Andrade (1994) observed that corn planted at later dates had greater radiation use efficiency from emergence to silking compared with corn planted at earlier dates.

With the increase in dryland corn production in Kansas, the common perception has been that corn should be planted early to allow pollination to occur before midsummer heat and precipitation deficiencies occur. However, some researchers have reported yield success with corn planted after the traditionally optimal date. Staggenborg (1999) reported that planting in early April or early May produced similar yields. Norwood and Currie (1997) suggested planting dryland corn in mid-May, but reported an exception in one year when early and late-May plantings were similar. A mid-May planting yielded less than either early or late-May, suggesting that stress influenced corn planted at that date more severely than for the other dates.

The intensification of corn production in central Kansas requires management options that provide flexibility to deal with challenging climatic conditions. Adequate heat units for delayed planting are generally available through central Kansas, suggesting that termination of the plant prior to physiological maturity is not likely for the first three dates used in this study or in early-maturity hybrids for the final planting date (Table 2.1). Delaying planting may allow pollination to occur after periods of greatest physiological stress while potentially capturing late-summer precipitation that can be more efficiently utilized compared with traditional planting dates. The objective of this study was to evaluate the effects of planting date and hybrid maturity on corn growth and development including leaf area at tasselling, days to silking, plant height, grain yield, harvest index, test weight, and kernel weight at three locations in central Kansas.

Materials and Methods

Six field studies were conducted at three dryland locations in Kansas in 2007 and 2008 to assess the effects of planting date and hybrid maturity on corn growth, development, and yield. Studies were conducted on a Reading silt loam soil (fine-silty, mixed, mesic Pachic Argiudoll) at the Agronomy Research Farm near Manhattan (39°11’N 96°35’W), a Crete silt loam soil (fine, smectitic, mesic Pachic Argiustoll) at the North Central Experiment Field near Belleville (39°48’N 97°40’W), and an Ost loam soil (fine-loamy, mixed, superactive mesic Udic Arguistoll) at the South Central Experiment Field near Hutchinson (38°04’N 97°54’W) (Tables 2.1 and 2.2; Kansas State Weather Library, 2008; HPRCC, 2008).

Planting dates, hybrid maturities, and their interactions were evaluated using a split-plot treatment structure in a complete randomized block design with four replications. Planting dates (D1, D2, D3, D4) were assigned to the main plots and hybrid maturities (H1, H2, H3) to the subplots. Three corn hybrids were planted in each year at dates ranging from early April through late June (Table 2.2). In 2007 at Belleville, only D2 and D3 were planted due to wet conditions preventing planting of D1 and D4. In 2007, hybrids were Dekalb DKC50-20 (100-d relative maturity [RM], 2561 growing degree units [GDUs]), Dekalb DKC58-80 (108-d RM, 2700 GDUs), and Asgrow RX752 RR2/YGPL (112-d RM, 2750 GDUs). In 2008, lack of seed availability resulted in the use of different, but closely related hybrids: Dekalb DKC50-48 (100-d RM, 2530 GDUs), Dekalb RX674 VT3 (109-d RM, 2750 GDUs), and Dekalb RX715 VT3 (111-d RM, 2770 GDUs). Target plant population was 59 000 seeds ha^{-1} at all locations. Soybean was the previous crop both years at Manhattan and Belleville. Sorghum was the previous crop both years at Hutchinson. Fertilizer was applied to ensure that nutrient availability was not a limiting factor.

Leaf area was measured at several important growth stages (6-leaf – V6, tassel – VT, and dent – R5). Leaf area was measured using a LI-COR (LI-COR, Inc., Lincoln, NE) LI-3100 Area Meter. Five plants per subplot were sampled at V6 and two plants per subplot were sampled at VT and R5. Sampled plants were divided into leaf and stem parts in 2007 and leaf, stem, and reproductive parts in 2008. Samples were dried in a forced-air dryer at 65° C until dry and weighed to obtain dry weight. Plant height measurements were obtained at growth stage R5.

Yield estimates were obtained by hand harvesting a length of 12.2 m in 2007 and 6.1 m in 2008 from the center two rows at Manhattan. Number of plants, primary ears, and secondary ears were recorded. Harvested ears were shelled using an ALMACO sheller (Model ECS, ALMACO, Nevada, IA). A length of 18.3 m was machine harvested from the center two rows at Belleville and 15.2 m at Hutchinson. In 2008, 6.1 m were hand harvested from D4 plots at Hutchinson because cool air temperatures slowed grain drying, preventing timely machine harvest. Grain moisture and test weight were estimated with a DICKEY-john GAC 2000 (DICKEY-john Corp., Springfield, IL). Yields from all locations were standardized to 15.5 percent moisture. Kernel weight was determined by weighing 250 kernels. Kernel number per ear was calculated using ear number, total grain weight, and kernel weight.

Harvest index was calculated by harvesting two plants per plot at R5. Harvest index (HI) was calculated as:

$$HI = \frac{Grain(^{kg}/_{ha})}{Total\ Biomass(^{kg}/_{ha})} \qquad [2.1]$$

Significance of main effect differences and their interactions was determined using the PROC MIXED procedure (SAS Institute, 2004) with year, location, planting date, and hybrid designated as fixed effects and replications as random effects. Mean separations were performed for the main treatment effects (planting date and hybrid) if the F-tests for treatment effects were significant ($\alpha = 0.05$).

Results and Discussion

Cumulative precipitation for the three locations in 2007, 2008, and the 30-year average is illustrated in Figure 2.1. At Manhattan, where the average yearly precipitation is 88.4 cm, precipitation was greater than average in both 2007 and 2008 beginning in May and June, respectively. At Belleville, cumulative precipitation for both 2007 and 2008 was similar to the 30-year average of 78.4 cm. At Hutchinson, where the annual average is 77.1 cm, precipitation trended below average early in the year, but eventually rebounded and closely followed the average in May and June in both years. Beginning in July of 2007, precipitation leveled off, eventually dropping well below average. In 2008, cumulative precipitation began to exceed the average in early September.

VT Leaf Area (VTLA)

A significant ($\alpha = 0.05$) interaction between planting date and hybrid was observed for VT Leaf area (VTLA) in 2007 at Manhattan (Table 2.3). The greatest VTLA was observed for H1 and H2 planted at D2 and D3, and the smallest was observed for the D1 and D4 planting dates. No planting date differences were observed for H3. When hybrids were compared within planting dates, H2 and H3 produced the greatest VTLA when planted at D1, D3, and D4. When planted at D2, H2 produced the greatest VTLA, and H1 produced the least. Planting date response did not interact with hybrid in 2008. No differences in VTLA were detected between the first three planting dates, but VTLA was less for corn planted at the last planting date when averaged across hybrids. When hybrids were averaged across planting dates, H3 produced the greatest VTLA, but no difference was detected between H1 and H2.

In 2007, no difference was detected between corn planted at D2 and D3 (Table 2.4). The hybrid response at Belleville in 2007 was similar to that observed in Manhattan in 2008. Corn planted at H3 produced the greatest VTLA, but no differences were detected between H1 and H2. In 2008, corn planted at D1 produced greater VTLA than that planted at D2 and D3. Corn planted at D4 did not differ in VTLA than that planted at the other dates. When hybrids were compared, VTLA increased with increasing hybrid maturity.

No differences in VTLA were detected ($\alpha = 0.05$) between the first three planting dates at Hutchinson or between hybrids in 2007 (Table 2.5). Corn planted at D4 in 2007 had lower VTLA than for corn planted at the earlier dates, likely caused by decreased water availability later in the growing season. In 2008, which received more precipitation compared with 2007 (Figure 2.1), a significant planting date x hybrid interaction ($\alpha = 0.05$) existed. For H2 and H3, no differences in VTLA were observed between planting dates. For H1, no difference was observed between the first three planting dates, but the last planting date had less VTLA. Several different trends were evident in hybrid comparisons. When planted at D1, H1 produced more VTLA than H2, and H3 was not different than either H1 or H2. When planted at D2 and D4, H2 and H3 produced more leaf area than H1. No differences were identified between hybrids when planted at D3.

Plant Height

No planting date x hybrid interactions were observed at any location-year for plant height ($\alpha = 0.05$). Plant height responded to planting dates differently in each year at all locations. In 2007 at Manhattan, D2 and D3 produced the tallest plants, the same trend observed in VTLA (Table 2.6). Corn planted at D1 and D4 was the shortest. No difference was detected between D1 and D3 or between D1 and D4. H3 was taller than H1, but H2 was intermediate and did not differ from the other two hybrids. In 2008, D3 produced the tallest plants. The same trend among hybrids that was observed in VTLA was also observed in plant height. H3 produced the tallest plants, but no difference was detected between H1 and H2.

Plant heights at Belleville identically matched VTLA trends in 2007, with no difference between corn planted at D2 and D3, and H3 producing the tallest plants (Table 2.7). In 2008, the greatest plant heights were observed for the D3 and D4 planting dates. No difference was detected between D1 and D2. Once again, H3 produced the tallest plants, but H1 and H2 were not different.

Opposite trends were observed at Hutchinson, where precipitation differed greatly between 2007 and 2008 (Figure 2.1). In 2007, the tallest plants were observed in corn planted at D2 and D3 (Table 2.8). D4 produced the shortest plants, and D1 was intermediate. No differences existed between hybrids. In 2008, D4 produced the greatest plant height and D1 and D2 produced the shortest heights. When hybrids were averaged across planting dates, plant height increased with increasing hybrid maturity.

Normally, plant height increases as planting is delayed (Roozeboom et al., 2007). Only two of the six location-years in this study strongly reflect this trend. However, limited research exists regarding plant height when planting is delayed to the extent it was in this study. In three of the six location-years, plant height decreased from D3 to D4, likely due to water limitations or daily temperatures above the optimum range limiting stem elongation. At Hutchinson in 2008, plant height increased during this interval. In 2008, water was abundant and temperatures were moderate at all locations, allowing growth to occur with little limitation.

Vegetative Growth Interval

Limited crop observations at Belleville and Hutchinson prevented accurate identification of silking dates at those locations. Therefore, only Manhattan was used to evaluate vegetative growth interval, the number of days from emergence to silking. Intervals for each hybrid and planting date are located in Table 2.9. In 2007, a significant planting date x hybrid interaction was detected. For all hybrids, vegetative growth interval decreased at each planting date from D1 to D4. Different trends existed within hybrids, however. In corn planted at D1 and D4, H2 and H3 had the longest vegetative intervals. In corn planted at D2 and D3, H2 produced the longest interval and H1 the shortest. In 2008, the same trend among planting dates existed as observed in 2007, with the vegetative growth interval decreasing significantly with each successive planting date. The vegetative growth interval increased with increasing hybrid maturity in 2008.

In both years, the vegetative growth interval decreased as planting was delayed. This is consistent with findings by Nielsen et al. (2002). The probable reason for this trend is that plants planted at later dates intercepted greater amounts of radiation on a daily basis, increasing growth rates (Cirilo and Andrade, 1994).

Grain Yield

The amount and distribution of in-season precipitation greatly affected grain yields. Precipitation was above average both years at Manhattan, but yield responded differently each year. In 2007, yield did not decrease with delayed planting until D4 (Table 2.10). In 2008, no difference was detected between planting dates. In 2007, H3 produced the greatest yields, and no difference was detected between H1 and H2. In 2008, H3 produced the greatest yields, and H1 yielded the least. Although growing conditions in 2008 were similar to conditions in 2007, yields were less. Field observations identified nitrogen deficiencies, likely caused by leaching or denitrification of inorganic N by heavy rains in June when soils were already saturated.

At Belleville in 2007, a significant planting date x hybrid interaction was observed (Table 2.11). For all hybrids, corn planted at D3 produced greater yields than that planted at D2. In 2007, the greatest yield was observed for H2, and the lowest for H1 when planted at D2. For D3, H3 produced the greatest yields, and H1 the least. H2 yields were intermediate and did not differ from either H1 or H3. In 2008, no difference in yield was observed between planting dates, and yield increased with increasing hybrid maturity.

Distinct differences in grain yield response existed at Hutchinson between years. In 2007, grain yield decreased with each planting date from D1 to D3. Yield for D4 did not differ from D3 (Table 2.12). No differences were observed among hybrids in 2007. In 2008, the yield pattern was reversed, with no difference in yield between D1 and D2 and increases with each subsequent planting date. In 2008, yields increased with increasing hybrid maturity.

Yield at each location was heavily dependant on precipitation received during the growing season, especially at Hutchinson, with higher average daily temperatures and soils with lower water holding capacities compared with the other locations. The probability of an early, killing frost is greatest at Belleville, potentially limiting grainfill, especially for later planting dates. Manhattan has the greatest yield potential due to lower probabilities of drought or an early-killing frost than for the other two locations. In both years, precipitation at Manhattan was above-average (Figure 2.1). Moderate temperatures and adequate, evenly distributed precipitation resulted in no yield reductions until D4 in 2007 and no differences in 2008. At Belleville, precipitation was near normal both years, but was more evenly distributed in 2008 (Figure 2.1). Uneven precipitation distribution in 2007 limited yield of corn planted at D2, resulting in greater yields for D3. In 2008, no difference between planting dates was detected in yield, despite below-average temperatures through September. Although yields did not differ, harvest moisture content was a concern at Belleville in 2008, particularly for D3 and D4. However, when plots were harvested on 3 November, the difference in grain moisture between D1 and D4 was only 3.4% (14.2% for D1, 17.6% for D4). Temperature effects were evident at Hutchinson, where in-season precipitation was below average in 2007 and above average in 2008. In 2007, grain yield decreased through the first three planting dates. D1 produced the greatest yields, probably due to greater water availability during key developmental periods. As in-season precipitation decreased and daily temperature increased later in the season, grain yield decreased with later planting. However in 2008, when daily temperatures were below normal, especially early in the growing season, later planting dates responded positively to increased late-season precipitation, with the greatest yield for D4.

In five of the six location-years, H3, the hybrid with the greatest GDD requirement, produced the greatest or not different than the greatest grain yield. At Belleville in 2007, where significant planting date x hybrid interaction existed, H3 produced the greatest yield in corn planted at D3. Further research regarding >112-d hybrids warrants consideration in determining the maximum hybrid maturity for later planting dates.

Harvest Index

At Manhattan, no differences in harvest index were detected between planting dates in 2007 or 2008 (Table 2.13). In 2007, no differences existed between hybrids. In 2008, H1 and H2 produced the greatest harvest index values, and H3 the smallest. This low value suggests that H3 was less efficient at producing grain yield in conjunction with biomass production at this location.

At Belleville, year-to-year variability existed in harvest index response between years (Table 2.14). In 2007, harvest index was greatly affected by grain yield, as D3 produced a significantly greater value compared with D2. Further investigation of the data revealed that vegetative biomass production for the two dates was similar, but grain mass was the varying component. When hybrids were averaged across planting dates, H2 produced the greatest and H1 the smallest harvest index. No difference was detected between H1 and H3 or H2 and H3. In 2008, when no yield differences between planting dates were detected, harvest indexes also did not differ. Although H3 produced a harvest index of 0.580, it was still the lowest of the three hybrids. This trend also was observed at Manhattan in 2008 (Table 2.13), providing further evidence that longer-season hybrids may be less efficient in comparison with shorter-season hybrids.

Harvest index responded differently to planting date in each year at Hutchinson (Table 2.15). In 2007, when precipitation was a limiting factor (Figure 2.1), D1 and D2 produced the greatest harvest indexes, and D4 produced the lowest harvest index. This is consistent with the precipitation pattern in 2007 when water was available for vegetative growth, but was limited during grainfill for D4. In these conditions, H1 and H3 produced the greatest harvest index values, but H2 produced a distinctly smaller value. In 2008, when precipitation was not the dominant limiting factor, the greatest harvest index value was observed in corn planted at D3. No differences in harvest index were detected between D1, D2, and D4 or between D3 and D4. Investigation of biomass production determined that grain biomass was again the determining variable for changes in harvest index. No differences existed between hybrids, a response different than that seen at the other locations.

In four of the six location-years, differences in harvest index between planting dates were influenced by grain mass because vegetative biomass remained relatively consistent. Harvest index trends in these location-years were identical to trends observed in grain yield. In all location-years, vegetative biomass was unaffected by precipitation, suggesting that water was not limiting before pollination at any location.

Test Weight

Test weight trends differed at Manhattan in 2007 and 2008. In 2007, no difference was detected between planting dates or hybrids (Table 2.16). In 2008, a significant planting date x hybrid interaction was present ($\alpha = 0.05$). For H1, no difference was observed between planting dates. For H2, D3 and D4 produced the greatest test weights, and no difference was detected between D1 and D2. For H3, D3 again produced the greatest test weight, and D1 and D2 produced the lowest values.

At Belleville, only data from 2008 was available (Table 2.17). No differences were detected between the first three planting dates or between hybrids averaged across planting dates. Corn planted at D4 produced grain with lighter test weight than for the first three planting dates.

At Hutchinson in 2007, the lowest test weight existed in corn planted at D2 (Table 2.18). No differences were detected between D1, D3, and D4. In hybrid comparisons, no differences were identified, consistent with Manhattan in 2007 and Belleville in 2008. A significant planting date x hybrid interaction was detected in 2008 at Hutchinson ($\alpha = 0.05$). For H1, D2 produced the lowest test weight, but no differences were detected between D1, D3, and D4. For H2, D4 test weight was the greatest, but no differences were detected between the other planting dates. For H3, D4 again produced the greatest test weight, and D3 was the lightest. No difference existed between D1 and D2. When hybrids were compared, each planting date represented a different trend. For corn planted at D1, no difference was detected among hybrids. In corn planted at D2, H2 and H3 produced the greatest test weights. In corn planted at D3, H1 and H2 produced the greatest test weights. At D4, H3 produced the greatest test weight, and H1 produced the lightest.

Average Kernel Weight

Average kernel weights for Manhattan are listed in Table 2.19. In 2007, no differences were observed between planting dates. In hybrid comparisons, H3 produced the greatest kernel weight, and no difference was observed between H1 and H2. In 2008, the greatest average kernel weight was found in corn planted at D3, but the other dates did not differ in kernel weight. H2 produced the greatest average kernel weight, but no difference was observed between H1 and H3.

In 2008 at Belleville, kernel weights reflected the same trends as were observed for test weights. D1, D2, and D3 did not differ in kernel weight, and D4 produced the smallest average kernel weights (Table 2.20). No differences were found between hybrids.

At Hutchinson in 2007, D1 and D4 produced the greatest average kernel weights. No difference was detected between D2 and D3, or between hybrids when averaged across planting dates. In 2008, a significant planting date x hybrid interaction existed. For H1, D3 and D4 produced the greatest average kernel weights, and no difference was detected between D1 and D2. For H2, D3 and D4 again produced the greatest average kernel weights, and D2 produced the smallest. For H3, the greatest average kernel weight was observed at D3, and the smallest values were seen in corn planted at D1 and D2. In hybrid comparisons, H1 and H2 produced the greatest average weights for corn planted at D1. In corn planted at D2, the greatest average kernel weight was seen for H1 and the smallest was observed for H2. No differences were observed between hybrids at D3 and D4.

Conclusions

Yield and yield components produced varying responses to delayed planting, depending on in-season precipitation amount and distribution. In Manhattan, where high temperatures and plant-available water were not limiting factors, yield was not reduced until D4 in 2007 or at all in 2008. No differences between planting dates were observed in harvest indexes within years, suggesting that vegetative biomass was generally constant throughout planting dates. Further research of the productivity of hybrids that are greater than 112-day RM at later planting dates warrants consideration at this location. At Belleville, where the length of growing season can be limited by early, killing frosts, delayed planting unexpectedly exhibited yield advantages in both years. However, in 2008, test weight decreased for D4, suggesting that the length of growing season may limit kernel dry weight accumulation for later planting dates, especially for the full season hybrid. In 2007, when precipitation was limited at silking in corn planted at D2, yields were significantly less than for corn planted at D3. In 2008, when temperatures were moderate and precipitation was adequate and more evenly distributed, there were no yield differences between the four planting dates. At Hutchinson, where crop growth and development is more apt to be affected by high temperatures and low or poorly distributed precipitation, opposite yield trends occurred each year. In 2007, where in-season precipitation was below normal, D1 produced the greatest yields, and yields decreased until D3. In 2008, temperatures were cooler than normal, particularly during vegetative growth for D1 and D2, and in-season precipitation was adequate and evenly distributed, resulting in significant yield increases for later planting dates.

Results of the study suggest that yields were unaffected when planting was delayed until mid- to late- June when water was not limiting and was evenly distributed. In environments where water was limited or poorly distributed, yield was reduced as planting was delayed. The earliest planting date produced the greatest yield due to receiving the greatest amount of precipitation during its growing season. In 2008, grain dry down following maturity was delayed at all locations, especially for the final planting date, due to below average temperatures in late-September and beyond. Another potential consequence of delayed planting that was evident in this study is the increased potential of shortened grainfill caused by early frost. These possible consequences require consideration when considering delayed planting, particularly in northern areas of this study, where the frequency cooler temperatures and early-killing frosts are greatest.

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CHAPTER 2 - Tables

Table 2.1. Available growing degree units and season termination date for various planting dates at three locations in central Kansas.

	Planting Date											
	11-Apr	18-Apr	25-Apr	2-May	9-May	18-May	23-May	1-Jun	10-Jun	17-Jun	24-Jun	End of Season†
	GDUs											
Belleville	3466	3406	3331	3254	3180	3068	2959	2909	2734	2577	2407	3 Oct.
Hutchinson	3794	3729	3648	3564	3468	3364	3247	3082	2889	2718	2531	13 Oct.
Manhattan	3656	3590	3507	3421	3323	3215	3098	2947	2771	2616	2446	7 Oct.

† End of season date is defined as 10 days prior to the average date of first 0° C freeze, where probability of freeze occurring prior to date is 20 percent. GDUs determined from 30-year normals from the High Plains Regional Climate Center (2008).

Table 2.2. Planting dates and monthly rainfall distribution at three locations in central Kansas.

Location	Planting Dates	April	May	June	July	August	September	Total
Belleville		cm						
2007	14 May, 5 June	6.4	23.6	6.1	15.8	7.4	10.4	69.6
2008	23 April, 5 May, 20 May, 9 June	8.6	9.9	11.4	12.7	6.4	10.9	66.8
Normal†		6.6	10.7	11.2	9.9	9.4	9.1	56.9
Hutchinson								
2007	23 April, 14 May, 7 June, 21 June	7.4	26.4	13.7	11.9	7.6	3.8	70.6
2008	2 April, 30 April, 13 June, 1 July	7.1	15	13.7	5.8	5.8	14	61.5
Normal†		6.4	10.4	10.9	9.1	7.4	7.6	51.8
Manhattan								
2007	20 April, 14 May, 6 June, 25 June	9.4	30.2	15	11.9	5.6	5.1	77.2
2008	7 April, 1 May, 5 June, 26 June	5.3	12.2	30.5	13	11.7	17.8	90.4
Normal†		6.1	10.7	11.9	11.9	7.6	8.6	56.9

† 1970-2000 Normals, Kansas State University Weather Library (2008).

Table 2.3. VT leaf area at Manhattan, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid						
	H1		H2		H3		Average
	cm^2						
	2007						
D1	10 992	Bb	13 289	Ba	13 630	Aa	12 637
D2	12 172	Ac	14 800	Aa	13 118	Ab	13 363
D3	12 043	Ab	14 136	Aa	13 630	Aa	13 270
D4	10 383	Bb	12 749	Ba	12 868	Aa	12 000
Average	11 398		13 744		13 312		
	2008						
D1	11 554		11 816		13 591		12 320 A
D2	11 384		11 730		14 667		12 594 A
D3	11 674		12 083		13 750		12 502 A
D4	10 234		10 491		12 446		11 057 B
Average	11 212	b	11 530	b	13 614	a	

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.4. VT leaf area at Belleville, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	H1	H2	H3	Average
			cm^2	
			2007	
D1				
D2	11 377	11 216	13 268	11 954 A
D3	11 079	10 971	12 224	11 425 A
D4				
Average	11 228 b	11 094 b	12 746 a	
			2008	
D1	12 652	13 769	16 284	14 235 A
D2	11 535	13 390	15 275	13 400 B
D3	12 082	12 757	15 391	13 410 B
D4	11 734	13 705	16 495	13 978 AB
Average	12 000 c	13 405 b	15 861 a	

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.5. VT leaf area at Hutchinson, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid			
	H1	H2	H3	Average
	cm^2			
	2007			
D1	11 932	11 297	11 528	11 586 A
D2	11 788	12 088	12 341	12 072 A
D3	11 269	11 463	12 408	11 713 A
D4	10 065	10 192	9 169	9 809 B
Average	11 263 a	11 260 a	11 362 a	
	2008			
D1	10 697 Aa	9 848 Ab	10 416 Aab	10 321
D2	9 899 ABb	10 736 Aa	10 915 Aa	10 517
D3	10 185 Aa	10 533 Aa	10 806 Aa	10 508
D4	8 657 Bb	9 607 Aa	10 265 Aa	9 510
Average	9 860	10 181	10 601	

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.6. Plant height at Manhattan, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid							
	H1		H2		H3		Average	
	m							
	2007							
D1	2.51		2.63		2.80		2.65	BC
D2	2.85		2.91		3.00		2.92	A
D3	2.77		2.81		2.83		2.80	AB
D4	2.57		2.53		2.43		2.51	C
Average	2.68	b	2.72	ab	2.77	a		
	2008							
D1	2.38		2.42		2.57		2.46	B
D2	2.46		2.39		2.54		2.46	B
D3	2.51		2.56		2.59		2.55	A
D4	2.39		2.51		2.55		2.48	B
Average	2.44	b	2.47	b	2.56	a		

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.7. Plant height at Belleville, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid							
	H1		H2		H3		Average	
	m							
	2007							
D1								
D2	2.29		2.29		2.32		2.30	A
D3	2.24		2.28		2.39		2.31	A
D4								
Average	2.27	b	2.29	b	2.36	a		
	2008							
D1	2.52		2.47		2.67		2.55	B
D2	2.50		2.61		2.63		2.58	B
D3	2.77		2.72		2.86		2.79	A
D4	2.83		2.80		2.87		2.83	A
Average	2.66	b	2.65	b	2.75	a		

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.8. Plant height at Hutchinson, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid							
	H1		H2		H3		Average	
	m							
	2007							
D1	2.24		2.30		2.22		2.25	B
D2	2.35		2.39		2.54		2.43	A
D3	2.35		2.35		2.40		2.37	A
D4	2.03		2.03		1.99		2.02	C
Average	2.24	a	2.27	a	2.29	a		
	2008							
D1	2.06		2.10		2.11		2.09	C
D2	2.10		2.16		2.20		2.15	C
D3	2.25		2.34		2.13		2.33	B
D4	2.40		2.38		2.45		2.41	A
Average	2.20	c	2.24	b	2.29	a		

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05

Table 2.9. Vegetative growth interval Manhattan, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid							
	H1		H2		H3		Average	
	Days							
	2007							
D1	56.0	Ab	57.5	Aa	57.5	Aa	57.0	
D2	49.8	Bc	52.5	Ba	51.3	Bb	51.2	
D3	43.8	Cc	46.8	Ca	45.5	Cb	45.3	
D4	41.0	Db	42.0	Da	42.8	Da	41.9	
Average	47.6		49.7		49.3			
	2008							
D1	60.3		61.5		63.0		61.6	A
D2	57.0		57.8		58.8		57.8	B
D3	46.0		47.0		48.3		47.1	C
D4	44.5		45.3		47.0		45.6	D
Average	51.9	c	52.9	b	54.2	a		

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, $\alpha = 0.05$.

Table 2.10. Grain yield at Manhattan, KS, in 2007 and 2008for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid						
	H1		H2		H3		Average
	$Mg\ ha^{-1}$						
	2007						
D1	9.47		9.59		10.03		9.66 A
D2	9.16		9.85		10.09		9.72 A
D3	9.41		9.22		10.60		9.66 A
D4	8.22		8.27		9.16		8.53 B
Average	9.03	b	9.22	b	9.97	a	
	2008						
D1	7.54		7.74		8.35		7.87 A
D2	6.18		7.18		7.94		7.09 A
D3	6.75		7.39		7.88		7.34 A
D4	7.84		7.72		8.20		7.90 A
Average	7.08	c	7.51	b	8.35	a	

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.11. Grain yield at Belleville, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid H1		H2		H3		Average	
	Mg ha^{-1}							
	2007							
D1								
D2	2.89	Bc	6.02	Ba	4.58	Bb	4.52	
D3	7.09	Ab	7.84	Aab	8.53	Aa	7.84	
D4								
Average	5.02		6.96		6.52			
	2008							
D1	10.51		11.19		12.11		11.27	A
D2	10.92		11.56		12.11		11.53	A
D3	10.92		11.70		12.26		11.63	A
D4	10.83		12.08		12.04		11.65	A
Average	10.79	c	11.63	b	12.11	a		

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, $\alpha = 0.05$.

Table 2.12. Grain yield at Hutchinson, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid						
	H1		H2		H3		Average	
	Mg ha^{-1}							
	2007							
D1	7.40		6.27		6.58		6.77	A
D2	5.89		6.02		6.15		6.02	B
D3	3.07		3.39		3.26		3.26	C
D4	2.51		2.76		2.70		2.63	C
Average	4.70	a	4.58	a	4.70	a		
	2008							
D1	5.35		5.88		6.13		5.79	C
D2	5.81		5.97		6.57		6.12	C
D3	7.16		7.24		7.33		7.24	B
D4	8.01		8.26		8.47		8.24	A
Average	6.58	c	6.84	b	7.13	a		

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.13. Harvest Index at Manhattan, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid			
	H1	H2	H3	Average
	2007			
D1	0.575	0.529	0.517	0.540 A
D2	0.484	0.516	0.520	0.506 A
D3	0.549	0.504	0.561	0.538 A
D4	0.514	0.531	0.491	0.512 A
Average	0.530 a	0.520 a	0.522 a	
	2008			
D1	0.511	0.474	0.458	0.481 A
D2	0.471	0.515	0.470	0.485 A
D3	0.504	0.516	0.506	0.509 A
D4	0.527	0.511	0.451	0.496 A
Average	0.503 a	0.504 a	0.471 b	

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.14. Harvest Index at Belleville, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	H1		H2		H3		Average	
	2007							
D1								
D2	0.205		0.416		0.288		0.303	B
D3	0.530		0.521		0.540		0.530	A
D4								
Average	0.367	b	0.468	a	0.414	ab		
	2008							
D1	0.619		0.598		0.578		0.598	A
D2	0.629		0.629		0.590		0.616	A
D3	0.626		0.614		0.582		0.607	A
D4	0.622		0.628		0.572		0.607	A
Average	0.624	a	0.617	a	0.580	b		

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, $\alpha = 0.05$.

Table 2.15. Harvest Index at Hutchinson, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid						
	H1		H2		H3		Average
	2007						
D1	0.454		0.357		0.459		0.429 A
D2	0.465		0.424		0.447		0.445 A
D3	0.302		0.350		0.271		0.308 B
D4	0.201		0.195		0.247		0.214 C
Average	0.454	a	0.357	b	0.459	a	
	2008						
D1	0.533		0.556		0.545		0.545 B
D2	0.580		0.520		0.543		0.548 B
D3	0.606		0.610		0.591		0.602 A
D4	0.576		0.576		0.558		0.570 AB
Average	0.574	a	0.565	a	0.559	a	

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.16. Test weight at Manhattan, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid							
	H1		H2		H3		Average	
	$kg\ (m^3)^{-1}$							
	2007							
D1	729.2		711.1		715.0		715.0	A
D2	716.3		684.1		697.0		697.0	A
D3	707.3		703.4		708.6		708.6	A
D4	698.3		736.9		722.7		722.7	A
Average	712.4	a	708.6	a	711.1	a		
	2008							
D1	686.7	Aab	708.6	Ba	664.8	Cb	686.4	
D2	672.5	Ab	699.6	Ba	660.9	Cb	677.7	
D3	711.1	Ab	740.8	Aa	751.1	Aa	734.2	
D4	681.5	Ab	722.7	Aa	698.3	Bab	688.0	
Average	717.6		693.1		686.7			

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.17. Test weight at Belleville, KS, in 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid						
	H1		H2		H3		Average	
	kg $(m^3)^{-1}$							
	2008							
D1	731.8		762.7		751.1		748.5	A
D2	752.4		764.0		745.9		753.7	A
D3	745.9		745.9		751.1		742.7	A
D4	722.7		725.3		730.5		725.3	B
Average	738.2	a	749.8	a	744.6	a		

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.18. Test weight at Hutchinson, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid H1		H2		H3		Average	
	$kg\ (m^3)^{-1}$							
	2007							
D1	726.6		716.3		716.3		718.9	A
D2	658.3		693.1		681.5		677.7	B
D3	717.6		727.9		703.4		716.3	A
D4	716.3		712.4		709.9		712.4	A
Average	704.7	a	712.4	a	703.4	a		
	2008							
D1	694.4	Aa	703.4	Ba	698.3	Ba	698.3	
D2	685.4	Bb	703.4	Ba	708.6	Ba	699.6	
D3	703.4	Aa	694.4	Ba	675.1	Cb	690.5	
D4	702.1	Ac	734.3	Ab	747.2	Aa	727.9	
Average	695.7		708.6		707.3			

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, $\alpha = 0.05$.

Table 2.19. Average kernel weight at Manhattan, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid						
	H1		H2		H3		Average	
	g							
	2007							
D1	0.336		0.336		0.354		0.342	A
D2	0.329		0.340		0.350		0.340	A
D3	0.308		0.317		0.372		0.332	A
D4	0.323		0.343		0.373		0.346	A
Average	0.324	b	0.334	b	0.362	a		
	2008							
D1	0.274		0.270		0.244		0.263	B
D2	0.245		0.275		0.254		0.258	B
D3	0.305		0.346		0.322		0.324	A
D4	0.253		0.274		0.255		0.261	B
Average	0.269	b	0.291	a	0.269	b		

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.20. Average Kernel weight at Belleville, KS, in 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid H1		Hybrid H2		Hybrid H3		Average	
	g							
	2008							
D1	0.227		0.239		0.233		0.232	A
D2	0.234		0.237		0.232		0.234	A
D3	0.232		0.232		0.233		0.232	A
D4	0.224		0.225		0.227		0.225	B
Average	0.229	a	0.233	a	0.231	a		

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, α = 0.05.

Table 2.21. Average kernel weight at Hutchinson, KS, in 2007 and 2008 for four planting dates (D1-D4) and three hybrids of differing maturity (H1-H3)†.

Planting Date	Hybrid H1		H2		H3		Average	
	g							
	2007							
D1	0.294		0.279		0.291		0.288	A
D2	0.229		0.229		0.221		0.226	B
D3	0.231		0.240		0.244		0.239	B
D4	0.284		0.287		0.298		0.290	A
Average	0.260	a	0.259	a	0.264	a		
	2008							
D1	0.262	Ba	0.266	Ba	0.239	Cb	0.256	
D2	0.257	Ba	0.223	Cc	0.233	Cb	0.238	
D3	0.307	Aa	0.308	Aa	0.320	Aa	0.312	
D4	0.302	Aa	0.310	Aa	0.294	Ba	0.302	
Average	0.282		0.277		0.272			

† Values in a column followed by the same upper-case letter and values in row followed by the same lower-case letter are not significantly different, $\alpha = 0.05$.

CHAPTER 2 - Figures

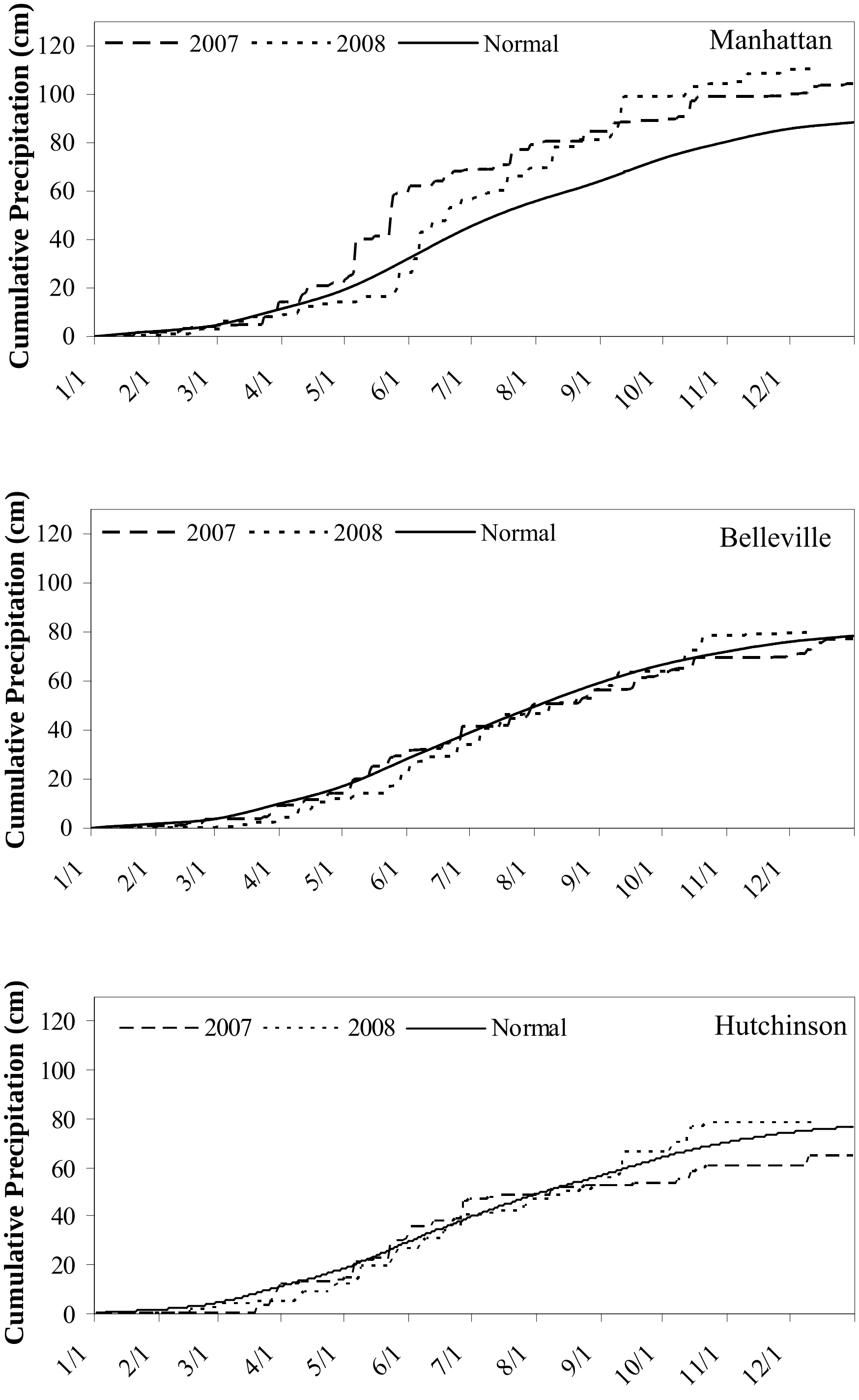

Figure 2.1. Cumulative precipitation (2007, 2008, and 30-year normal) at Manhattan, Belleville, and Hutchinson, KS.

CHAPTER 3 - Prediction of Delayed Planting Effects on Dryland Corn Production in Central Kansas using CERES-Maize

Abstract

Historically, dryland corn (*Zea mays* L.) production in central Kansas has varied due to year-to-year precipitation and temperature fluctuations. In Kansas, grain sorghum (*Sorghum bicolor* L.[Moench]) has been documented to have more consistent grain yields than corn in dryland production due to its ability to avoid drought periods by delaying pre-flowering growth and development. Although corn does not exhibit this ability, delaying planting can produce a similar outcome. In Kansas, little research has been conducted regarding delayed planting and its impact in different years. Long-term research requires substantial investments of time, labor, and money. Crop simulation models can predict yields based on historical weather data and site-specific soil information. A study was conducted to evaluate the long-term performance of delayed planting of corn in central Kansas. The study used 51 years of weather data from three locations: Manhattan, KS, Belleville, KS, and Hutchinson, KS. Four planting dates ranging from the optimal period in early April to late June were used in conjunction with three hybrids of 100-, 108-, and 112-d maturities. Yield averages over 51 years did not differ between planting dates at Manhattan and Belleville. Harvest index averages did not differ at any location. At Hutchinson, yield decreased from the earliest to latest planting dates. Chi-squared tests revealed that frequency of economically profitable yields was greater than 0.5 for all date x hybrid combinations at Manhattan and Belleville. At Hutchinson, all but two planting date x hybrid combinations produced economically profitable yields at frequencies less than 0.5. The two remaining combinations, earliest planting of the latest hybrid and latest planting of the latest

hybrid, produced economically profitable yields at frequencies not different than 0.5. These results suggest that economical viability of delayed planting of corn is heavily dependent on location.

Introduction

Historically, long-term research regarding cropping systems and production practices has required large investments of time, labor and money, as evident in studies by Norwood et al. (1990), who conducted trials for 14 years to study rotation sequence and tillage effects on soil water, and Varvel (2000), who collected 16 years of yield data to investigate the long-term effects of nitrogen rates and rotations on corn yields. In the Great Plains, in particular Kansas, short-term (1 to 2 years) crop research may not accurately represent the most probable outcome due to year-to-year variation in weather effects. Through the use of crop simulation models, predictions can be formulated using historical weather data and site-specific soil information. By coupling short-term field experiments with long-term information provided by crop simulation models, insightful inferences can be made with a much smaller investment of time, labor, and other resources compared to traditional long-term field research.

Crop models can be defined as quantitative schemes for predicting growth, development, and yield of a crop given a set of genetic coefficients and relevant environmental variables (Monteith, 1996). The most simplistic crop models appeared near the conclusion of World War II (Sinclair and Seligman, 1996). Early crop models were developed to estimate light interception in crop canopies (Loomis and Williams, 1963; Duncan et al., 1967). Crop models have evolved dramatically and have been used to predict agronomic responses in various crops, environments, and management situations, including assessing soybean (*Glycine max*) response to planting date and row spacing (Boote et al., 1996), investigating rotational effects on wheat (*Triticum aestivum*), sorghum, and soybeans (Staggenborg and Vanderlip, 2005), predicting optimal nitrogen rates in corn (Miao et al., 2006), and predicting yields in corn,(Hodges et al., 1987), soybean (Egli and Bruening, 1992), and wheat (Aggarwal and Kalra, 1994).

Crop-Environment Resource Synthesis (CERES)-Maize is a management-level model of corn growth and development (Jones and Kiniry, 1986). This model uses a daily-time step system to simulate physiological growth and development using soil, weather, and genetic information. Several studies have confirmed the validity of CERES-Maize. Kiniry et al. (1997) simulated dryland production in nine states and found that simulated grain yields were within 5% of the grain yields reported by the National Agricultural Statistics Service (NASS). Kiniry and Bockholt (1998) used nine sites (four irrigated, five dryland) in Texas to study year-to-year variability and found model-simulated mean yields to be within 10% of the measured yields at eight of the nine sites. The authors hypothesized that the site that was not within 10% of measured yields was affected by drought field conditions causing greater errors in yield component estimates when simulated by a harvest index approach. Hodges et al. (1987) estimated corn production in 14 states in the Corn Belt for four years and found that simulated yields were within 8% of the yields reported by NASS. CERES-Maize has been used successfully to evaluate the interaction of corn hybrid maturity and planting date in northeast Colorado (Anapalli et al., 2005). The results reported in these studies support the conclusion that CERES-Maize is suitable for simulations across a wide range of scales where adequate temperature and precipitation data is available and for simulating different hybrid maturities and planting dates in the Great Plains region.

Recommended planting dates for corn in central Kansas range from April 7 to May 15, depending on latitude, elevation, and soil texture and depth (Roozeboom et al., 2007). Historically, sorghum is recommended after this planting range has expired due to its greater ability to manage periods of high temperatures and low precipitation compared to corn. However, limited information is available regarding the effects of delayed planting on corn in central Kansas. Field studies often capture only a few of the infinite number of possible environmental scenarios that a corn crop can experience. Therefore, the objective of this study was to predict the effects of delayed planting on corn production in central Kansas on a long-term basis using CERES-Maize.

Materials and Methods

CERES-Maize was used to estimate corn production in central Kansas for the years 1958-2008 by simulating photosynthesis, respiration, phenology, leaf initiation and growth, stem and root growth, soil water extraction, evapotranspiration, light interception, grain initiation, and grain growth (Hodges et al., 1987).

Weather and site information required for the model to estimate corn production is presented in Table 3.1. Temperature, precipitation, and solar radiation data from automated weather stations at Manhattan, Belleville, and Hutchinson, were obtained from the Kansas State University Weather Data Library (2008) and the High Plains Regional Climate Center (2008). Potential evapotranspiration calculations are based on the Ritchie (1972) adaptation of the Priestley-Taylor method (Priestley and Taylor, 1972). The Ritchie adaptation does not require wind speed and vapor pressure data that were not available for the locations and years included in this study. Soils used for the simulations were a Reading silt loam (fine-silty, mixed, mesic

Pachic Argiudoll) at Manhattan; Crete silt loam soil (fine, smectitic, mesic Pachic Argiustoll) at Belleville, and Ost loam soil (fine-loamy, mixed, superactive mesic Udic Arguistoll) at Hutchinson, representing the dominant soils at each location. Soil physical properties at all sites were characterized by the USDA-NRCS and were obtained from the National Soil Survey Characterization database (Soil Survey, 2008), (Table 3.2). Additional definition of plant-available water was estimated using a soil bulk properties calculator obtained from the University of Albany (2008). Any additional, secondary values not determined from the previous sources were calculated with the soil pedotransfer functions embedded in CERES-Maize.

Genetic coefficients for three hybrids were developed based on initial adjustments by Pachta (2007). Hybrids varied in relative maturity, consisting of 100- (H1), 108- (H2), and 112-day (H3) hybrids (Table 3.3). Actual values for silking date, maturity date, grain yield, and leaf area index (LAI) obtained from field studies in 2007 and 2008 were used to calibrate the genetic coefficients.

Management input parameters were the same for all simulations. Simulated planting dates were 10 April (D1), 1 May (D2), 25 May (D3), and 20 June (D4). The first two planting dates fell within the recommended range for the region. Target plant density at emergence was 5.68 plants m^{-2} planted in 76 cm rows. Planting depth was 6.3 cm. Nitrogen was assumed to be non-limiting in all simulations. Soybean was the previous crop at Manhattan and Belleville, and sorghum was the previous crop at Hutchinson.

Statistical analysis was conducted on yield and harvest index (HI) using the PROC MIXED function of SAS (SAS Institute, 2004). Years were considered to be replications, as demonstrated by Baumhardt et al. (2007). Frequencies of each planting date x hybrid combination meeting or exceeding an economic break-even yield were calculated as the number of occurrences divided by the total number of years simulated. Break-even yields were determined from Kansas State University Farm Management Guides (Dumler and Thompson, 2007; Fogleman and Duncan, 2007; O'Brien, Duncan, and Olson, 2007). Chi-squared analysis of hybrid x planting date frequencies at $\alpha = 0.10$ determined if observed frequencies were significantly different from the expected frequency of 0.5 using the formula:

$$\chi^2 = \frac{(Observed - 0.5)^2}{0.5}. \qquad [3.1]$$

Results/Discussion

Validation

Although not an objective of this study, successful interpretation of planting date and hybrid selection effects depends on the validity of the model estimates. Yield data pooled from five location-years of delayed planting trials was compiled and used for the validation of CERES-Maize. Planting dates were from early April until late June. Measured yields within this dataset ranged from 2260 kg ha^{-1} to 10 883 kg ha^{-1}, with a mean of 7190 kg ha^{-1}. The CERES-Maize-simulated grain yields for the same years and locations ranged from 2507 kg ha-1 to 10 619 kg ha^{-1}, with a mean of 7299 kg ha^{-1} and a bias of -1.5% from the measured mean. The regression of simulated yield on measured yield ($r^2 = 0.79$; RMSE = 1257.3 kg ha^{-1}) shows that the frequency of CERES-Maize overpredicting yield increased as yield increased (Figure 3.1). The results support findings by Kiniry and Bockholt (1998) and Xie et al. (2001), who observed that simulated yields were underpredicted for growing seasons with below-normal precipitation.

Grain Yield and Harvest Index

Although CERES-Maize reports several parameters related to plant productivity, only grain yield and harvest index were extracted for investigation. Analysis of the data over 51 years revealed no differences ($\alpha = 0.05$) in harvest index at all locations or in grain yield at Manhattan and Belleville across planting dates (Tables 3.4-3.6). At Hutchinson, a significant hybrid x planting date interaction existed for grain yield. At that location, no difference in yields existed between the first two planting dates and the latest planting date produced the smallest yields for all hybrids.

Hybrid effects differed for harvest index and yield. No significant differences in harvest index were detected between hybrids at any location. At Manhattan and Hutchinson, H3 produced the greatest and H1 produced the smallest yields. At Belleville, no difference was detected in yield between hybrids.

These results, particularly for yield, were unexpected, because several studies have documented decreases in grain yield as planting date is delayed (Staggenborg et al., 1999; Lauer et al., 1999; Nafziger, 1994; Swanson and Wilhelm, 1996). However, plotting yearly grain yield graphically illustrates the variability of yield at each planting date, demonstrating the risk associated with each planting date. At Manhattan (Figure 3.2), the standard deviation of the average of the three hybrids increased from 2124 kg ha^{-1} at D1, to 2144 kg ha^{-1} at D2, to 2292 kg ha^{-1} at D3, to 2358 kg ha ha^{-1} at D4. At Belleville (Figure 3.3), standard deviations increased from 2106 kg ha^{-1} at D1, to 2284 kg ha^{-1} at D2, to 2411 kg ha^{-1} at D3, to 2455 kg ha^{-1} at D4. One probable explanation for greater yield variability at later planting dates is that grain fill occurs at cooler temperatures. Also plants are more susceptible to a killing frost occurring prior to physiological maturity when planted later at these locations.

Although yield variability increased as planting was delayed at Manhattan and Belleville, the opposite trend was observed at Hutchinson. At D1, the standard deviation for yield was 1883 kg ha^{-1}, 1782 kg ha^{-1} at D2, 1644 kg ha^{-1} at D3, and 1564 kg ha^{-1} at D4 (Figure 3.4). Before 1988, greater variability was observed in yield for D4 compared with earlier planting dates. Yields were more stable after 1988 for D4 even though yield potential was more limited compared with earlier planting dates, possibly due to a shortened growing season. Several factors may have contributed to this simulated trend after 1988. Although the growing season is shortened due to later planting, its effect is not as severe as that observed at Manhattan and Belleville due to Hutchinson's lower latitude compared to the other locations. Precipitation also has a dominating effect (Figure 3.5). In many years, tasseling and silking of early planting dates (D1-D3) occurred during periods of peak heat and water stress, causing the greater degree of variability in yields for these planting dates. At a later planting date (D4), pollination usually occurred after peak stress periods. Despite smaller simulated yields for delayed planting dates at Hutchinson (Table 3.6), variability was the smallest at the final planting date because most of the plant's growth and development occurred after periods of maximum water and temperature stress.

Frequencies of profitable hybrid x planting date combinations

The overall objective of this study was to determine the effects of delayed planting in central Kansas. To evaluate this, we determined the frequency that each hybrid x planting date combination surpassed an economic break-even yield based on current input and commodity prices. Break-even yield thresholds were created using production costs and grain prices from each region rather than state averages. Observed frequencies were evaluated using chi-squared test to determine differences from an expected frequency of 0.5 at $\alpha = 0.10$. Frequencies that were greater than 0.5 and significant were considered to be acceptable. Frequencies that were less than 0.5 and significant were regarded as high risk. If frequencies were not significantly different from 0.5 (NS), they were considered to be acceptable, yet still carrying some degree of risk.

Manhattan

In general, Manhattan was considered to be the location with the greatest yield potential and fewest yield limitations. Located in the northeastern part of the state, frequencies of early crop termination due to lack of water or an early frost are generally the lowest of the three locations tested. The economic break-even yield was determined to be 3680 kg ha^{-1} (Fogleman and Duncan, 2007).

Calculated frequencies for Manhattan are provided in Table 3.7. As expected, frequencies for profitable grain yields were the greatest at this location, with frequencies greater than 0.90 for all hybrid x planting date combinations. Simulation results suggest that delayed planting at this location may produce stable yields that are above an economically break-even threshold and comparable in stability to earlier, more traditional planting dates.

Belleville

Break-even yields at Belleville were determined to be 3680 kg ha^{-1} (O’Brien, Duncan, and Olson; 2007). When compared with the higher, more stable frequencies of Manhattan, values at Belleville were smaller, ranging from 0.69 to 0.86 (Table 3.7). Early termination of the crop due to an early freeze or low precipitation levels is likely the primary reason for these smaller frequencies. While values were smaller than Manhattan, all frequencies were still greater than 0.5. Unlike Manhattan, where frequencies remained consistent through planting dates, frequencies declined from 0.82 at D1 to 0.71 at D3, with a slight increase to 0.73 at D4. The decrease from D1 to D3 can likely be attributed to cooler temperatures, or even a killing frost, limiting grain fill (Table 3.8). As planting was delayed, the occurrence of delayed grain fill or early termination increased with each subsequent planting date.

In addition to affects prior to crop maturity, the effect of delayed planting on grain dry-down merits consideration, especially at Belleville. Since physiological maturity occurs at much cooler temperatures than for earlier planting dates, the rate of grain drying may be decreased. The resulting delay in harvest increases the risk of grain loss and causes an additional management expense if the grain is dried artificially. This was not taken into consideration in the economic analysis due to the year-to-year variability in severity and difficulty in quantification.

In all planting dates excluding D1, the H3 hybrid produced the greatest frequency of profitable yield. At D1, the greatest frequency was observed for H1. The greatest frequencies for each hybrid were observed at the D1 planting date. Results at this location suggest that delayed planting dates successfully produced profitable yields more often than not, but risk generally increased when planting was delayed until early June. The results also suggest that early planting dates, namely D1 and D2, are more likely to produce profitable yields due to the reduced risk of an early, killing frost.

Hutchinson

Break-even yields at Hutchinson were determined to be 3780 kg ha^{-1} (Dumler and Thompson, 2007). Although all combinations of planting date and hybrid maturity produced profitable yields at frequencies significantly greater than 0.5 at Manhattan and Belleville, the opposite was observed at Hutchinson. Because Hutchinson is located at a lower latitude than Manhattan and Hutchinson, the probability of an early-killing frost is less. However, several characteristics of this location contribute to limited grain production potential: less yearly precipitation, greater average daily temperatures, and soils with low water holding capacity. Of the twelve hybrid x planting date combinations, ten combinations were profitable less than half the time (Table 3.7). The two remaining combinations (D1 x H3 and D4 x H3) were not statistically different from 0.5.

When planting occurs in a region, such as Hutchinson, where precipitation during the growing season can frequently be lower than for areas like Manhattan and Belleville, results from the simulation emphasize the importance of planting the crop early to utilize precipitation that occurred during the previous winter and spring. When planting is delayed in this area, evaporation can be very high, further depleting stored water that is often initially lower than desired. Due to geographic location of this site, early planting (before 15 April) can be successful because soil temperatures are higher than at Manhattan or Belleville. Early planting also allows pollination to occur before periods of water and heat stress, which are more common at this location. The smaller frequencies of profitable yield for the D2 and D3 planting dates supports this, because these dates are usually subject to lower available water amounts, and important physiological stages (tasseling and silking) are exposed to peak periods of water or heat stress, resulting in lower frequencies of economically productive yields as observed in Table

3.7. Frequencies increased at D4 largely due to pollination occurring after these important physiological stages.

Although no differences existed among planting dates in H1 and H2, differences were detected in H3. The average frequency for H3 was to 0.39 at D1 and D4, suggesting that D1 and D4 could potentially produce more stable yields than D2 and D3. One undesired characteristic of the D4 planting date is the amount of time that the soil would be exposed to high temperatures and radiant energy, increasing evaporative losses. However, when the crop is growing during this period, its water demand is relatively low compared to crops planted at D2 and D3, which would typically be nearing or undergoing reproductive development. Because corn growing at D4 requires less water during the periods of water or heat stress that are common in this area, the likelihood of producing stable, profitable yields are increased, provided adequate precipitation occurs later in the growing season. The growing season at this location is generally longer than for the other locations, due to increased average daily temperatures and a later date for the first killing frost than at Belleville and Manhattan.

Conclusions

Dryland corn growth and rain yield was simulated for planting date and hybrid maturity using CERES-Maize, long-term weather records, and on-site growth measurements for model calibration. Linear regression of simulated grain yield on measured grain yield at 5 location-years produced an r^2 value of 0.79 with a RMSE of 1257.3 kg ha^{-1}, suggesting that the model was providing acceptable data.

Yield and harvest index means were determined for all combinations of four planting dates and three hybrid maturities for each location. There was no significant difference in yield averaged across hybrid maturity at Manhattan or Belleville, but significant differences were detected between planting date x hybrid combinations, where the planting date x hybrid interaction was significant. In all cases, yields were found to be the greatest at D1 and the smallest at D4. When hybrids were compared across planting dates, H3 produced the greatest yields and H1 produced the smallest yields at Manhattan and Hutchinson. At Belleville, no differences were detected between hybrids. When harvest index was compared across planting dates and hybrids, no differences were detected.

While conventional planting date studies in Kansas have focused on determining planting dates where the highest grain yields are obtained (Staggenborg et al., 1999), the objective of this study was to determine planting date x hybrid combinations that were economically realistic. Results from 51 years of simulated corn yield data indicate that all planting date x hybrid combinations at Manhattan have the ability to produce economically viable yields at a frequency of at least 92% due to the location's high yield potential and low probability of drought or early killing frosts compared to the other locations. At Belleville, where early-frosts are more frequent, simulated yield results indicate that planting corn early (10 April – 1 May) allows full maturation of the crop before the end of the growing season. Although frequencies of profitable yields at later dates (D3 and D4) are still acceptable (≥ 0.71), they are at least 5% less than the first two planting dates. At Hutchinson, where drought is a greater concern than season length, the simulation results indicate that planting should be avoided from about 1 May to 30 May. When planted during this time, plants are most likely to undergo pollination during periods of maximum water or heat stress, which can severely limit kernel set (Claassen and Shaw, 1970; Harder et al., 1982). Therefore, planting before or after this period is likely to provide the greatest chance of success, because planting dates outside of this window generally will allow pollination to occur at cooler temperatures. Simulation results for the D1 and D4 planting dates support this conclusion. Of the two options, planting at D1 may be more desirable, because it will allow the crop to utilize water that is already available from stored precipitation from the previous winter and spring. If planting at D4, late-season precipitation is necessary for proper grain fill. Basing expected yield on expected rainfall may be less realistic than stored water, a more consistent indicator of potential success.

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CHAPTER 3 - Tables

Table 3.1. Inputs required for simulation in CERES-Maize.

Environmental Information
1. Maximum temperature
2. Minimum temperature
3. Precipitation
4. Solar radiation†
5. Day length‡
6. Soil characterization data

Field Data
1. Latitude
2. Planting Date
3. Planting population and depth
4. Plant genetic coefficients

† Measured or simulated
‡ Calculated from latitude and date

Table 3.2. Physical properties of soils used in simulations.

Soil Description	Soil Depth	Sand	Clay	LL†	UL‡	Sat§	Bulk Density
	cm	%		cm^3 cm^{-3}			g cm^{-3}
Reading Silt Loam	0-24	15	25	0.140	0.321	0.419	1.51
	24-48	18	30	0.172	0.336	0.402	1.59
	48-85	20	33	0.186	0.334	0.364	1.63
	85-118	18	30	0.176	0.339	0.368	1.65
	18-163	21	35	0.201	0.285	0.374	1.58
Crete Silt Loam	0-18	11	18	0.111	0.223	0.342	1.31
	18-33	12	21	0.123	0.241	0.365	1.39
	33-53	13	40	0.224	0.362	0.391	1.59
	53-89	11	46	0.262	0.377	0.416	1.78
	89-112	10	33	0.189	0.335	0.424	1.63
	112-152	12	29	0.160	0.315	0.388	1.44
	152-191	10	27	0.155	0.300	0.375	1.39
Ost Loam	0-19	35	21	0.135	0.247	0.302	1.66
	19-30	33	27	0.152	0.266	0.316	1.58
	30-47	32	27	0.155	0.261	0.308	1.64
	47-60	23	29	0.163	0.272	0.322	1.70
	60-97	26	27	0.158	0.261	0.300	1.75
	97-135	33	24	0.144	0.240	0.296	1.78
	135-165	44	21	0.193	0.293	0.331	1.71

† LL, water content at lower limit

‡ UL, water content at upper limit

§ Sat, water content at saturation

Table 3.3. Genetic coefficients used in CERES-Maize simulations.

Coefficient Definition	Hybrid Maturity		
	100-d	108-d	112-d
	Coefficient		
Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8^{o} C) during which the plant is not responsive to changes in photoperiod.	160.0	180.0	200.0
Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours).	0.520	0.520	0.520
Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8^{o} C).	800.0	800.0	800.0
Maximum possible number of kernels per plant.	1100	1100	1100
Kernel filling rate during the linear grain filling stage and under optimum conditions (mg day^{-1}).	13.00	13.00	13.00
Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances	38.90	38.90	38.90

Table 3.4. Simulated yield and harvest index values from 1958-2008 for three hybrids (100-, 108-, and 112-d) at four planting dates (10 April, 1 May, 25 May, and 20 June) at Manhattan, KS.

Planting Date	Grain Yield			
	H1	H2	H3	Average
	kg ha^{-1}			
D1	8521	8721	8878	8707 A
D2	8291	8632	8873	8599 A
D3	8441	8689	8750	8627 A
D4	8821	9026	9110	8986 A
Average	8519 c	8767 b	8903 a	
	Harvest Index			
D1	0.566	0.557	0.546	0.556 A
D2	0.558	0.555	0.549	0.554 A
D3	0.565	0.558	0.634	0.586 A
D4	0.555	0.669	0.640	0.621 A
Average	0.561 a	0.585 a	0.592 a	

Table 3.5. Simulated yield and harvest index values from 1958-2008 for three hybrids (100-, 108-, and 112-d) at four planting dates (10 April, 1 May, 25 May, and 20 June) at Belleville, KS.

Planting Date	Grain Yield						
	H1		H2		H3		Average	
	kg ha^{-1}							
D1	7930		6912		7083		7309	A
D2	6450		6786		7043		6760	A
D3	6527		6677		6928		6711	A
D4	6684		6855		7088		6875	A
Average	6898	a	6807	a	7036	a		
	Harvest Index							
D1	0.551		0.531		0.611		0.559	A
D2	0.531		0.532		0.528		0.531	A
D3	0.659		0.539		0.547		0.582	A
D4	0.549		0.527		0.517		0.531	A
Average	0.569	a	0.532	a	0.551	a		

Table 3.6. Simulated yield and harvest index values from 1958-2008 for three hybrids (100-, 108-, and 112-d) at four planting dates (10 April, 1 May, 25 May, and 20 June) at Hutchinson, KS.

Planting Date	Grain Yield							
	H1		H2		H3		Average	
	kg ha^{-1}							
D1	3868	A	4039	A	4154	A	4020	
D2	3500	AB	3676	AB	3824	AB	3667	
D3	3210	BC	3329	B	3393	B	3311	
D4	3017	C	3253	B	3510	B	3260	
Average	3399	c	3574	b	3720	a		
	Harvest Index							
D1	0.541		0.531		0.517		0.530	A
D2	0.529		0.498		0.508		0.512	A
D3	0.508		0.515		0.501		0.575	A
D4	0.523		0.529		0.528		0.527	A
Average	0.526	a	0.518	a	0.514	a		

Table 3.7. Frequency of profitable yields for 12 hybrid x planting date combinations at Manhattan, Belleville, and Hutchinson, KS.

	H1		H2		H3		Average
Manhattan							
D1	0.92	*	0.92	*	0.96	*	0.93
D2	0.92	*	0.94	*	0.98	*	0.95
D3	0.94	*	0.94	*	0.92	*	0.93
D4	0.94	*	0.96	*	0.98	*	0.96
Average	0.93		0.94		0.96		
Belleville							
D1	0.86	*	0.80	*	0.80	*	0.82
D2	0.75	*	0.80	*	0.80	*	0.78
D3	0.71	*	0.67	*	0.75	*	0.71
D4	0.69	*	0.71	*	0.80	*	0.73
Average	0.75		0.75		0.79		
Hutchinson							
D1	0.29	*	0.35	*	0.39	NS	0.34
D2	0.27	*	0.25	*	0.31	*	0.28
D3	0.20	*	0.25	*	0.27	*	0.24
D4	0.27	*	0.36	*	0.39	NS	0.34
Average	0.26		0.30		0.34		

Table 3.8. Simulated occurrence of delayed grain fill or crop termination due to an early-killing frost at D4 at Manhattan, Belleville, and Hutchinson, KS, from 1958-2008.

	Delayed Grain Fill			Crop Termination		
	H1	H2	H3	H1	H2	H3
Manhattan	2	3	6	1	1	1
Belleville	3	5	9	1	1	2
Hutchinson	0	0	3	0	0	0

CHAPTER 3 – Figures

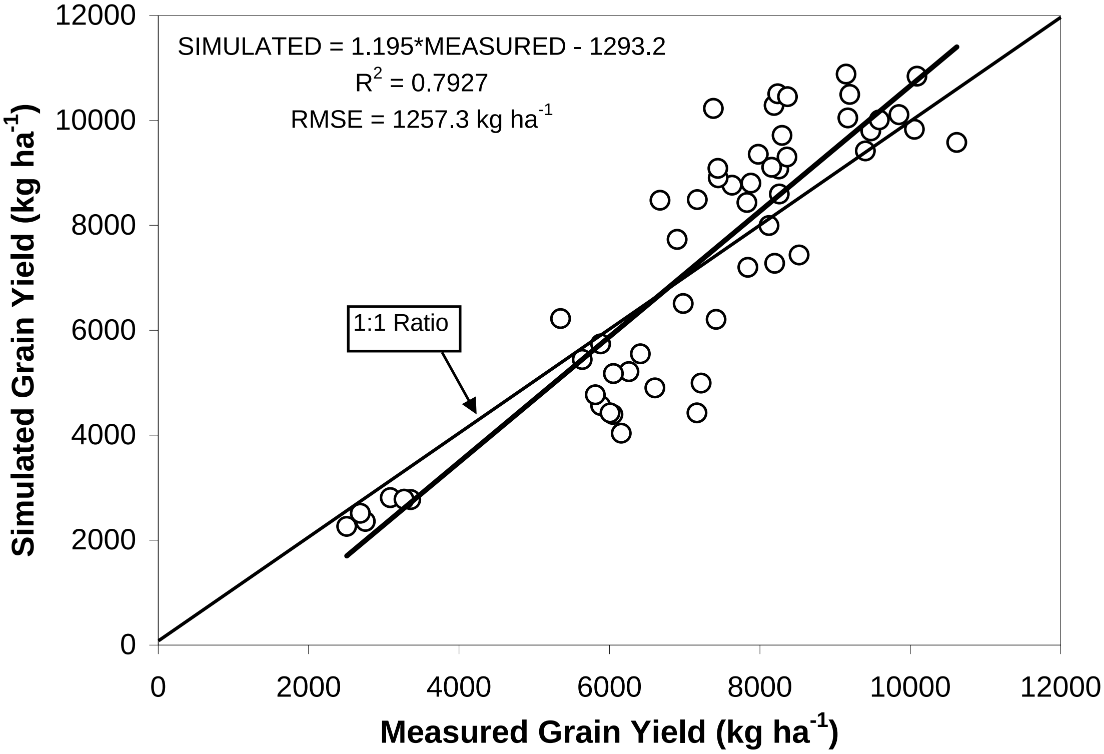

Figure 3.1. Comparison of corn grain yields simulated with CERES-Maize with yields from field studies in 2007 and 2008.

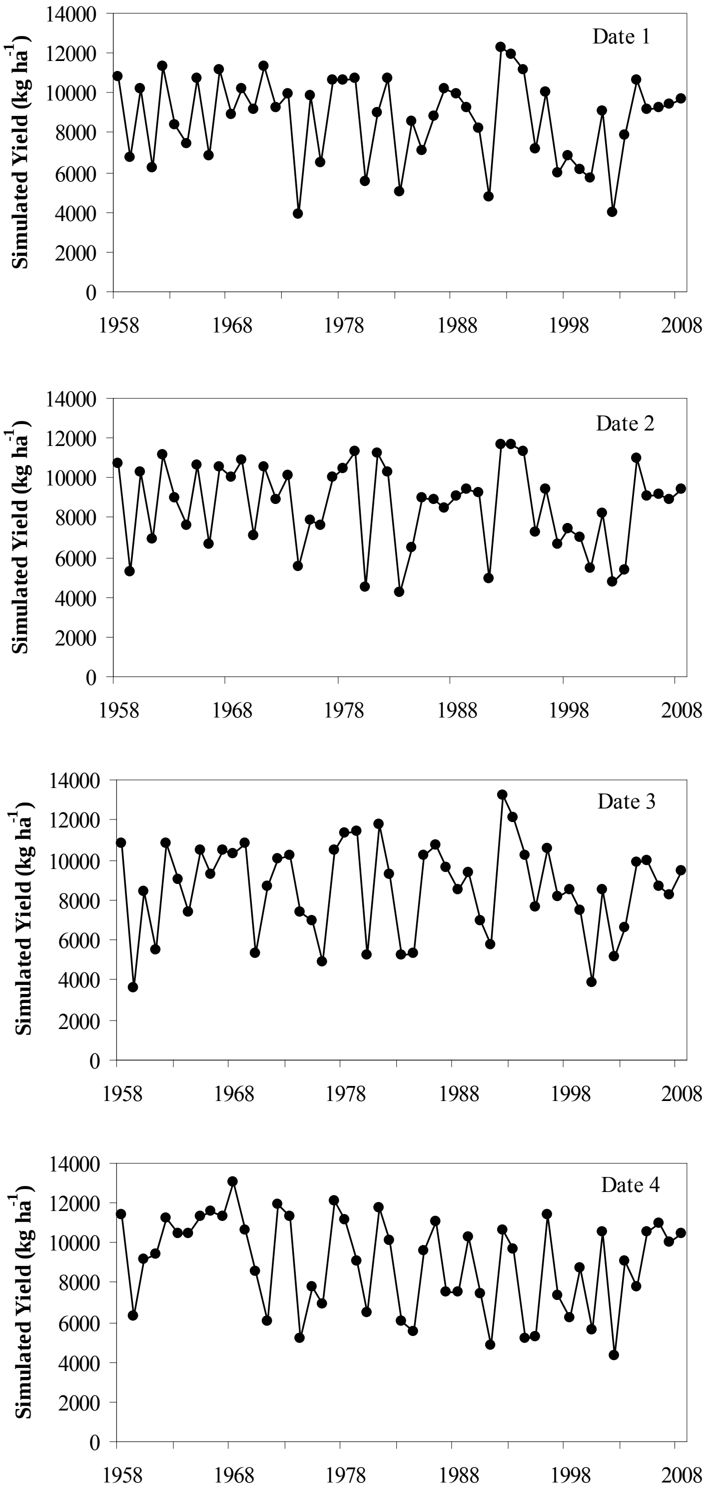

Figure 3.2. Simulated average grain yields at Manhattan, KS, 1958-2008.

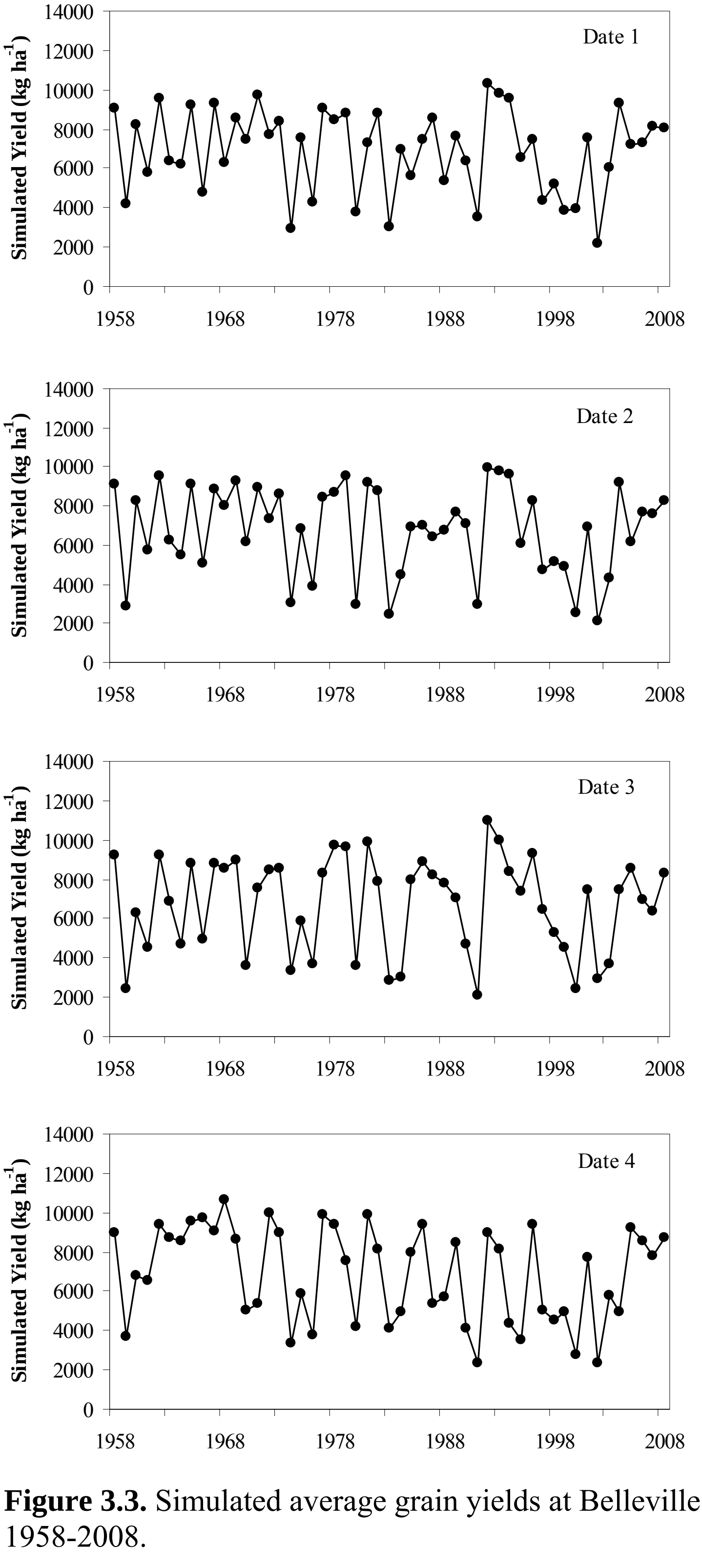

Figure 3.3. Simulated average grain yields at Belleville, KS, 1958-2008.

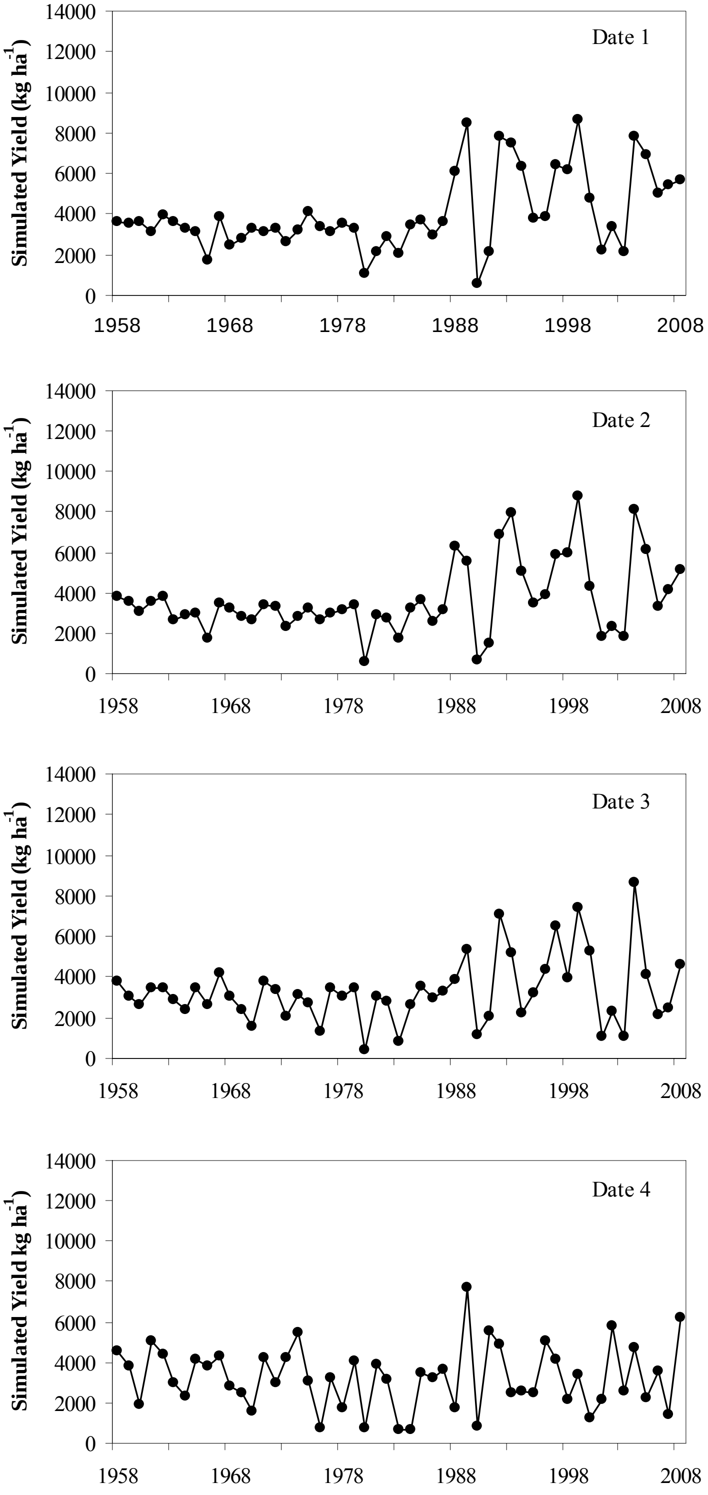

Figure 3.4. Simulated average grain yields at Hutchinson, KS, 1958-2008.

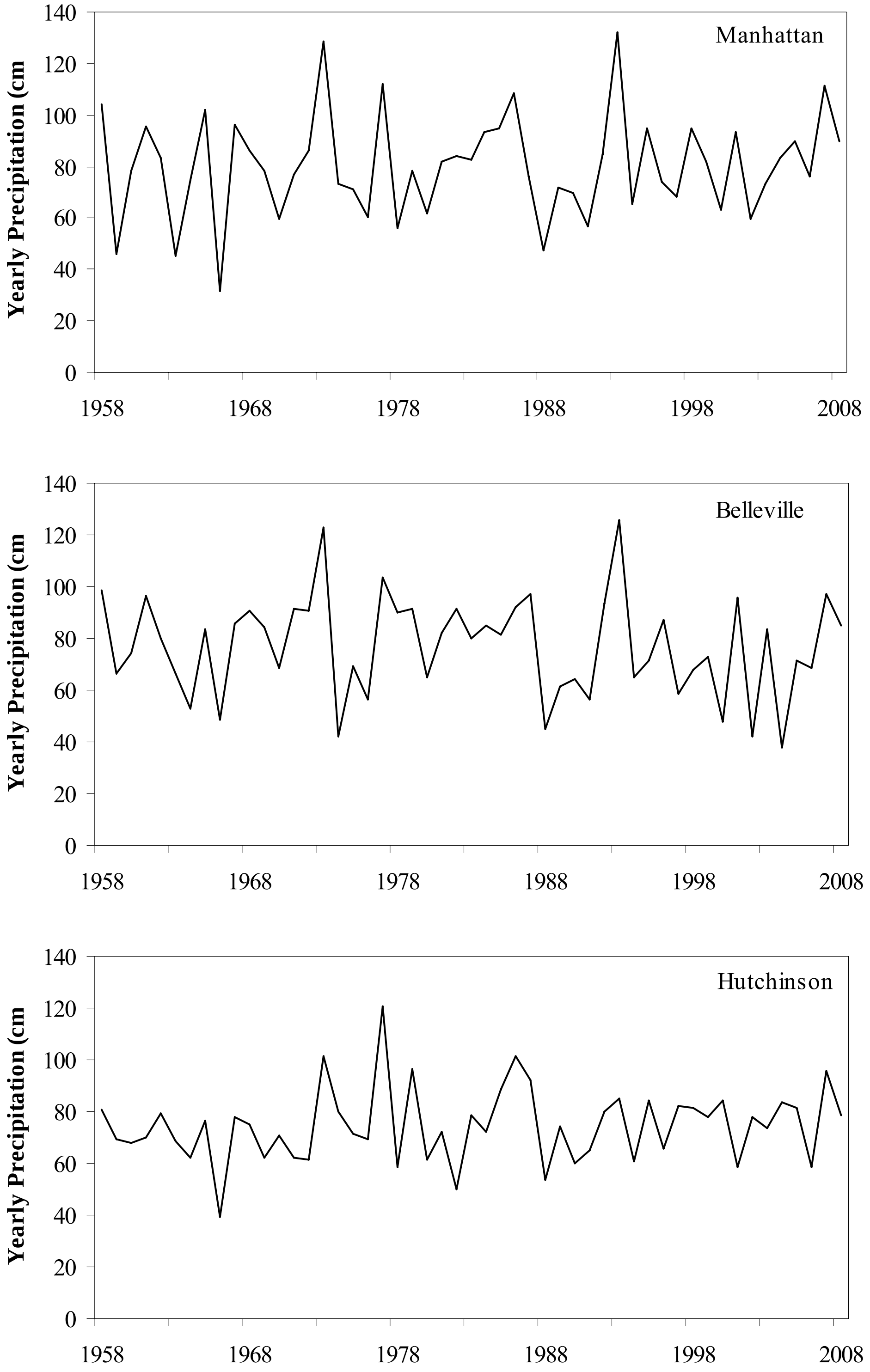

Figure 3.5. Yearly precipitation at Manhattan, Belleville, and Hutchinson, KS, 1958 to 2008.

APPENDIX A – Chapter 2

Table A.1. P-values of grain yield and yield components at Manhattan, Belleville, and Hutchinson, KS, in 2007 and 2008.

Effect	VT Leaf Area	Days to Silk	Plant Height	Yield	Harvest Index	Test Weight	Average Kernel Weight
				Pr > F			
Year	0.3517	<0.0001	0.0020	<0.0001	<0.0001	0.0100	<0.0001
Location	<0.0001	0.0120	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Year * Location	<0.0001	0.0218	<0.0001	<0.0001	<0.0001	0.1072	<0.0001
Date of Planting	<0.0001	<0.0001	0.0001	0.0046	0.0085	0.0024	<0.0001
Year * Date of Planting	0.3616	<0.0001	<0.0001	<.0001	<0.0001	0.0014	<0.0001
Location * Date of Planting	0.0021	<0.0001	0.0030	<0.0001	<0.0001	<.0001	<0.0001
Year * Location * Date of Planting	0.2022	<0.0001	0.0003	<0.0001	<0.0001	<.0001	0.0059
Hybrid	<0.0001	0.0165	<0.0001	<0.0001	0.3210	0.0042	0.0245
Year * Hybrid	0.0003	0.7392	0.4222	0.5682	0.1670	0.0128	<0.0001
Date of Planting * Hybrid	0.7434	0.9996	0.1386	0.6561	0.6110	0.1212	0.1008
Location * Hybrid	<0.0001	0.9068	0.5723	0.0003	0.3018	0.6460	0.0080
Location * Date of Planting * Hybrid	0.8198	1.0000	0.2253	0.9063	0.1684	0.0004	0.7267
Year * Date of Planting * Hybrid	0.7028	0.9952	0.3735	0.3284	0.5822	0.8723	0.5908
Year * Location * Hybrid	<0.0001	0.6130	0.9849	0.4046	0.3758	0.0200	0.0120
Year * Location * Date of Planting * Hybrid	0.0840	1.0000	0.2994	0.6678	0.3820	0.0183	0.2435

Table A.2. P-values of VT leaf area at Manhattan, Belleville, and Hutchinson, KS, in 2007 and 2008.

	2007		2008	
	F Value	Pr>F	F Value	Pr>F
Manhattan				
DOP	10.73	0.0025	14.76	0.0008
HYB	73.36	<.0001	35.85	<.0001
DOP x HYB	2.95	0.0267	0.62	0.7138
Belleville				
DOP	1.51	0.3072	3.11	0.0892
HYB	6.85	0.0104	129.25	<.0001
DOP x HYB	0.41	0.6751	1.21	0.3378
Hutchinson				
DOP	14.06	0.0010	1.59	0.2593
HYB	0.03	0.9686	9.24	0.0011
DOP x HYB	0.68	0.687	3.79	0.0085

Table A.3. P-values of plant height at Manhattan, Belleville, and Hutchinson, KS, in 2007 and 2008.

	2007		2008	
	F Value	Pr>F	F Value	Pr>F
Manhattan				
DOP	10.42	0.0028	8.87	0.0047
HYB	2.42	0.1099	10.55	0.0005
DOP x HYB	2.13	0.0874	1.43	0.2454
Belleville				
DOP	0.06	0.8162	14.91	0.0008
HYB	7.48	0.0019	11.24	0.0004
DOP x HYB	2.87	0.0705	2.01	0.1043
Hutchinson				
DOP	16.55	0.0005	43.07	<.0001
HYB	0.78	0.4711	9.88	0.0008
DOP x HYB	1.33	0.2827	0.93	0.4899

Table A.4. P-values of vegetative growth interval at Manhattan, Belleville, and Hutchinson, KS, in 2007 and 2008.

	2007		2008	
	F Value	Pr>F	F Value	Pr>F
Manhattan				
DOP	980.64	<.0001	1183.95	<.0001
HYB	57.89	<.0001	97.41	<.0001
DOP x HYB	3.94	0.0070	1.03	0.4296
Belleville				
DOP	193.42	0.0008	0.32	0.8094
HYB	13.30	0.0009	0.68	0.5168
DOP x HYB	0.70	0.5158	0.35	0.9057
Hutchinson				
DOP	1.65	0.2464	1935.89	<.0001
HYB	0.56	0.578	94.74	<.0001
DOP x HYB	0.32	0.9182	1.47	0.2293

Table A.5. P-values of grain yield at Manhattan, Belleville, and Hutchinson, KS in 2007 and 2008.

	2007		2008	
	F Value	Pr>F	F Value	Pr>F
Manhattan				
DOP	6.01	0.0157	4.97	0.0265
HYB	6.71	0.0049	1.07	0.3576
DOP x HYB	0.55	0.7622	1.45	0.2373
Belleville				
DOP	193.42	0.0008	0.92	0.4975
HYB	13.30	0.0009	38.26	<.0001
DOP x HYB	0.70	0.5158	0.95	0.4811
Hutchinson				
DOP	84.73	<.0001	11.43	0.0022
HYB	0.02	0.9767	3.49	0.0469
DOP x HYB	0.22	0.9677	1.77	0.1475

Table A.6. P-values of harvest index at Manhattan, Belleville, and Hutchinson, KS, in 2007 and 2008.

	2007		2008	
	F Value	Pr>F	F Value	Pr>F
Manhattan				
DOP	0.73	0.5588	0.82	0.5131
HYB	0.08	0.9227	3.94	0.0331
DOP x HYB	0.56	0.7561	1.57	0.198
Belleville				
DOP	17.72	0.0245	0.78	0.5347
HYB	2.63	0.1127	13.86	<.0001
DOP x HYB	3.24	0.0751	0.42	0.8615
Hutchinson				
DOP	21.76	0.0002	4.29	0.0386
HYB	0.33	0.7208	0.72	0.4962
DOP x HYB	0.77	0.6035	1.25	0.3149

Table A.7. P-values of test weight at Manhattan, Belleville, and Hutchinson, KS, in 2007 and 2008.

	2007		2008	
	F Value	Pr>F	F Value	Pr>F
Manhattan				
DOP	3.03	0.0862	25.26	0.0001
HYB	0.11	0.8921	11.54	0.0003
DOP x HYB	2.34	0.0637	2.77	0.0342
Belleville				
DOP			25.26	0.0001
HYB			11.54	0.0003
DOP x HYB			2.77	0.0342
Hutchinson				
DOP	51.64	<.0001	26.35	<.0001
HYB	0.70	0.5055	10.21	0.0006
DOP x HYB	1.00	0.4499	13.07	<.0001

Table A.8. P-values of average kernel weight at Manhattan, Belleville, and Hutchinson, KS, in 2007 and 2008.

	2007		2008	
	F Value	Pr>F	F Value	Pr>F
Manhattan				
DOP	0.51	0.6826	39.23	<.0001
HYB	12.50	0.0002	4.13	0.0288
DOP x HYB	1.26	0.3103	0.83	0.5579
Belleville				
DOP			6.17	0.0145
HYB			1.42	0.2619
DOP x HYB			0.79	0.5855
Hutchinson				
DOP	36.15	<.0001	33.85	<.0001
HYB	0.42	0.6603	2.35	0.1173
DOP x HYB	0.76	0.6612	3.82	0.0081

APPENDIX B – Chapter 3

Table B.1. P-values for grain yield at Manhattan, Belleville, and Hutchinson, KS.

	Manhattan		Belleville		Hutchinson	
	F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
DOP	1.12	0.3429	1.03	0.3821	5.35	0.0016
HYB	52.09	<.0001	0.46	0.6342	68.18	<.0001
DOP x HYB	1.67	0.1272	1.21	0.3076	2.79	0.0113

Table B.2. P-values for harvest index at Manhattan, Belleville, and Hutchinson, KS.

	Manhattan		Belleville		Hutchinson	
	F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
DOP	1.07	0.3636	0.93	0.4276	1.19	0.3156
HYB	0.37	0.6878	0.79	0.4555	1.85	0.0899
DOP x HYB	0.51	0.8008	1.1	0.3588	2.06	0.057

Table B.3. P-values for probabilities derived from chi-squared test.

	Manhattan			Belleville			Hutchinson		
	H1	H2	H3	H1	H2	H3	H1	H2	H3
D1	35.28	35.28	42.32	25.92	18.00	18.00	8.82	4.50	2.33
D2	28.88	38.72	46.08	11.52	18.00	18.00	10.22	12.01	10.22
D3	38.72	38.72	35.28	8.00	5.58	12.01	18.48	12.10	6.99
D4	38.72	42.32	46.08	6.92	8.41	18.00	10.22	4.32	2.33