CORN HYBRID RESPONSE TO SKIP-ROW PLANTING CONFIGURATIONS AND PLANT POPULATION IN WESTERN NORTH DAKOTA

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Corn Hybrid Response to Skip-Row Planting Configurations

And Plant Population in Western North Dakota

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

ABSTRACT

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Management practices are needed for stable corn (*Zea mays* L.) production in drought prone regions of western North Dakota. Analysis of weather data suggests areas like those near Mandan and Hettinger suffer severe drought about 50% of the time. Since most of the rainfall in western North Dakota is in early summer, the soil water reserves may be completely utilized by anthesis, which can result in low yields or crop failure because of corn's water requirement and sensitivity to stress during this period. Skip-row planting configurations can conserve water and improve grain yield in certain environments. The objective of this research was to identify hybrids and hybrid characteristics that are better adapted to skip-row planting configurations and the optimum plant population when rows are skipped. Three field trials were conducted in 2009 and 2010 in western North Dakota. Six hybrids with two populations were used within three planting configurations: plant every row (P All), plant two - skip one row (P2S1), and plant one – skip one row (P1S1). Weather data were also analyzed to determine the frequency of drought. The long-term average precipitation in Mandan is 43.3 cm annually. In 2009 and 2010, there was 48.4 and 48.0 cm of rain, respectively. Grain yields for the three environments analyzed, 2009 dry pea, 2010 dry pea, and 2010 sunflower residue, were 6.93, 6.97, and 6.97 Mg ha^{-1}, respectively. Planting configuration affected grain yield and plant population at harvest with P All having significantly more grain yield and final plant population than P2S1 and P1S1, which were not significantly different from one another. The P All, P2S1, and P1S1 grain yields were 7.89, 6.78, and 6.27 Mg ha^{-1}, and the plant populations at harvest were 63,149, 51,608, and 45,622 plants ha^{-1}, respectively. The plant population partially explains the difference in grain yield for the three planting configurations. The two plant populations used in these experiments were 59,280 (high) and 44,460 (low) plants ha^{-1}, but at harvest they actually were 57,953 and 48,967 plants ha^{-1}, respectively. The higher plant population had significantly more grain yield and significantly less test weight. The grain yield for the high and low plant populations was 7.19 and 6.73 Mg ha^{-1}. The six hybrids tested were NuTech 3T-484, PH 38R51, NuTech 3C-389, DKC 33-54, DKC 30-23, and PH 39D97, and their grain yields were 7.76, 7.50, 7.07, 6.81, 6.42, and 6.20 Mg ha^{-1}, respectively. Overall, later maturing hybrids had significantly more grain yield than earlier maturing hybrids due to the optimal growing conditions. The earliest maturing hybrid PH 39D97 had significantly less grain yield than all of the other hybrids tested because it had a significantly lower plant population at harvest. The plant population of the other five hybrids did not differ significantly. In wet years such as 2009 and 2010, highest grain yield is attained by planting all rows with a plant population of 59,280 plants ha^{-1} with later maturing hybrids, especially NuTech 3T-484.

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"Dedicated to my family and friends"

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INTRODUCTION

Corn (*Zea mays* L.) production has expanded throughout North Dakota in recent years with substantial hectares in western North Dakota where drought frequently constrains yield (Alessi and Power, 1974). The expansion of corn into western North Dakota has also been promoted by ethanol plants in Richardton and Underwood, ND. Corn is a very water-use efficient crop, producing approximately 85 kg of grain cm^{-1} of water. However, since corn is a high yielding crop, it still requires as much water as it can get without flooding conditions. Moreover, corn is very sensitive to water stress during the period just before tasseling through early grain filling (Hall and Tidwell, 2002). Since drought frequently constrains corn yields in western North Dakota, production techniques are needed to improve yield sustainability (or minimize risk by keeping grain yields similar in both good and bad growing seasons) for corn grown in drought prone environments and to reduce crop failure.

Skip-row planting may be one way to improve yield sustainability. Planting all rows has been compared to skip-row planting configurations that consisted of either planting two rows – skipping one, and planting one row – skipping one. The theory is that there should be an extra pool of soil water in the skip rows that the corn will be able to extract during water stress later in the season (Routley et al., 2003). Corn hybrids have different traits or characteristics that could enhance or be detrimental to the skip-row configuration. Possible traits or characteristics that could impact how hybrids interact with skip-row techniques being looked at are fix versus flex ear, which is the ability of a hybrid to increase the ear size as plant density is reduced or if growing conditions improve, maturity length, stay green which refers to a hybrid's potential to maintain healthy green leaves late into the growing season, drought tolerance, and northern and western corn rootworm (*Diabrotica barbari* and *Diabrotica virgifera virgifera*, respectively) resistance. Plant population may also play an important role, especially as fewer rows are planted. The results of this study may impact the producers of western North Dakota and in other drought prone environments. This research will hopefully offer a management technique that allows producers the ability to sustainably grow corn in all regions of North Dakota.

LITERATURE REVIEW

There is very little data and information on how to manage corn (*Zea mays* L.) in drought prone regions of North Dakota as well as a lack of analysis of the risks of growing corn. The growing season of the semiarid region of western North Dakota is short and usually lacks available water during grain formation and fill, causing it to be the limiting factor for corn production (Alessi and Power, 1974). Most of the rainfall in western North Dakota is received in early summer, so soil water reserves may have been completely utilized by anthesis, resulting in low yields or crop failure.

According to Hall and Tidwell (2002), the greatest damage to corn grain yield from heat and water stress occurs during the period of pollination and fertilization, which starts a few days after the tassels appear. Sinclair et al, (1990) in Florida found that the most limiting factor to grain yield was water stress at anthesis which is the period of time between the opening of a flower and the formation of a fruit, so it contains the period of pollination and fertilization. This is the growth stage when maximum biomass accumulation and water use occurs. Also, water stress impairs uptake and transport of nutrients and causes a lack of synchronization between pollen shed and silking, resulting in non-fertilized ovules (Thelen, 2007). Water stress tends to slow down silk elongation and accelerates pollen shed and the rate of desiccation of silks that do emerge causing them to be unreceptive (Nielsen, 1996). This affects seed set which ultimately affects ear size or the number of kernels cob^{-1}, and once ear size is determined during this period low yield potential is irreversible and, the plant cannot respond to rainfall later in the season (Hall and Tidwell, 2002; Thelen, 2007).

Norwood (2001a) found that above average rainfall in June was adequate for potential maximum ear size, but a lack of rainfall in July restricted ear development in all hybrids. However, if there was a lack of rainfall in June, there was still adequate ear development and when followed by above average rainfall in July normal ears developed. This shows the importance of rain in July. Unfortunately, Jensen (1998) found that rainfall in western North Dakota decreases rapidly in both July and August. Therefore, management practices that capture or conserve soil water for the corn plant, so stored soil water can be used during anthesis which typically occurs in late July in western North Dakota, are critical.

Plant populations also have a significant effect on grain yield under drought stress as reported by Alessi and Power (1976) and Norwood (2001b). Norwood (2001b) found that higher plant populations usually removed more water from the soil, and lower plant populations on average used the least amount of water. Alessi and Power (1974) found that plants under water stress or drought conditions tended to be larger at lower plant populations. This remained true regardless of the relative maturity of the hybrid. Whether relative maturity was 68 or 85 day, the number of ears per stalk and ear weight decreased as the plant population increased.

Research also has found that the relative maturity of a hybrid can influence the amount of water used. Norwood (2001b) found that at the same plant population the earliest hybrids always removed less water than the later maturing hybrids. Alessi and Power (1974) found early maturing corn hybrids had fewer barren plants and higher ear weight when stressed while later maturing hybrids used more soil water and showed symptoms of stress sooner than early maturing hybrids. This was also found to be true in research by Norwood (2001b). He found that an early hybrid yielded as much as a later hybrid in a dry year, so early maturing hybrids would be better adapted for dryland agriculture where water is limiting.

Norwood (2001a) also looked at the effect of planting dates in western Kansas on water use and found that later planting dates (early-May) removed more soil water, produced more grain yield, and had higher water-use efficiency than early planting dates (mid-April). The reason was that the soil at the time of planting was warmer. Cold soils slow germination and plant growth and in a drought region, it is generally followed by hot and dry conditions.

Hanson et al. (2007) looked at soil water depletion and recharge in different crops. They found that later maturing and more deeply rooted oilseed crops, such as sunflower (*Helianthus annuus* L.), have the greatest water use, compared to shorter season crops, such as dry pea (*Pisum sativum* L.), which has the lowest. However, Benjamin et al. (2008) found in eastern Colorado the response of dryland corn yield to soil water at planting varied with the amount of rain during the critical period for yield formation. Regardless of soil water at planting, there was no grain yield when only 15 mm of rain occurred from tasseling through the dough stage.

Skip-row planting configurations have been evaluated as a management tool for conserving soil water for later season use. Alessi and Power (1976) found that row spacing had little effect on average water use showing lateral root development was sufficient to remove soil water. However, Alessi and Power (1974) found that spacing plants wider apart within a given row spacing produced bigger ears per stalk than more closely spaced plants. This could be problematic for skipping rows and maintaining plant populations because as the plant spacing within the row decreases, the plants became more tightly packed, possibly causing more competition between plants. Liu et al. (2004) found that whether or not there are gaps or doubles in the row versus a uniform stand there was no significant yield advantage to any within-row spacing of 6.7 to 16.2 cm. This suggests that skip-row planting configurations could be a management practice that conserves soil water for corn, and could be a way of reducing drought risk for growing corn in western North Dakota.

Weed competition is a serious issue in skip-row planting configurations because weeds, if not controlled, will use the soil water being stored. This is evident even when rows are not being skipped. Sharratt and McWilliams (2005) studied corn grown at a standard row spacing of 0.76 m versus narrow row spacing of 0.38 m. They found that narrow rows had higher root densities and occasionally suppressed soil evaporation because the canopy shaded out weeds and created cooler soil temperatures, even though the soil temperatures between the standard and narrow row spacing were not significantly different. A skip-row planting configuration is going to have an even wider spacing, so it will be harder for the plants to shade out weeds, so excellent weed control is essential in this type of system.

Relatively more extensive root systems under optimal growing conditions are generally a response to environmental stresses in the rooting zone (Richner et al., 1996). Therefore, in a skip-row configuration, a drought prone environment should provide enough root growth to reach any stored moisture in the mid row region. However, Richner et al. (1996) found a pause or stagnation of root growth when temperatures decreased to between 10-15 °C. Since soil temperatures in July typically are much higher than that in western North Dakota, soil temperature should not constrain root growth and roots should be able to reach available moisture between skip-rows. Routley et al. (2003) found increased yield levels with skip-rows compared to solid plant configurations in grain sorghum (*Sorghum bicolor* L.) when yields were below 2.6 Mg ha^{-1}, and that this effect was due to the conservation of soil water in the center of the skip area for use by the plant during the grain filling stage. Klein (2005) did similar research with corn and found that skipping rows yielded more grain than planting every row even when there was above average moisture. Also, Lyon et al. (2009) did an extensive study with corn using skip-row planting patterns and found that lower yielding environments had improved grain yield when skip-rows were compared to a standard planting pattern. Pavlista et al. (2010) went another step farther and found that the grain yield from the primary ear was increased by skipping rows; however, the secondary ear had the reverse trend. Also, regardless of plant population, skipping rows offered the best opportunity to increase yield when planting all rows yielded 5.0 Mg ha^{-1} or less.

Hybrids have the potential to interact with skip-row planting configurations. No research has been done on how different corn hybrids interact with different skip-row planting patterns. In the studies reported, there has always been only one hybrid used when skip-row planting was investigated. Typically, shorter maturing hybrids yield the same as longer maturing hybrids in drought environments as previously mentioned, but that may not be the case in a skip-row planting configuration where more moisture will be available at a key growth stage. Also, different hybrids have different drought tolerances which could interact with skip-row spacing practices. Furthermore, ear type (flex v. fix ear) may be an important trait when skipping rows. The hypothesis was that different hybrids will interact with skip-row planting patterns.

OBJECTIVES

The first objective of this research project was to determine if skip-row planting configurations could increase corn yield sustainably in the drought prone regions of North Dakota. Within this objective, finding the optimum plant population when rows are skipped, the skip-row pattern that works best, and hybrid characteristics that might be synergized by skip-row planting patterns were investigated. The second objective was to determine the frequency of drought in western North Dakota.

MATERIALS AND METHODS

Weather

Weather data were collected from the North Dakota Agriculture Weather Network (NDAWN) to determine the frequency and intensity of drought in Mandan and Hettinger, ND. Drought in this study is defined as significant periods of water deficit stress. The data analyzed were from the years 2000 to 2010 and within those years only data from April 15 to Nov. 1 were used. For each day for this period, maximum temperature, minimum temperature, rainfall, daily growing degree days (GDDs), accumulated GDDs, crop water use, accumulated crop water use, crop water deficit, and accumulated crop water deficit were recorded from NDAWN. These data were used to produce the average water deficit, minimum water deficit, maximum water deficit, and the frequency of drought during the period of tasseling through physiological maturity for hybrids with differing maturities (NuTech 3T-484, NuTech 3C-389, DKC 30-23, DKC 33-54, Pioneer 38R51, and Pioneer 39D97) that were included in field experiments in 2009 and 2010. All hybrids were Roundup Ready™. Corn yield data for Morton (Mandan) and Adams (Hettinger) counties in North Dakota were also collected from the USDA's National Agriculture Statistics Survey website (www.nass.usda.gov) to show how grain yield was affected by water deficit from tasseling through physiological maturity at the county level. Linear regression analysis on county corn grain yield as provided by NASS and average water deficit was performed to determine if average water deficit as calculated by NDAWN correlated with grain yield.

The severity of drought is determined by calculating the GDDs for each individual hybrid to determine when that hybrid starts tasseling until it reaches physiological maturity (Table 1). During this period the data from NDAWN for accumulated corn crop water deficit was recorded for each individual day. The number of days when accumulated water deficit exceeded 12.7 cm per day during this period was divided by the total number of days within the period of tasseling to physiological maturity to determine the frequency of water deficit greater than 12.7 cm. This threshold was used because it was identified as the level at which drought symptoms just began to show on the leaves in research plots in Michigan (Thelen, 2007).

Location Information

Experiments were conducted in five locations during 2009 and 2010 in Western North Dakota. Four of the trials were conducted at the Northern Great Plains Research Laboratory in Mandan, ND, at two different field locations (Latitude 46.773407 N and Longitude -100.948691 W) in both 2009 and 2010. One field each year followed a previous crop of sunflower, and one field followed a previous crop of dry pea. These previous crop residues were chosen with the expectation that there would be more soil moisture following dry pea than sunflower because typically dry pea uses less water and has shallower roots (Merrill, 2007). All experiment locations were over-fertilized with urea after planting with a rate of 135 kg ha^{-1} for their yield goal of five Mg ha^{-1}, so nitrogen, phosphorus, and potassium levels were not yield limiting. According to soil tests phosphorus and potassium levels were adequate. The soil type at Mandan was a Temvik-Wilton silt loams (fine-silty, mixed, superactive, frigid Typic Haplustolls). In 2010 an additional experiment was conducted near the Hettinger Research Extension Center in Hettinger, ND (Latitude 46.030709 N and Longitude -102.687199 W) because drought is even more frequent and severe there than at Mandan. The soil type for this location was Belfield-Savage-Daglum silt loams (fine, smectitic, frigid Glossic Natrustolls). The previous crop at this location was wheat (*Triticum aestivum* L.) and was not taken to yield due to extreme wildlife damage.

Experimental Design

Experiments consisted of a factorial combination of skip-row planting configuration [plant every row (P All), plant two – skip one row (P2S1), plant one – skip one row (P1S1)], plant population (59,280 and 44,460 plants ha^{-1}), and hybrids with diverse characteristics that were Roundup Ready™ (DKC 30-23, DKC 33-54, Pioneer 39D97, Pioneer 38R51, NuTech 3T-484, NuTech 3C-389) resulting in 36 unique treatments. Experiments were laid out as a randomized complete block design (RCBD) with a split plot restriction and three replications. The skip-row planting configuration was the whole plot, and a factorial combination of hybrid and population were the subplots. Plot length was 7.62 m for all plots, and the plot width varied depending on skip-row planting configuration. The P All, P2S1, and P1S1 plots were 3 m, 2.3 m, and 1.5 m wide, respectively (Fig. 1). The standard row spacing within the plots was 76.2 cm.

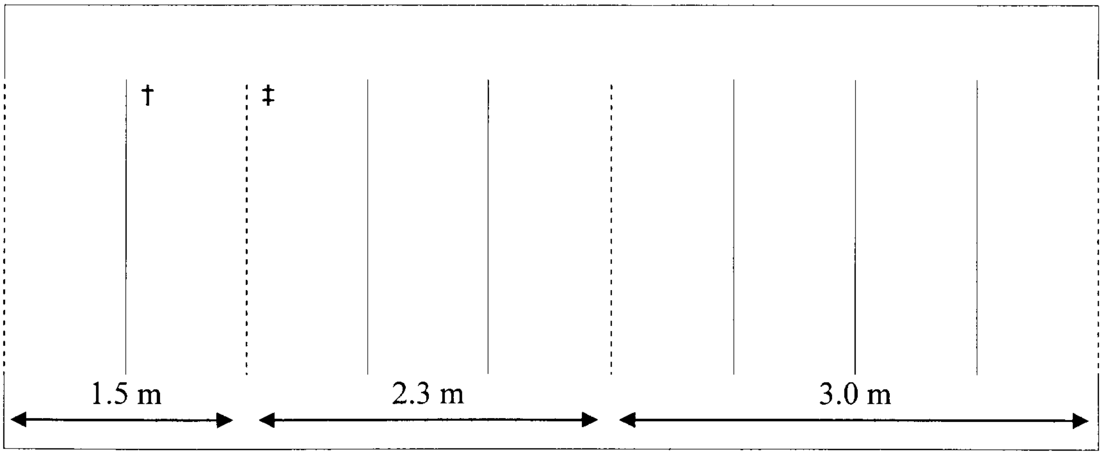

Fig. 1. A depiction of one replication from an experiment showing three planting configurations and how their widths differed.

† Planted row.

‡ Skipped row.

Planting

All plots in both years were planted no-till with all previous residues being retained for several years. In 2009 at Mandan, the corn plots were planted with a John Deere 1020 tractor and a two-row John Deere 7100 finger planter set with a 76.2 cm spacing with a Kincaid twin finger pick-ups (Haven, KS) installed on the planter instead of the original planter boxes. In 2010, the corn plots at Mandan and Hettinger, ND were planted with a New Holland 75TT tractor and the same planter as the previous year. Plots at Mandan were planted May 8 in 2009. In 2010, plots at both Mandan and Hettinger were planted April 30. The P1S1 plots consisted of a single planted row with a skipped row on both sides of the planted row. The entire single row was harvested. The P2S1 plots consisted of two planted rows, and a skipped row on each side of the two planted rows. A single row on the north or west side of the plot depending on the orientation of the experiment was harvested. The P All plots consisted of three planted rows, with the middle row harvested.

Hybrids Tested

Six hybrids were chosen with different characteristics that were thought to potentially interact with skip-row planting configurations (Table 1). The characteristics considered were relative maturity, drought tolerance, ear type, stay green, and rootworm resistance. Relative maturity was considered as a factor because hybrids that differ in the length of time in days that it takes to reach maturity vary in plant size, phenological development, yield potential, and water requirements. Earliness may allow a hybrid to avoid an environmental stress such as drought during anthesis by reaching anthesis before the drought occurs. Drought tolerance is a complex trait that allows a hybrid to yield relatively better under drought conditions. The relative tolerance to drought of the hybrids

Table 1. Characteristics of hybrids tested.

Hybrid †	Company	RM	Drought Tolerance	Ear Type	Stay Green	Rootworm Resistance	GDDs ‡
39D97	Pioneer	79	4	Flex	5	No	605-1120
DKC 30-23	Dekalb	80	3	N/A §	4	Yes	615-1145
DKC 33-54	Dekalb	83	3	N/A	4	No	625-1160
3T-484	NuTech	84	1.4	SD ¶	N/A	Yes	635-1210
3C-389	NuTech	89	1.6	SD	N/A	No	655-1270
38R51	Pioneer	93	2	Mod. Flex	4	No	670-1345

† NuTech seed ranking for all traits - 1=Excellent, 5=Very Poor.

† Dekalb seed ranking for all traits - 1=Excellent, 9=Poor.

† Pioneer seed ranking for all traits - 1=Excellent, 9=Poor.

‡ Growing Degree Days from tasseling through physiological maturity in °C.

§ N/A - No Rating given.

¶ SD - Semi Determinate (allows some flexing of ear).

included was assigned by the company marketing the hybrid (Table 1). Ear type (flex v. fix ear) reflects the ability of a hybrid to increase the ear size as plant density is reduced or if growing conditions improve. All characteristics were assigned by the seed companies (Table 1). Stay green refers to a hybrid's potential to maintain healthy green leaves late into the growing season even after reaching maturity. The last hybrid characteristic is northern and western corn rootworm (*Diabrotica barbari* and *Diabrotica virgifera virgifera,* respectively) resistance. Genetic rootworm resistance is commonly thought to help corn plants develop longer, healthier roots which in turn can result in better moisture uptake, especially in the presence of rootworms compared to hybrids without rootworm resistance (Ellsbury et al., 2005). Rootworm resistance is a transgenic trait and resistant hybrids contain a toxin from *Bacillus thuringiensis* (Bt). All hybrids tested were Roundup Ready™. The characteristics of the six different hybrids used in these experiments are summarized in Table 1.

Populations

The two planting populations targeted were 59,280 and 44,460 plants ha^{-1} (24,000 and 18,000 plants acre^{-1}, respectively). These two populations were chosen to represent a high and low population for the experiment locations based on current recommendations for these areas. These two populations were maintained even though the number of rows in a hectare was reduced. In order to maintain the two plant populations within the plots, all plots were planted at 123,500 plants ha^{-1} (50,000 plants acre^{-1}) and hand thinned to their desired population at the V3 growth stage, allowing enough time for all seedlings to emerge. The number of plants per row varied within the different planting configurations and desired plant populations. The 59,280 plants ha^{-1} for P All, P2S1, and P1S1 were 28, 41, and 56 plants per row, respectively. The 44,460 plants ha^{-1} for P All, P2S1, and P1S1 were 21, 28, and 41 plants per row, respectively.

Weed Control

Weeds were controlled or suppressed with glyphosate; all hybrids were Roundup Ready. At Mandan glyphosate (potassium salt) [N-(phosphonomethyl)glycine] at 1,464 ml ha^{-1} was tank mixed with dicamba [3,6-dichloro-2-methoxy benzoic acid] at 586 ml ha^{-1} and was applied on June 09 in 2009 and June 14 in 2010. For the second application of the season in 2009, glyphosate at 2,336 ml ha^{-1} was tank mixed with a premix of dicamba, diflufenzopyr [2-(1-((((3,5-difluorophenyl)amino)carbonyl) hydrazono)ethyl)3-pyridinecarboxylic acid], and isoxadifen [ethyl-5,5-diphenyl-2-isoxazoline-3 carboxylate] at 183 ml ha^{-1} and was applied on June 30 in 2009. The second application in 2010 was glyphosate at 1,464 ml ha^{-1} tank mixed with a premix of dicamba, diflufenzopyr, and isoxadifen at 183 ml ha^{-1} and was applied on July 13 in 2010.

At Hettinger the first herbicide application in 2010 was glyphosate at 1,609 ml ha^{-1} tanked mixed with isoxaflutole [(5-cyclopropylisoxazol-4-yl)[2-(methylsulfonyl)-4-(trifluoromethyl)phenyl] methanone] at 148 ml ha^{-1} and clopyralid [3,6-dichloro-2-pyridinecarboxylic acid] at 219 ml ha^{-1}, and it was applied May 19. The second application was glyphosate at 804 ml ha^{-1} tank mixed with nicosulfuron [3-pyridinecarboxamide, 2-((((4,6-dimethoxypyrimidin-2-yl)aminocarbonyl) aminosulfonyl))-N, N-dimethyl] at 35 ml ha^{-1} and a premix of dicamba and diflufenzopyr at 367 ml ha^{-1} to control weeds on June 25. Herbicides were applied by staff at the research centers at Mandan and Hettinger.

Water and Measurements

Nine neutron probe access tubes were installed in each of the experimental sites in Mandan in 2009 and 2010. The access tubes were made of EMT conduit, and a rubber stopper was put in the end of the tube, so rain water would not leak in. These tubes were installed in the plots of differing skip-row configurations for one selected hybrid (PH 39D97), population (59,280 plants ha^{-1}) and each replication. This hybrid was chosen because it was the earliest maturing and would likely make it to physiological maturity regardless of the season. The access tubes were installed to a depth of 2.4 m. In the P1S1 configuration, the access tube was placed in the skipped row. The P2S1 configuration had the tube installed between the skipped row and the planted row, and the P All configuration had the access tube installed between two planted rows (Fig. 2). Soil moisture readings were taken throughout the season using a Model 503 DR neutron moisture probe. The soil moisture readings were taken to determine how much soil water might be available to the corn throughout the growing season. Measurements were taken at five depths by lowering the neutron probe into each tube at: 0.3, 0.6, 0.9, 1.2, and 1.5 m. The number read on the device is called a count ratio which is a detection of an electrical pulse. The count ratio is used in an equation to calculate volumetric soil water content. The equation is: soil water content (swc) = (a*count ratio) + b. The coefficients a (slope of line) and b (y-intercept) must be determined for the specific soil type that soil water measurements are being read in. In these experiments the coefficients were a = 10.16996 and b = -3.470818.

Approximately one week before tasseling, sensors were installed in Mandan to record relative humidity, temperature, and dew point temperature every half hour [Model U23-001 HOBO® Pro v2 (Onset Computer Corp., Bourne, MA)]. In 2009, the sensors were

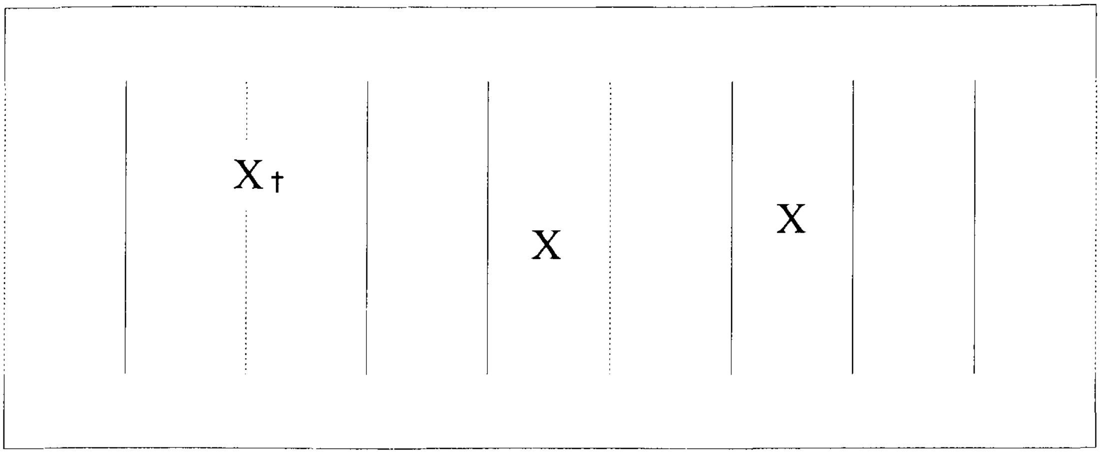

Fig. 2. A depiction of one replication from an experiment showing where access tubes and HOBO® sensors were installed in three planting configurations.
† X marks location of the access tubes and HOBO® sensors.

installed in one replication of each skip-row main plot at both locations. In the dry pea residue, the sensors were installed in the first replication and in the third replication in the sunflower residue. In 2010 they were installed only in the dry pea residue in the first and second replications, in order to have replicated information within an experiment. These sensors were placed in the plots that had the hybrid Pioneer 38R51, at the population of 59,280 plants ha^{-1} at each planting configuration within the replication. The sensors were placed between the skipped row and the planted row for P2S1 and P1S1 planting configurations. In the plant all rows, the sensor was placed between the rows (Fig. 2). The sensors were tied to a T-post at the height of the corn ear, so all data collected would be reflective of the actual relative humidity, temperature, and dew point temperature that surrounded the ear.

Plant greenness readings were taken at both locations in Mandan and in Hettinger in 2010 using an infra-red chlorophyll sensor [GreenSeeker NDVI Model 505 (NTech Industries, Inc., Ukiah, CA)]. This sensor was used to determine which planting configuration and hybrid had greener plants (less stress). The readings were taken July 21 when the corn plots were at the V8 stage. Readings were recorded by walking through the plots at a consistent speed (approximately 4 km hr^{-1}) and holding the device approximately one meter above the canopy. The reading given by the device is referred to as Normalized Difference Vegetative Index (NDVI). This index was obtained using the following formula: (NIR reflected – Red reflected) / (NIR reflected + Red reflected).

Before harvest in 2009, silking dates and plant heights were taken. Silking dates were recorded on the day when silks emerged from the husk, and plant heights were recorded right before harvest. Plant height was measured from the soil surface to the top or last node of the plant. In 2010, only silking and tasseling dates were recorded at both locations in Mandan and in Hettinger. Plant height was not taken in 2010. Hettinger had a violent wind storm August 12 that knocked over many plots. Also, the plots at Mandan and Hettinger had the tops of the plants snapped off prior to harvest.

Harvest Methods 2009 and 2010

In both experiments at Mandan in 2009, one row from each plot was hand harvested. The plots on the sunflower residue were harvested October 22, and the dry pea residue October 23. Only a 5.3 m bordered portion of the row was actually harvested. The number of plants and number of cobs were counted and recorded in 5.3 m. All cobs were picked in that distance and weighed. From this sample a subsample of five random cobs were chosen. Those five cobs were weighed and then shelled with a Model ECS BC Almaco corn sheller (Allan Machine Co., Nevada, IA). Grain from the shelled subsamples was weighed on a Model E0H110 OHAUS Explorer scale (OHAUS Corp.). This weight was used to calculate the shelling percentage needed to calculate the final (corrected) grain yield for the plots. A

GAC 2100 Dickey-john (GSF Inc., Ankeny, IA) was used to determine moisture and test weight of the samples immediately after shelling. Test weight was not corrected for moisture. A thousand kernels were counted with a Model 850-3 OLD MILL seed counter (International Marketing and Design Corp., San Antonio, TX). The 1000 kernels were weighed after being dried to 155.0 g kg^{-1} to calculate thousand kernel weights (1000 kwt) for the plots. The 1000 kwt was used to calculate kernels cob^{-1} by using the equation [(((plot moisture*((100-plot moisture)/#ears in the plot)/1000kwt of the grain)*1000].

In 2010 the plots in Hettinger were not harvested due to extreme wildlife damage. In Mandan, both field trials were harvested November 9. All plots were trimmed to 5.3 m and the number of cobs and plants were recorded. A Hege 140 plot combine equipped with a Model HM-400 Harvest Data System with GrainGage™ and an Allegro CE/DOS handheld computer were used to harvest the plots and record the data. This harvest data system took total plot weight, moisture, and test weight for each individual plot at the time of harvest. One row was harvested out of each plot by hand picking the ears off the plants and then threshing them in the plot combine. A small subsample from each plot was used to measure 1000 kwt as previously described.

Statistical Methods

Data in these experiments were analyzed using the PROC GLM procedure of SAS (Cary, NC), using a mixed model with row spacing, hybrids, and population considered as fixed effects, and replications and environments as random effects. Environments contain the combination of years and previous crop residue. Analysis of variance was conducted within and across environments. Environments were found to be homogeneous and were combined. F-tests were considered to be significant at $p \leq 0.05$. Means were separated using Fisher's protected least significant difference at ($p \leq 0.05$). Only significant interactions were discussed.

Soil water data collected were analyzed using the PROC ANOVA procedure of SAS, using a mixed model with time, spacing, and depth considered as fixed effects, and replication and environments as random effects. Environments contain the combination of years and previous crop residue. An analysis of variance was conducted across environments. Environments were considered homogeneous and therefore combined in the analysis. F-tests were considered significant at $p \leq 0.05$. Means were separated using Fisher's protected least significant difference at ($p \leq 0.05$). Only significant interactions were discussed.

Since actual plant populations varied widely and did not equal targeted plant populations, the relationship between actual plant population and grain yield across all planting configurations was further evaluated using linear regression analysis for both actual plant population and hybrid.

RESULTS AND DISCUSSION

Frequency of Severe Droughts in Western, ND

The frequency of drought stress in two locations in North Dakota during key developmental stages of corn was analyzed using water use and water deficit data from tasseling to physiological maturity. This was done to estimate the relative drought frequency in these areas. Corn in Mandan would have experienced severe drought stress in four (2002, 2003, 2004, and 2006) of the last eleven years while corn in Hettinger would have experienced severe drought stress in six of the last eleven years (2000, 2002, 2003, 2004, 2006, and 2008) (Table 2). Based on these predicted data, corn grown in both locations would suffer severe drought about 50% of the time. Later maturing hybrids had a greater frequency of water deficits above 12.7 cm which was the identified critical water deficit threshold because that was the water deficit when the corn plots began to first show symptoms of drought on the leaves. In addition, the possibility that later maturing hybrids would not make physiological maturity due to frost damage was greater than for earlier hybrids (Table 2). Any hybrid under 84 RM always made it to physiological maturity over the years studied at Mandan and Hettinger. NuTech 3C-389 would not have made it to physiological maturity in 2004 and 2009 at both Mandan and Hettinger. Pioneer 38R51 would not have made it to physiological maturity in three years (2004, 2008, and 2009) at Mandan and in four years (2004, 2008, 2009, and 2010) at Hettinger.

County yields for Morton (Mandan) and Adams (Hettinger) were correlated with the average water deficit during tasseling through physiological maturity (Table 3). In Morton,

Table 2. Simulated water deficit of six hybrids using actual weather data from 2000-2010 during tasseling through physiological maturity.

MANDAN

		NuTech 3T-484 (84RM)				NuTech 3C-389 (89 RM)			
YIELD †	Year	Avg. ‡ Deficit	Min. §	Max. #	Frequency †† greater than 12.7 cm	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm
Mg ha^{-1}		----------------cm----------------				----------------cm---------------			
6.51	2000	15.19	1.33	24.98	0.62	18.14	2.72	25.29	0.75
6.21	2001	5.14	-5.58	16.71	0.19	7.85	-5.58	18.18	0.37
5.60	2002	24.34	12.84	32.02	1.00	25.98	14.96	32.63	1.00
5.25	2003	26.80	11.83	38.89	0.96	29.72	14.46	38.89	1.00
5.76	2004	20.22	12.19	23.54	0.99	20.64	13.04	23.54	1.00 §§
6.00	2005	9.24	0.80	16.82	0.29	11.06	1.12	17.58	0.43
4.32	2006	28.31	12.40	38.79	0.98	31.19	15.79	41.28	1.00
4.63	2007	2.18	-11.89	10.88	0.00	4.65	-8.97	12.02	0.00
3.83	2008	14.84	5.33	20.65	0.63	15.95	5.33	20.65	0.71
5.71	2009	4.87	-6.51	11.37	0.00	5.41	-4.28	11.37	0.00 §§
NA ‡‡	2010	15.46	7.59	22.62	0.74	15.43	7.59	22.62	0.78

HETTINGER

		NuTech 3T-484 (84RM)				NuTech 3C-389 (89 RM)			
YIELD	Year	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm
Mg ha^{-1}		----------------cm---------------				---------------cm---------------			
3.64	2000	22.18	6.05	34.63	0.80	25.63	8.95	36.34	0.91
3.77	2001	17.11	5.09	31.04	0.60	21.00	5.91	32.09	0.73
2.86	2002	34.67	20.66	44.97	1.00	36.73	22.40	46.36	1.00
2.29	2003	35.48	20.05	46.79	1.00	36.58	22.55	46.79	1.00
2.51	2004	27.13	12.83	33.67	1.00	28.67	16.12	33.67	1.00 §§
3.33	2005	16.45	5.44	24.79	0.72	18.32	6.56	25.19	0.80
1.41	2006	27.58	11.10	39.56	0.94	30.62	14.37	41.86	1.00
3.27	2007	12.38	-0.38	20.10	0.60	14.76	-0.38	21.38	0.72
3.20	2008	23.90	10.89	30.90	0.92	25.67	12.33	31.25	0.99
NA	2009	14.74	6.92	19.91	0.73	15.04	6.92	19.91	0.79 §§
NA	2010	14.74	4.10	20.75	0.77	14.78	4.56	20.75	0.81

Table 2. Simulated water deficit of six hybrids using actual weather data from 2000-2010 during tasseling through physiological maturity.

MANDAN

		NuTech 3T-484 (84RM)				NuTech 3C-389 (89 RM)			
YIELD †	Year	Avg. ‡ Deficit	Min. §	Max. #	Frequency †† greater than 12.7 cm	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm
Mg ha^{-1}		----------------cm----------------				----------------cm----------------			
6.51	2000	15.19	1.33	24.98	0.62	18.14	2.72	25.29	0.75
6.21	2001	5.14	-5.58	16.71	0.19	7.85	-5.58	18.18	0.37
5.60	2002	24.34	12.84	32.02	1.00	25.98	14.96	32.63	1.00
5.25	2003	26.80	11.83	38.89	0.96	29.72	14.46	38.89	1.00
5.76	2004	20.22	12.19	23.54	0.99	20.64	13.04	23.54	1.00 §§
6.00	2005	9.24	0.80	16.82	0.29	11.06	1.12	17.58	0.43
4.32	2006	28.31	12.40	38.79	0.98	31.19	15.79	41.28	1.00
4.63	2007	2.18	-11.89	10.88	0.00	4.65	-8.97	12.02	0.00
3.83	2008	14.84	5.33	20.65	0.63	15.95	5.33	20.65	0.71
5.71	2009	4.87	-6.51	11.37	0.00	5.41	-4.28	11.37	0.00 §§
NA ‡‡	2010	15.46	7.59	22.62	0.74	15.43	7.59	22.62	0.78

HETTINGER

		NuTech 3T-484 (84RM)				NuTech 3C-389 (89 RM)			
YIELD	Year	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm
Mg ha^{-1}		----------------cm----------------				----------------cm----------------			
3.64	2000	22.18	6.05	34.63	0.80	25.63	8.95	36.34	0.91
3.77	2001	17.11	5.09	31.04	0.60	21.00	5.91	32.09	0.73
2.86	2002	34.67	20.66	44.97	1.00	36.73	22.40	46.36	1.00
2.29	2003	35.48	20.05	46.79	1.00	36.58	22.55	46.79	1.00
2.51	2004	27.13	12.83	33.67	1.00	28.67	16.12	33.67	1.00 §§
3.33	2005	16.45	5.44	24.79	0.72	18.32	6.56	25.19	0.80
1.41	2006	27.58	11.10	39.56	0.94	30.62	14.37	41.86	1.00
3.27	2007	12.38	-0.38	20.10	0.60	14.76	-0.38	21.38	0.72
3.20	2008	23.90	10.89	30.90	0.92	25.67	12.33	31.25	0.99
NA	2009	14.74	6.92	19.91	0.73	15.04	6.92	19.91	0.79 §§
NA	2010	14.74	4.10	20.75	0.77	14.78	4.56	20.75	0.81

Table 2. (continued)

MANDAN

		Dekalb DKC 30-23 (80 RM)				Dekalb DKC 33-54 (83 RM)			
YIELD †	Year	Avg. ‡ Deficit	Min. §	Max. #	Frequency †† greater than 12.7 cm	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm
Mg ha^{-1}		----------------cm----------------				--------------cm--------------			
6.51	2000	13.86	1.33	23.41	0.56	14.49	1.33	23.62	0.59
6.21	2001	3.79	-5.58	14.26	0.09	4.26	-5.58	15.01	0.13
5.60	2002	23.91	13.84	32.02	1.00	24.03	13.84	32.02	1.00
5.25	2003	25.88	12.29	37.20	0.98	26.43	12.84	37.56	1.00
5.76	2004	20.01	12.71	23.54	1.00	20.17	12.71	23.54	1.00
6.00	2005	8.31	0.80	15.96	0.20	8.59	1.12	16.20	0.22
4.32	2006	27.32	13.12	37.35	1.00	27.55	13.12	37.68	1.00
4.63	2007	1.27	-11.89	8.38	0.00	1.82	-11.51	9.23	0.00
3.83	2008	14.12	5.33	20.65	0.58	14.37	5.33	20.65	0.60
5.71	2009	4.32	-5.81	11.37	0.00	4.39	-5.81	11.37	0.00
NA ‡‡	2010	14.86	5.91	22.62	0.62	15.06	6.60	22.62	0.64

HETTINGER

		Dekalb DKC 30-23 (80 RM)				Dekalb DKC 33-54 (83 RM)			
YIELD	Year	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm
Mg ha^{-1}		----------------cm----------------				--------------cm--------------			
3.64	2000	21.06	6.05	32.98	0.80	21.37	6.05	32.98	0.81
3.77	2001	15.75	5.09	28.79	0.56	16.26	5.91	29.32	0.58
2.86	2002	33.31	20.66	43.69	1.00	33.77	21.42	44.11	1.00
2.29	2003	34.76	20.05	46.32	1.00	35.07	21.05	46.32	1.00
2.51	2004	26.47	13.44	33.67	1.00	26.89	13.87	33.67	1.00
3.33	2005	15.21	6.39	24.26	0.68	15.56	6.56	24.59	0.70
1.41	2006	25.86	11.10	37.11	0.93	26.46	11.81	37.46	0.95
3.27	2007	11.91	-0.38	19.62	0.57	12.04	-0.38	19.62	0.58
3.20	2008	23.17	11.67	30.60	0.93	23.51	11.69	30.77	0.95
NA	2009	14.42	6.92	19.91	0.61	14.89	6.92	19.91	0.70
NA	2010	14.42	2.98	20.75	0.73	14.42	2.98	20.75	0.72

Table 2. (continued)

MANDAN

		Pioneer 38R51 (93 RM)				Pioneer 39D97 (79 RM)			
YIELD †	Year	Avg. ‡ Deficit	Min. §	Max. #	Frequency †† greater than 12.7 cm	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm
Mg ha^{-1}		---------------cm---------------				---------------cm-------------			
6.51	2000	19.53	3.50	25.29	0.82	13.10	1.33	22.76	0.53
6.21	2001	9.24	-5.58	18.18	0.47	3.32	-5.58	13.38	0.04
5.60	2002	27.55	15.51	33.77	1.00	23.44	12.84	32.02	1.00
5.25	2003	31.49	15.07	38.89	1.00	24.51	11.09	36.13	0.93
5.76	2004	20.80	13.99	23.54	1.00 §§	19.55	11.67	23.54	0.97
6.00	2005	12.19	1.12	17.90	0.56	7.73	0.19	15.45	0.15
4.32	2006	32.99	15.79	43.68	1.00	25.92	11.78	37.26	0.95
4.63	2007	5.62	-8.19	12.02	0.00	0.34	-11.90	8.36	0.00
3.83	2008	16.34	5.33	20.65	0.79 §§	13.54	5.15	20.65	0.54
5.71	2009	5.51	-3.69	11.37	0.00 §§	3.63	-7.26	11.37	0.00
NA ‡‡	2010	15.53	8.31	22.62	0.84	14.47	5.21	22.62	0.57

HETTINGER

		Pioneer 38R51 (93 RM)				Pioneer 39D97 (79 RM)			
YIELD	Year	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm	Avg. Deficit	Min.	Max.	Frequency greater than 12.7 cm
Mg ha^{-1}		---------------cm---------------				---------------cm-------------			
3.64	2000	28.58	9.76	36.45	0.95	19.75	6.05	31.98	0.75
3.77	2001	22.97	6.35	32.39	0.78	14.73	5.09	27.71	0.52
2.86	2002	40.11	23.22	46.94	1.00	32.63	19.71	42.91	1.00
2.29	2003	36.92	22.82	46.79	1.00	33.66	19.13	45.26	1.00
2.51	2004	28.80	16.94	33.67	1.00 §§	25.63	11.96	33.67	0.98
3.33	2005	19.63	6.56	25.34	0.86	14.49	4.71	23.73	0.64
1.41	2006	33.27	14.37	43.57	1.00	24.99	10.20	35.82	0.91
3.27	2007	16.10	-0.38	22.47	0.77	11.02	-0.58	19.62	0.52
3.20	2008	25.66	13.17	31.25	1.00 §§	22.33	10.07	30.03	0.89
NA	2009	15.08	6.92	19.91	0.79 §§	13.89	6.92	19.63	0.56
NA	2010	14.93	6.06	20.75	0.86 §§	13.78	1.59	20.75	0.65

† Yield data is the county average.
‡ Average crop water deficit.
§ Minimum crop water deficit.
\# Maximum crop water deficit.
†† Frequency of days that the water deficit was > than 12.7 cm during tasseling through physiological maturity.
‡‡ NA - Information was not available.
§§ Hybrid did not make physiological maturity.
All data were obtained from NDAWN website.

estimated water deficit did not correlate significantly with average county grain yield probably because of the presence of irrigated acres in the county mean. However, in Adams county, average water deficit correlated with grain yield significantly, which is a better representation of dryland corn production because there are no irrigated corn production acres. These data suggest that as the average water deficit from tasseling through physiological maturity decreases grain yield increases.

Table 3. Linear relationship between average water deficit and grain yield for two locations in western ND from 2000 - 2011.

Location	Regression Equation †	r^2 ‡
Mandan	$y = -2.462x + 28.362$	0.0495
Hettinger	$y = -6.4858x + 43.036$	0.3671*

† in the equation y = yield in Mg ha^{-1} and x = average water deficit.

‡ * significant correlation between average water deficit and grain yield at ≤ 10% level.

Weather 2009 and 2010

In Mandan, there was more rainfall than average in 2009 and 2010. The long-term (30 year) average annual rainfall in Mandan is 43.3 cm. In 2009 and 2010 there was 48.4 and 48.0 cm of rain, respectively. June is the month with the most rainfall in Mandan averaging 7.5 cm, but in 2009 and 2010 there was 19.4 and 10.6 cm of rain, respectively. Hettinger also received more rain in 2010 than the long-term average. The average seasonal rainfall there is 39.4 cm, but in 2010 there was 45.1 cm of rain. The average water deficit in 2009 and 2010 during the period of tasseling through physiological maturity was 4.87 cm and 15.46 cm, respectively in Mandan which represents the 2nd and 5th least deficit years in the last eleven years based on NDAWN data.

In 2009 the six hybrids planted in Mandan started anthesis from July 24 – Aug. 1. During the period of tasseling through physiological maturity the plots received 6.1 cm of rain. However, the temperature during 2009 was 3°C less than the long-term average which varies from 18-21°C from June through August (Table 4). Because of the cooler temperatures there was not as much heat stress on the plants which possibly led to less transpiration (Table 4). In 2010 the mean relative humidity was significantly higher than in 2009, and is probably due to more rain during tasseling through physiological maturity. Two hybrids, NuTech 3C-389 and Pioneer 38R51, did not make physiological maturity. The limited rainfall of 6.1 cm from tasseling through physiological maturity should normally have reduced yield in 2009, but the plants were well watered going into tasseling. In 2010, the six hybrids started anthesis between July 16 and July 24. During the period of tasseling through physiological maturity there was 13.2 cm of rain, and the temperature was average for that period of the year. All hybrids made physiological maturity and visually showed very little drought stress. Nevertheless, the different environments affected grain moisture, test weight, kernels cob^{-1}, ears plant^{-1}, and plant density (Table 5).

Table 4. Effect of planting configuration on temperature and relative humidity in Mandan, ND, in 2009 and 2010 for ten weeks after anthesis.

Planting Configuration †	Temperature		Relative Humidity	
	2009	2010	2009	2010
	----------°C----------		----------%----------	
P All	15.5 ‡	17.2	72.2	75.3
P2S1	15.3	17.0	73.3	75.9
P1S1	15.4	17.1	71.8	75.8
Mean	15.4 §	17.1	72.4	75.7
LSD (0.05) ¶	0.7		1.3	

† P All = Plant All rows, P2S1 = Plant 2 rows – Skip 1 row, P1S1 = Plant 1 row – Skip 1 row.

‡ Mean of ten weeks.

§ Mean of three planting configurations.

¶ LSD (0.05) compares means of planting configurations only.

Corn grown on dry pea residue in 2009 had more grain moisture at harvest than either location in 2010 and less test weight (Table 5). Grain moisture was high in 2009 because of the cooler than normal season. The high moisture-content undoubtedly adversely affected test weight. The corn in the dry pea residue in 2009 was harvested a few weeks earlier in the growing season than both locations in 2010. Also, as mentioned earlier, the 2009 growing season was much cooler than the 2010 season. The growing degree day (GDDs) accumulations from planting to harvest were 1209 in 2009 as compared to 1358 in 2010. The lack of GDDs during the season is why grain moisture was higher, and test weight lower in 2009.

The corn grown on dry pea residue in both years had less kernels cob^{-1} and more ears plant^{-1} than the corn grown on sunflower residue in 2010 (Table 5). Differences in actual plant population probably influenced these variables as there were more corn plants in the dry pea residue in 2009 increasing inter-plant competition. This could have possibly reduced cob size because there were less kernels cob^{-1} and 1000 kwt was not different, so the kernels tended to be the same size. The corn grown on the sunflower residue experiment had more kernels cob^{-1} than either corn trial grown on the dry pea residue experiment, but it had less ears plant^{-1} (Table 5). The corn plants in the sunflower residue experiment possibly put more energy into making one cob while the corn plants in the dry pea residue tended to put on a second ear.

Planting Configuration

Planting configurations significantly affected final grain yield and actual plant population in all environments. Planting all rows resulted in significantly more grain yield than P2S1 or P1S1 across all three environments (Table 6). Likewise, P2S1 had

Table 5. Effect of environment on grain moisture, test weight, kernels cob^{-1}, ears plant^{-1}, and actual plant population in Mandan, ND, in 2009 and 2010 averaged over all factors.

Environment †	Grain Yield	Grain Moisture	Test Weight	Kernels	Ears	Actual Plant Population	1000 kwt
	Mg ha^{-1}	g kg^{-1}	kg m^{-3}	cob^{-1}	plant^{-1}	plants ha^{-1}	grams
2009 DP	6.93	272	46.8	454	1.09	59,576	210.4
2010 DP	6.97	147	53.2	501	1.15	48,529	218.7
2010 SF	6.97	142	52.5	534	1.01	52,274	215.4

† DP = Dry Pea Residue, SF = Sunflower Residue.

significantly more grain yield than P1S1, except for corn on sunflower residue in 2010 which had the same yield. The lack of difference in yield between P2S1 and P1S1 in this environment may have been due to the fact that actual plant populations were the same for both planting configurations. The P1S1 had the least grain yield on the dry pea residue in both 2009 and 2010. Grain yields were quite high relative to the normal yield in this region of North Dakota both years as there was very little water stress. Lyon et al. (2009) found that skip-row planting configurations did not increase grain yield unless the yields were below five Mg ha^{-1}.

Grain yield was favored at the higher plant population in P All planting configurations, especially, on dry pea residue in 2009 (Table 6). Actual plant population at P All as measured at the end of the season was always higher than for the other two planting configurations. All targeted plant populations were to be the same for all planting configurations, however, there were emergence problems within the plots and not all plants emerged at the same time. This was most obvious at the P1S1 planting configuration where very close plant-to-plant spacing was required (Table 6). Poor or uneven emergence within rows can cause competition between plants. Within all three environments P1S1 had the least plant density. The reason is there are twice as many seeds per row in a P1S1 planting configuration when compared to the P All because there are less rows planted in a given area. When plants are spaced closer together within a row, they compete for nutrients and water which can cause reductions in plant population. When there is uneven emergence, plants that emerge earlier have an advantage over plants that emerge later because they have more extensive root structures and leaf tissue to utilize more water, nutrients, and sunlight which can cause the late emerging plants to be outcompeted and potentially die. Ultimately, losing plant density to poor or uneven emergence will affect final grain yields (Nafziger et al., 1991) of 6-9% when the unevenness of emergence occurs in a week and a half time span. If the time span for plant emergence increases, grain yield and final plant densities will decrease, if plant mortality results from this competition.

Table 6. Effect of planting configuration and environment on grain yield and actual plant population of corn at harvest in Mandan, ND, in 2009 and 2010.

Environment †	Planting Configuration ‡	Grain Yield	Actual Plant Population
		Mg ha^{-1}	plants ha^{-1}
2009 DP	P All	7.80	73,211
	P2S1	6.82	58,638
	P1S1	6.17	46,881
2010 DP	P All	8.02	56,916
	P2S1	6.96	47,945
	P1S1	5.94	40,726
2010 SF	P All	7.85	59,319
	P2S1	6.55	48,242
	P1S1	6.51	49,261
LSD (0.05)		0.44	3,658

† DP = Dry Pea Residue, SF = Sunflower Residue.
‡ P All = Plant All rows, P2S1 = Plant 2 rows-Skip 1 row, P1S1 = Plant 1 row-skip 1 row.

Averaged over environments grain yield and plant populations were affected by planting configurations (Table 7). P All had significantly greater grain yield and actual plant population then P2S1 and P1S1. The P2S1 and P1S1 planting configurations were not significantly different in grain yield and actual plant population. Part of the increased grain yield at the P All planting configuration could be attributed to higher plant population at harvest because there were higher actual plant populations as fewer rows were skipped. Soil water availability did not differ greatly between treatments (Fig. 3) and was probably not a limiting factor in any of the treatments in the three environments. However, P2S1 had significantly more water than P1S1 and P All; the values of soil water averaged throughout the environments, dates, and depths are very similar with an LSD (0.05) = 0.30. The P All, P2S1, and P1S1 were 9.55, 9.98, and 9.62 cm of water per 30 cm of soil, respectively (Fig. 3).

Table 7. Effect of planting configuration on grain yield and actual plant population averaged over three environments in Mandan, ND, in 2009 and 2010.

Planting Configuration †	Grain Yield	Actual Plant Population
	Mg ha^{-1}	plants ha^{-1}
P All	7.89	63,149
P2S1	6.78	51,608
P1S1	6.27	45,622
LSD (0.05)	0.59	10,030

† P All = Plant All rows, P2S1 = Plant 2 rows-Skip 1 row, P1S1 = Plant 1 row-Skip 1 row.

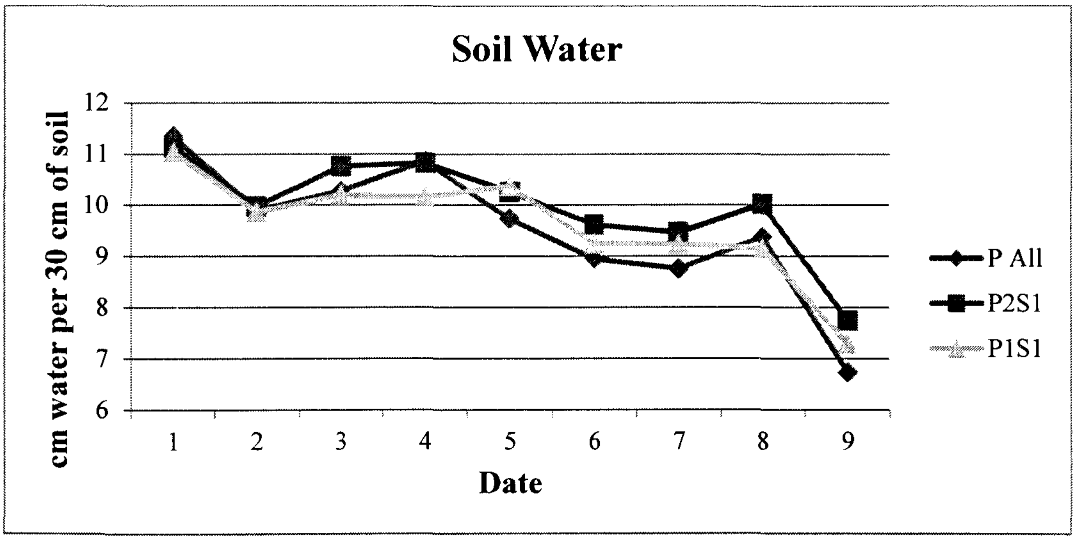

Fig. 3. Soil water for three planting configurations at nine random dates averaged across five depths and four environments in Mandan, ND, in 2009 and 2010.
LSD (0.05) = ns.

Plant Population

There was a significant targeted plant population by planting configuration interaction at harvest (Fig. 4) in the combined analysis. The interaction resulted from a difference in magnitude. There was always a higher actual plant population for the high targeted plant population for all three planting configurations. However, the difference between the two plant populations becomes less as more rows are skipped. The difference between the high and low population for P All, P2S1, and P1S1 are 13,117, 10,041, and 3,799 plants ha^{-1}, respectively. The P1S1 had less difference between the high and low plant populations than P All and P2S1 because we did not achieve the closer plant-to-plant spacing required. In the P1S1 the plant spacing within the row becomes very tight and possibly leads to competition between the plants.

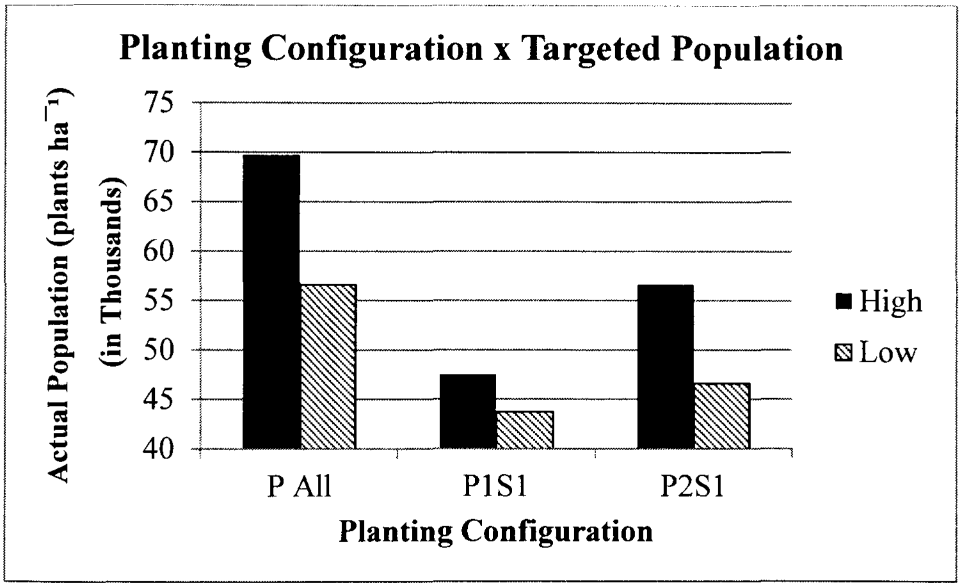

Fig. 4. Effect of planting configuration and targeted plant population on actual plant population at harvest, averaged over three environments in Mandan, ND, in 2009 and 2010.
LSD (0.05) = 3,257 for differences between high and low actual plant populations at harvest for three planting configurations.

In the combined analysis actual plant population affected grain yield and test weight (Table 8). The two targeted populations were 59,280 (high) and 44,460 (low) plants ha^{-1}, but at harvest they actually were 57,953 (high) and 48,967 (low) plants ha^{-1} when averaged across all three environments. The high plant population had significantly more grain yield, but the test weight was significantly lower (Table 8). The high population had more grain yield because again soil water was not a limiting factor nor were fertility levels, so the growing conditions were fairly optimal for the region and the extra plants were needed to achieve higher yields. Test weight was lower at the high population because there was less kernels cob^{-1} than at the low population; the kernels were bigger and did not pack as well. The plant density was higher for the high population than for the low population because the differences in planted populations held true, relatively speaking (Table 8).

Table 8. Effect of actual plant population on grain yield and test weight in three environments in Mandan, ND, in 2009 and 2010.

Actual Plant Population	Grain Yield	Test Weight
-plants ha^{-1}-	Mg ha^{-1}	kg m^{-3}
57,953 (High)	7.19	650.6
48,967 (Low)	6.73	658.2
F-test significance	* †	*

† *indicates significance at the 5% level.

There was wide variability in the actual plant populations measured at harvest, so these values were regressed on yield to get a more precise estimate of the influence of plant population on yield. When looking at plant population's effect on yield at different planting configurations, the only significant linear trends were in 2009 with corn grown on dry pea residue (Table 9). The P2S1 and P1S1 planting configuration's yields were significantly correlated to plant population at harvest. Also, the correlation of plant population to grain yield became stronger as more rows were skipped in 2009. However, this trend did not hold true in 2010 on both dry pea and sunflower residue where the correlation was insignificant. Perhaps because of more favorable conditions for corn growth and a smaller range in actual plant populations, plant population became less of a determinant of yield in 2010 compared to 2009.

Hybrids

There was a significant interaction between hybrids and planting configurations for plant population at harvest (Fig. 5). This interaction was due to a difference in magnitude. Moreover, all hybrids had a higher plant population in the P All planting configuration followed by P2S1 and then P1S1. There were higher plant populations as fewer rows were skipped regardless of hybrid. However, the hybrid Pioneer 39D97 was more affected than other hybrids by skipping rows possibly because it has weaker stalk strength than the other hybrids.

In the combined analysis, hybrids differed for grain yield, test weight, and actual plant population (Table 10). Later maturing hybrids (NuTech 3T-484, NuTech 3C-389, and Pioneer 38R51) had significantly higher grain yields than early maturing hybrids (DKC 30-23 and Pioneer 39D97). However, 2009 and 2010 had above average rainfall, so certain hybrid characteristics (drought tolerance, stay green, and rootworm resistance) that were thought to potentially interact with skip-row planting configurations for yield did not. In general, the later maturing hybrids had better grain yields. The earliest maturing hybrid, Pioneer 39D97, was the lowest in grain yield (Table 10), but it also had a significantly lower actual plant population than all other hybrids, so much of the reduction in grain yield could be explained by the lower actual plant population. The opposite effect took place on test

Table 9. Linear relationship between actual plant population at harvest (plants ha^{-1}) and grain yield (Mg ha^{-1}) for three planting configurations in three environments in Mandan, ND in 2009 and 2010.

Environment	Planting Configuration	Actual Plant Population Range (Plants ha^{-1}) (Min-Max)	Regression Equation †	r^2 ‡
2009 DP	P All	51,630 - 98,343	y = 3E-05x + 5.73	0.15
	P2S1	36,057 - 73,752	y = 6E-05x + 3.25	0.36*
	P1S1	31,960 - 60,231	y = 0.0001x + 0.64	0.58*
2010 DP	P All	42,018 - 69,205	y = 8E-05x + 3.32	0.30
	P2S1	31,307 - 65,910	y = 8E-05x + 3.34	0.22
	P1S1	23,480 - 60,555	y = 5E-05x + 3.91	0.15
2010 SF	P All	42,018 - 79,092	y = 5E-05x + 4.80	0.17
	P2S1	32,955 - 69,205	y = 6E-05x + 3.87	0.13
	P1S1	33,367 - 64,262	y = 3E-05x + 5.13	0.05

† in the equation y = yield in Mg ha^{-1} and x = corn plants

‡ * Significant correlation between plant population and grain yield at the 5% level

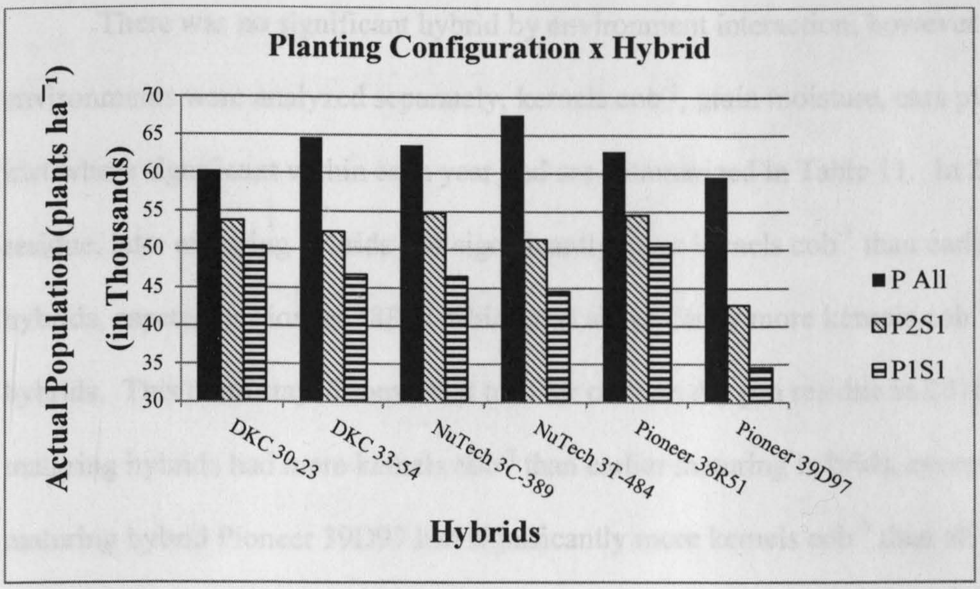

Fig. 5. Effect of planting configuration by hybrid on actual plant population over three environments in Mandan, ND, in 2009 and 2010.

LSD (0.05) = 4,298 for differences in actual plant population at harvest between planting configurations.

weight. Earlier maturing hybrids tended to have higher test weights than later maturing hybrids because grain moisture for these hybrids was lower than later maturing hybrids; even though grain moisture did not differ significantly when averaged across environments.

Table 10. Effect of hybrid on grain yield, test weight, actual plant population at harvest, and grain moisture at harvest over three planting configurations, two populations and three environments in Mandan, ND, in 2009 and 2010.

Hybrids	Grain Yield	Test Weight	Actual Plant Population	Grain Moisture
	Mg ha^{-1}	kg m^{-3}	plants ha^{-1}	g kg^{-1}
Pioneer 39D97 (79 RM)	6.20	668	45,669	172
DKC 30-23 (80 RM)	6.42	677	54,819	172
DKC 33-54 (83 RM)	6.81	662	54,591	172
NuTech 3T-484 (84 RM)	7.76	630	54,521	185
NuTech 3C-389 (89 RM)	7.07	647	55,020	203
Pioneer 38R51 (93 RM)	7.50	642	56,138	217
LSD (0.05)	0.45	26	6,088	ns

There was no significant hybrid by environment interaction; however when environments were analyzed separately, kernels cob^{-1}, grain moisture, ears plant^{-1}, and 1000 kwt where significant within each year and are summarized in Table 11. In 2009 on dry pea residue, later maturing hybrids had significantly more kernels cob^{-1} than earlier maturing hybrids, especially Pioneer 38R51 which had significantly more kernels cob^{-1} than all other hybrids. This trend stayed somewhat true for corn on dry pea residue in 2010 where later maturing hybrids had more kernels cob^{-1} than earlier maturing hybrids, except, the earliest maturing hybrid Pioneer 39D97 had significantly more kernels cob^{-1} than all other hybrids due to its lower actual plant population. In the sunflower residue in 2010 the opposite trend was observed with earlier maturing hybrids having significantly more kernels cob^{-1} and Pioneer 39D97 having significantly more kernels cob^{-1} than all other hybrids. The exception on the sunflower residue was DKC 30-23 which is an earlier maturing hybrid that had significantly less kernels cob^{-1} than all other hybrids (Table 11). This hybrid was the lowest in all three environments for this trait. DKC 30-23 has large kernels, so it takes fewer kernels to fill a cob. This is evident in the 1000 kwt where this particular hybrid typically had significantly higher 1000 kwt than other hybrids.

Both Pioneer 38R51 and Pioneer 39D97 are categorized as flex ear hybrids, so by having good growing conditions those two hybrids were able to put on bigger and/or more ears. Pioneer 39D97 tended to put on secondary ears because the plant size is much smaller and the number of ears plant^{-1} was significantly higher than Pioneer 38R51 which did not tend to put on secondary ears (Table 11).

Grain moisture was significantly higher in later maturing hybrids than earlier maturing hybrids (Table 11). This was fairly consistent in all three environments. Earlier

Table 11. Effect of hybrid on kernels cob^{-1}, grain moisture, ears plant^{-1}, and 1000 kwt for each individual environment in Mandan, ND, in 2009 and 2010.

Environment †	Hybrids	Kernels	Grain Moisture	Ears	1000 kwt
		cob^{-1}	g kg^{-1}	plant^{-1}	g
2009 DP	DKC 30-23 (80 RM)	386	233	1.07	239
	Pioneer 39D97 (79 RM)	406	234	1.27	201
	Pioneer 38R51 (93 RM)	560	343	1.04	192
	DKC 33-54 (83 RM)	390	240	1.14	217
	NuTech 3T-484 (84 RM)	491	268	0.99	223
	NuTech 3C-389 (89 RM)	491	313	1.02	200
	LSD (0.05)	39	183	0.09	16
2010 DP	DKC 30-23 (80 RM)	447	144	1.13	220
	Pioneer 39D97 (79 RM)	570	143	1.12	207
	Pioneer 38R51 (93 RM)	495	158	1.07	228
	DKC 33-54 (83 RM)	451	140	1.29	205
	NuTech 3T-484 (84 RM)	533	144	1.11	238
	NuTech 3C-389 (89 RM)	514	153	1.17	215
	LSD (0.05)	109.5	106	0.11	8
2010 SF	DKC 30-23 (80 RM)	447	140	0.99	218
	Pioneer 39D97 (79 RM)	610	140	1.00	203
	Pioneer 38R51 (93 RM)	516	149	1.00	224
	DKC 33-54 (83 RM)	569	135	0.99	207
	NuTech 3T-484 (84 RM)	552	142	1.02	228
	NuTech 3C-389 (89 RM)	511	144	1.05	213
	LSD (0.05)	65.5	69	ns	7

† DP = Dry Pea Residue, SF = Sunflower Residue

maturing hybrids reach physiological maturity quicker, so they have a longer period of time for the grain to dry before harvest.

Due to the wide variability in the actual plant populations as discussed earlier, actual plant population values were regressed on grain yield to show their effects on individual hybrids (Table 12). In 2009 on the dry pea residue, actual plant population was significantly correlated with grain yield except for the hybrid NuTech 3C-389. In 2010 on the dry pea residue, actual plant population was significantly correlated with yield for three hybrids (Pioneer 38R51, NuTech 3T-484, and NuTech 3C-389) while there was no significant correlations on the sunflower residue. The difference between the two years is the possibility that the actual plant population range was greater in 2009 than at the other environments in 2010. This could also be the reason why NuTech 3C-389 was not significant in 2009. The actual plant populations may actually have a tighter range than is shown in Table 10, because either at the minimum or maximum end of the range there could be an outlier. The three hybrids in 2010 on dry pea residue that had a significant correlation are the three latest maturing hybrids. Perhaps because of their greater yield potential actual plant population became more important in these hybrids.

Table 12. Linear relationship between actual plant population at harvest (plants ha^{-1}) and grain yield (Mg ha^{-1}) for individual corn hybrids in three environments in Mandan, ND, in 2009 and 2010.

Environment	Hybrid	Actual Plant Population Range (plants ha^{-1}) (Min-Max)	Regression Equation †	r^2 ‡
2009 DP	DKC 30-23	36,876 - 81,133	y = 6E-05x + 2.74	0.71*
	Pioneer 39D97	31,960 - 76,216	y = 9E-05x + 1.51	0.80*
	Pioneer 38R51	44,252 - 78,674	y = 6E-05x + 4.02	0.58*
	DKC 33-54	40,564 - 98,343	y = 6E-05x + 3.41	0.72*
	NuTech 3T-484	39,335 - 93,426	y = 4E-05x + 4.97	0.74*
	NuTech 3C-389	43,022 - 93,426	y = 2E-05x + 5.23	0.25
2010 DP	DKC 30-23	43,665 - 65,910	y = 4E-05x + 4.88	0.04
	Pioneer 39D97	23,480 - 61,791	y = 8E-05x + 2.76	0.36
	Pioneer 38R51	42,018 - 69,205	y = 0.0001x + 1.77	0.67*
	DKC 33-54	28,424 - 66,734	y = 0.0001x + 1.33	0.45
	NuTech 3T-484	35,839 - 69,205	y = 0.0001x + 2.16	0.69*
	NuTech 3C-389	28,424 - 61,791	y = 1E-04x + 2.52	0.74*
2010 SF	DKC 30-23	42,841 - 69,205	y = 2E-05x + 4.92	0.03
	Pioneer 39D97	32,955 - 62,614	y = 0.0001x + 1.68	0.50
	Pioneer 38R51	39,546 - 76,620	y = 8E-05x + 3.15	0.32
	DKC 33-54	36,250 - 71,677	y = 3E-05x + 5.24	0.04
	NuTech 3T-484	32,955 - 79,092	y = 6E-05x + 4.42	0.34
	NuTech 3C-389	44,489 - 79,092	y = 9E-05x + 2.54	0.44

† in these equations y = yield in Mg ha^{-1} and x = corn plants

‡ * Significant correlation between plant population and grain yield at the 5% level

CONCLUSIONS

Based on the analysis of recent weather data (past 11 years), western North Dakota, specifically Mandan and Hettinger, suffers severe drought about 50% of the time. These data strongly indicate the need for effective drought management techniques if corn is to be grown profitably in these areas.

A conclusion on the usefulness of skip-row planting on the stability of grain yield in drought prone regions could not be made based on this research, as there was little or no drought stress during the course of the research.

In years when there is limited drought and weather conditions are favorable, later maturing hybrids are more productive, and skipping rows is detrimental to yield and should not be recommended. Maintaining plant population, at least during favorable years, appears to be critical to maintaining yield, particularly as fewer rows are planted. Hybrid selection, even within a maturity group, is important for yield because hybrids respond differently within a given environment. Based on the results of this research, we were not able to detect important and practical interactions between hybrids and planting configuration.

Mandan typically averages eight cm more rain than the locations (southern Great Plains) where research on skip-row corn has been conducted. Furthermore, it has a shorter growing season. It is possible that due to a shorter growing season and eight cm more rain may be enough to reduce the potential effectiveness of skip-row planting configurations. Maintaining a plant population when rows are skipped was found to be difficult in the research reported here and may be a practical challenge at the farm level. The data supports the need for maintaining plant populations in years when moisture is not significantly constraining.

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APPENDIX

Table A1. Analysis of variance and expected means for the three-factor treatment (A, B, and C) design conducted in a randomized complete block with a split-plot arrangement for a single environment in Mandan, ND in 2009 and 2010.

Source of variation	df†	Mean Square		F-test
		Obs.	Expected††	
Rep (R)	(r-1) = 2	M1	$\sigma^2_e + bc\sigma^2_\delta$	-
Spacing (A)	(a-1) = 2	M2	$\sigma^2_e + bc\sigma^2_\delta + rbc\phi_A$	M2/M3
Error (a)	(r-1)(a-1) = 4	M3	$\sigma^2_e + bc\sigma^2_\delta$	M3/M10
Hybrid (B)	(b-1) = 5	M4	$\sigma^2_e + rac\phi_B$	M4/M10
Population (C)	(c-1) = 1	M5	$\sigma^2_e + rab\phi_C$	M5/M10
A x B	(a-1)(b-1) = 10	M6	$\sigma^2_e + rc\phi_{AB}$	M6/M10
A x C	(a-1)(c-1) = 2	M7	$\sigma^2_e + rb\phi_{AC}$	M7/M10
B x C	(b-1)(c-1) = 5	M8	$\sigma^2_e + ra\phi_{BC}$	M8/M10
A x B x C	(a-1)(b-1)(c-1) = 10	M9	$\sigma^2_e + r\phi_{ABC}$	M9/M10
Error (b)	Total-above = 66	M10	σ^2_e	
Total	rabc-1 = 107			

† df = degrees of freedom. The letters a, b, c, and r refer to the number of levels of factors A, B, C, and the number of replications, respectively.

†† $\phi_A = \Sigma A_i^2/(a-1)$; $\phi_B = \Sigma B_j^2/(b-1)$; $\phi_C = \Sigma C_k^2/(c-1)$; $\phi_{AB} = \Sigma(AB)_{ij}^2/[(a-1)(b-1)]$; $\phi_{AC} = \Sigma(AC)_{ik}^2/[(a-1)(c-1)]$; $\phi_{BC} = \Sigma(BC)_{jk}^2/[(b-1)(c-1)]$; $\phi_{ABC} = \Sigma(ABC)_{ijk}^2/[(a-1)(b-1)(c-1)]$.

Table A2. Combined analyses of variance for the three-factor treatment (A, B, and C) design conducted in randomized complete blocks with a split-plot arrangement across three North Dakota environments in Mandan, in 2009 and 2010.

Source of variation	df†	Mean Square		F-test
		Obs.	Expected††	
Environment (E)	(e-1) = 2	M1	$\sigma^2_e + bc\sigma^2_\delta + abc\sigma^2_{R(E)} + rabc\sigma^2_E$	-
Rep (E)	e(r-1) = 6	M2	$\sigma^2_e + bc\sigma^2_\delta + abc\sigma^2_{R(E)}$	-
Spacing (A)	(a–1) = 2	M3	$\sigma^2_e + bc\sigma^2_\delta + rbc\sigma^2_{AE} + rbce\phi_A$	M3/M4
A x E	(a-1)(e-1) = 4	M4	$\sigma^2_e + bc\sigma^2_\delta + rbc\sigma^2_{AE}$	M4/M5
Error (a)	e(r-1)(a-1) = 12	M5	$\sigma^2_e + bc\sigma^2_\delta$	M5/M18
Hybrid (B)	(b–1) = 5	M6	$\sigma^2_e + rac\sigma^2_{BE} + race\phi_B$	M6/M7
B x E	(b-1)(e-1) = 10	M7	$\sigma^2_e + rac\sigma^2_{BE}$	M7/M18
Population (C)	(c-1) = 1	M8	$\sigma^2_e + rab\sigma^2_{CE} + rabe\phi_C$	M8/M9
C x E	(c-1)(e-1) = 2	M9	$\sigma^2_e + rab\sigma^2_{CE}$	M9/M18
A x B	(a-1)(b-1) = 10	M10	$\sigma^2_e + rc\sigma^2_{ABE} + rce\phi_{AB}$	M10/M11
A x B x E	(a-1)(b-1)(e-1) = 20	M11	$\sigma^2_e + rc\sigma^2_{ABE}$	M11/M18
A x C	(a-1)(c-1) = 2	M12	$\sigma^2_e + rb\sigma^2_{ACE} + rbe\phi_{AC}$	M12/M13
A x C x E	(a-1)(c-1)(e-1) = 4	M13	$\sigma^2_e + rb\sigma^2_{ACE}$	M13/M18
B x C	(b-1)(c-1) = 5	M14	$\sigma^2_e + ra\sigma^2_{BCE} + rae\phi_{BC}$	M14/M15
B x C x E	(b-1)(c-1)(e-1) = 10	M15	$\sigma^2_e + ra\sigma^2_{BCE}$	M15/M18
A x B x C	(a-1)(b-1)(c-1) = 10	M16	$\sigma^2_e + r\sigma^2_{ABCE} + re\phi_{ABC}$	M16/M17
A x B x C x E	(a-1)(b-1)(c-1)(e-1) = 20	M17	$\sigma^2_e + r\sigma^2_{ABCE}$	M17/M18
Error (b)	Total-above = 198	M18	σ^2_e	-
Total	erabc-1 = 323			

† df = degrees of freedom. The letters a, b, c, and r refer to the number of levels of factors A, B, C, and the number of replications, respectively.

†† $\phi_A = \Sigma A_i^2/(a-1)$; $\phi_B = \Sigma B_j^2/(b-1)$; $\phi_C = \Sigma C_k^2/(c-1)$; $\phi_{AB} = \Sigma(AB)_{ij}^2/[(a-1)(b-1)]$; $\phi_{AC} = \Sigma(AC)_{ik}^2/[(a-1)(c-1)]$; $\phi_{BC} = \Sigma(BC)_{jk}^2/[(b-1)(c-1)]$; $\phi_{ABC} = \Sigma(ABC)_{ijk}^2/[(a-1)(b-1)(c-1)]$.

*** 2009 sunflower residue location was left out because it was missing a whole plot.

Table A3. Combined analyses of variance for soil water content in randomized complete blocks with a split-split plot arrangement in time and space across four North Dakota environments in Mandan, in 2009 and 2010.

Source of variation	df[†]	Mean Square		F-test
		Obs.	Expected[††]	
Environment (E)	(e-1) = 3	M1	$\sigma^2_\theta + td\sigma^2_\varepsilon + sd\sigma^2_\delta + dst\sigma^2_{R(E)} + rdst\sigma^2_E$	M1/M2
Rep(E)	e(r-1) = 8	M2	$\sigma^2_\theta + td\sigma^2_\varepsilon + sd\sigma^2_\delta + dst\sigma^2_{R(E)}$	M2/M5
Time (T)	(t–1) = 8	M3	$\sigma^2_\theta + td\sigma^2_\varepsilon + sd\sigma^2_\delta + rds\sigma^2_{ET} + race\phi_T$	M3/M4
E x T	(e-1)(t-1) = 24	M4	$\sigma^2_\theta + td\sigma^2_\varepsilon + sd\sigma^2_\delta + rds\sigma^2_{ET}$	M4/M5
Error (a)	e(r-1)(t-1) = 64	M5	$\sigma^2_\theta + td\sigma^2_\varepsilon + sd\sigma^2_\delta$	M5/M8
Spacing (S)	(s–1) = 2	M6	$\sigma^2_\theta + td\sigma^2_\varepsilon + rdt\sigma^2_{ES} + rdte\phi_S$	M6/M7
E x S	(e-1)(s-1) = 6	M7	$\sigma^2_\theta + td\sigma^2_\varepsilon + rdt\sigma^2_{ES}$	M7/M8
Error (b)	e(r-1)(s-1) = 16	M8	$\sigma^2_\theta + td\sigma^2_\varepsilon$	M8/M18
S x T	(s-1)(t-1) = 16	M9	$\sigma^2_\theta + rd\sigma^2_{SET} + rd\phi_{ST}$	M9/M10
S x E x T	(s-1)(e-1)(t-1) = 48	M10	$\sigma^2_\theta + rc\sigma^2_{SET}$	M10/M18
Depth (D)	(d-1) = 4	M11	$\sigma^2_\theta + rst\sigma^2_{DE} + rste\phi_D$	M11/M12
E x D	(e-1)(d-1) = 12	M12	$\sigma^2_\theta + rst\sigma^2_{DE}$	M12/M18
D x T	(d-1)(t-1) = 32	M13	$\sigma^2_\theta + rs\sigma^2_{DET} + res\phi_{DT}$	M13/M14
D x E x T	(d-1)(e-1)(t-1) = 96	M14	$\sigma^2_\theta + rs\sigma^2_{DET}$	M14/M18
D x S	(d-1)(s-1) = 8	M15	$\sigma^2_\theta + rt\sigma^2_{DES} + rte\phi_{DS}$	M15/M17
D x S x T	(d-1)(s-1)(t-1) = 64	M16	$\sigma^2_\theta + rt\sigma^2_{DST}$	M16/M19
D x E x S	(d-1)(e-1)(s-1) = 24	M17	$\sigma^2_\theta + rt\sigma^2_{DES}$	M17/M19
D x S x E x T	(d-1)(s-1)(e-1)(t-1) = 192	M18	$\sigma^2_\theta + r\sigma^2_{DSET}$	M18/M19
Error (c)	Total-above = 992	M19	σ^2_θ	-
Total	erabc-1 = 1619			

[†] df = degrees of freedom. The letters t, s, d, e, and r refer to the number of levels of factors T, S, D, and the number of environment and replications, respectively.

[††] $\phi_T = \Sigma T_i^2 / (t-1)$; $\phi_S = \Sigma S_j^2 / (s-1)$; $\phi_D = \Sigma D_k^2 / (d-1)$; $\phi_{ST} = \Sigma(ST)_{ij}^2 / [(s-1)(t-1)]$; $\phi_{DT} = \Sigma(DT)_{ik}^2 / [(d-1)(t-1)]$; $\phi_{DS} = \Sigma(DS)_{jk}^2 / [(d-1)(s-1)]$.

Table A4. Mean squares for the analysis of variance for agronomical traits evaluated in Mandan, ND in 2009 on dry pea residue.

Source of variation	df†	Mean squares					
		Yield	Moisture	Test Weight	Kernels cob^{-1}	Ears plant^{-1}	Population
Rep	2	152.4	12.7	29.1	4,197.9	0.005	222,978,920**
Spacing (A)	2	6173.5**	17.3	55.5	886.9	0.050*	6,263,208,626**
Error (a)	4	94.1	22.3*	21.4	1,556.2	0.012	80,632,555*
Hybrid (B)	5	1945.6**	389.6**	120.7**	89755.03**	0.181**	379,812,817**
Population (C)	1	808.0**	45.2*	10.1	1,799.9	0.037	1,582,671,289**
A x B	10	181.8*	8.9	29.2	4,634.02	0.026	55,292,011
A x C	2	70.1	20.1	46.3	7,856.3	0.014	91,014,518
B x C	5	177.6	6.2	26.8	3,026.3	0.022	78,192,078*
A x B x C	10	65.0	7.7	13.1	5,501.8	0.047	39,934,110
Error (b)	66	79.4	7.5	28.5	3,506.2	0.018	30,446,854
CV %		8.06	10.1	11.4	13.05	12.4	9.3

†df = degrees of freedom.

*, ** Significant at 0.05 and 0.01 levels of probability, respectively.

Table A5. Mean squares for the analysis of variance for agronomical traits evaluated in Mandan, ND, in 2010 on dry pea residue.

Source of variation	df†	Mean squares					
		Yield	Moisture	Test Weight	Kernels cob^{-1}	Ears plant^{-1}	Population
Rep	2	48.3	11.3**	6.8*	5,677.3	0.0006	1,873,413
Spacing (A)	2	9,576.5**	1.41	6.5	617.8	0.013	2,320,004,030**
Error (a)	4	195.6	2.48*	3.2	5,776.6	0.043*	11,659,593
Hybrid (B)	5	1,882.9**	7.87**	11.5**	38,881.15**	0.1012**	476,285,804**
Population (C)	1	2,701.6**	0.39	7.1	7,649.7	0.242**	1,459,575,573**
A x B	10	250.2	0.61	1.6	7,187.1	0.0235	126,613,989**
A x C	2	565.6	0.27	3.6	2,444.1	0.074**	375,964,288**
B x C	5	293.4	1.13	2.1	13,143.8	0.0290	114,245,930**
A x B x C	10	198.0	0.39	2.0	4,669.7	0.0249	34,413,784
Error (b)	61	315.5	0.84	1.9	8,995.5	0.0141	21,399,595
CV %		15.9	6.25	2.6	18.9	10.35	9.5

†df = degrees of freedom.

*, ** Significant at 0.05 and 0.01 levels of probability, respectively.

Table A6. Mean squares for the analysis of variance for agronomical traits evaluated in Mandan, ND, in 2010 on sunflower residue.

Source of variation	df†	Mean squares					
		Yield	Moisture	Test Weight	Kernels cob^{-1}	Ears plant^{-1}	Population
Rep	2	404.6	0.26	8.59	6,558.8	0.015	47,298,498
Spacing (A)	2	5,271.0**	2.63**	0.67	3,294.4	0.027	1,349,354,528**
Error (a)	4	273.7	0.06	0.30	3,883.6	0.008	59,841,564
Hybrid (B)	5	1,558.6**	4.04**	11.83*	57,036.3**	0.01	352,142,608**
Population (C)	1	1,125.0	0.02	10.08	158,707.0**	0.008	3,818,825,425**
A x B	10	259.1	0.47	1.625	8,635.7	0.0035	70,770,671*
A x C	2	150.8	0.25	8.65	17,309.6	0.016	205,856,804**
B x C	5	703.3	1.35	3.62	25,425.5*	0.002	75,212,830
A x B x C	10	382.3	0.93	2.29	7,539.6	0.002	16,544,654
Error (b)	66	375.1	1.07	3.60	9,681.2	0.006	32,786,406
CV %		17.4	7.3	3.6	18.4	7.5	10.95

†df = degrees of freedom.

*, ** Significant at 0.05 and 0.01 levels of probability, respectively.

Table A7. Test of homogeneity for combinability of three individual environments in Mandan, ND, in 2009 and 2010.

Trait	2009 DP		2010 DP		2010 SF		Ratio
	CV (%)	EMS	CV (%)	EMS	CV (%)	EMS	†
Yield	8.06	79.4	15.9	315.5	17.4	375.1	4.7
Moisture	10.1	7.5	6.25	0.84	7.3	1.07	8.9
Test Weight	11.4	28.5	2.6	1.9	3.6	3.6	15.0
Kernels cob	13.05	3,506.2	18.9	8,995.5	18.4	9,681.2	2.8
Ears plant	12.4	0.018	10.35	0.014	7.5	0.006	3.0
Plant Population	9.3	30,446,854	9.5	21,399,595	10.95	32,786,406	1.5

† Test of homogeneity (greatest EMS/smallest EMS) should be smaller than 10-fold.

Table A8. Mean squares for the combined analysis of variance across three environments for agronomical traits evaluated in Mandan, ND, in 2009 and 2010.

Source of variation	df†	Mean squares					
		Yield	Moisture	Test Weight	Kernels cob^{-1}	Ears plant^{-1}	Population
Environment (E)	2	16.5	5814.2*	1311.5*	175638.9*	0.513*	3,389,468,189*
Rep (E)	6	201.8	8.1	14.8	5,478.1	0.007	90,716,770
Spacing (A)	2	19906.9*	4.5	26.9	722.2	0.045	8,521,390,505*
A x E	4	623.5*	8.4	17.9	2,016.6	0.013	704,888,257*
Error (a)	12	187.8	8.3	8.3	3,738.8	0.023	50,711,267
Hybrid (B)	5	4,900.8*	192.9	99.9*	88,533.2	0.115	804,893,666*
B x E	10	276.7	101.1	21.8	48,815.5	0.102	201,602,035
Population (C)	1	4,371.3*	11.6	27.0*	39,962.4	0.210	6,507,210,478*
C x E	2	176.7	16.7	0.06	62,445.8	0.034	171,053,370
A x B	10	290.6	2.7	13.8	6,949.3	0.023	176,242,784*
A x B x E	20	197.9	3.6	9.2	6,655.8	0.013	38,215,244
A x C	2	294.7	4.7	43.1	9,654.7	0.037	603,144,254*
A x C x E	4	256.8	7.7	7.5	8,861.3	0.032	37,189,811
B x C	5	369.5	1.9	6.7	13,822.2	0.010	116,149,006
B x C x E	10	393.2	3.3	12.9	13,714.2	0.025	75,945,486
A x B x C	10	214.2	3.4	6.7	7,525.04	0.027	44,802,932
A x B x C x E	20	215.3	2.7	5.3	5,109.4	0.021	22,893,237
Error (b)	198	255.2	3.2	11.52	7,361.27	0.012	28,245,527
CV %		14.38	33.7	13.7	4.6	10.03	9.94

†df = degrees of freedom.

*, ** Significant at 0.05 and 0.01 levels of probability, respectively.

Table A9. Mean squares for the combined analysis of variance of soil water content across four environments in Mandan, ND, in 2009 and 2010.

Source of Variation	df†	Mean Squares
		cm water per 30 cm of soil
Environment (E)	3	7.8
Rep (E)	8	12.4**
Time (T)	8	230.3**
E x T	24	40.5**
Error (a)	64	2.5
Spacing (S)	2	28.9*
E x S	6	4.1
Error (b)	16	7.2
S x T	16	4.6
S x E x T	48	3.1
Depth (D)	4	359.2**
E x D	12	10.9
D x T	32	10.6**
D x E x T	96	1.8
D x S	8	3.8
D x S x T	64	1.2
D x E x S	24	1.7
D x S x E x T	256	1.1
Error (c)	992	1.6
CV %		12.98

†df = degrees of freedom.

*, ** Significant at 0.05 and 0.01 levels of probability, respectively.