EFFECTS OF SPATIALLY VARIABLE PLANT AVAILABLE WATER ON OPTIMAL CORN SEEDING RATE – FIELD SCALE AND SITE-SPECIFIC APPROACHES

by

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B.S., Kansas State University, 2005

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2008

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Abstract

Spatial variability in plant available water can be caused by uncontrollable factors such as topography and soil texture as well as controllable factors such as residue management.

Research located on the High Plains evaluated the impact of wheat (*Triticum aestivum* L.) stubble height on snow catch, plant available water at seeding, and optimal corn seeding rates. Treatments consisted of stripper harvest height of 71 cm (28 in.), cut heights of 25 cm (10 in.), and 10 cm (4 in.) Measured snow depths were significantly different among treatments ($p<0.0001$) with equivalent precipitation of 5.77 (2.27), 3.25 (1.28), and 1.73 cm (0.68 in.) for the stripped, 25 cm, and 10 cm heights respectively. Available soil water at planting increased 24% as stubble height increased from 10 to 71 cm (4 to 28 in) in one year of the study. Two corn hybrids of varying maturity (97 and 108 days) were planted into the stubble treatments at seeding rates ranging from 2.47 to 5.43 plants m^{-2} (10 to 22 000 plants ac^{-1}). In the dry year, the long season hybrid responded positively to increasing population in tall stubble and negatively in short stubble. Yield of the short season hybrid increased with increasing stubble height and was mostly unresponsive to population. Grain yields of both hybrids responded positively to increasing plant population in a wet year. Treatments also affected the yield components of yield $plant^{-1}$, kernel weight, and kernels $plant^{-1}$.

Managing seeding rates for uncontrollable factors was attempted with small-plot and field scale research across 3 fields in northeast Kansas. A relationship between soil

electro-conductivity (EC) and measured water holding capacity values was developed for one study field. This quadratic relationship was significant ($p<0.0001$) and explained variability in water holding capacity with respect to EC quite well ($R^2=0.6239$). Responses from small plots showed that sites differing in population response characteristics could be identified. Field scale data was used to derive a function describing optimal seeding rate with respect to soil EC. In the field under study, optimal seeding rates varied from 3.08 to 8.74 plants m^{-2} (12 500 to 35 375 plants ac^{-1}).

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Acknowledgements

I thank Dr. Scott Staggenborg, my major professor, for being a source of guidance in both my professional and personal life. His passion for meaningful research, practical approaches, and get-it-done attitude are traits I have benefited from. I have enjoyed and profited from every one of our conversations which have ranged from cotton physiology to brands of Argentine combines and yield data filtering to county politics. I am thankful for the many opportunities Scott offered to me which are not typically available to graduate students. These experiences have been critical in furthering my education and developing my abilities. Scott has been many things to me including the traditional roles of teacher and mentor, but the role I value most is that of friend.

I thank my committee members Dr. Alan Schlegel, Tribune Experiment Station, and Dr. Mark Schrock, P.E., Emeritus Professor of Agricultural Engineering. Both of these gentlemen have provided enlightening ideas, critiques, and conversations regarding not only this work but many other subjects. I have been exposed to a wealth of knowledge and feel privileged to benefit from their service on my committee.

Thanks are extended to Dr. Randy Taylor, Professor of Agricultural Engineering and my undergraduate advisor, for cultivating a desire to learn. He equipped me well with the knowledge and experience necessary to start this endeavor. Without the freedom, opportunities, and encouragement provided to me while under his study I would not have pursued this path. I am thankful for the impact he has had on my life and his continued friendship.

My fellow graduate students in the crop production research group have provided me unending support both professionally and personally. The time spent in the field, the lab, and on the road is time I wouldn't trade for anything. I will carry stories and memories for the rest of my life involving Mauro Carignano, Sarah Evert, Mike Epler, Chris Pachta, Todd Whitney, Jon Propheter, and Kevin Swenson. There is not enough room to say everything I would like, so I will simply say thank you.

Very little research would be accomplished without the assistance of student technicians, who often get saddled with jobs that no one else wants to do. I owe special thanks to Derek Belton, Scott Kramer, and Kyle Shroyer. They were often my right hand men, and their dedication led to the completion of many projects for me and our entire group. Additional help in the lab and field was provided by Amos Duncan, Emily Bunk, Molly Kuhlman, Kelly Yunghans, Josh Carlin, Jessica Tittsworth, Lance Staggenborg, and Lucas Maddy. Please know that the countless hours you contributed are truly appreciated.

A special thank you to John Kramer, Kramer Bros. Farms, Milford, KS for his long running support of precision agriculture research at K-State. Thanks are also extended to Steve Arnold, Johnson, KS, Dietrich Kastens, Kastens Inc., Herndon, KS, Gayle Haag, Haag Farms, Bartley, NE, and the staff of the K-State Southwest Research-Extension Center – Tribune Branch. They all provided generous contributions of land, equipment, and labor in support of this research. I have learned a great deal about production agriculture from these gentlemen and sincerely appreciate their friendship.

All of the aforementioned individuals have helped make graduate school the experience of a lifetime. Thank you.

Dedication

This work is dedicated to my family. Their support and encouragement has never wavered in any of my numerous ventures. My brothers Buck and Denton, and grandfather Francis, provided help with plot work, equipment preparation, and countless other tasks. My sister Shelby also assisted in that regard and provided her expertise in reviewing and commenting on both written and oral presentations of this work. My father Gayle provided land, equipment, ideas and expertise, and his assistance in planting and harvesting of plots. Most importantly, he has shared with me his devotion to soil and water conservation. My mother Elaine used her tremendous talents to make sure our research crew was well cared for while visiting. There were always plentiful portions of home cooked meals, cold drinks, and a comfortable place to rest. Her genuine curiosity, interest, and support regarding our work in the field was a key source of support at the end of many long days. My entire family graciously shared their time in managing my business activities at home allowing me to work on this effort for which I am forever thankful.

A dedication would not be complete without recognizing and giving thanks to my heavenly father for providing me the talents and strength necessary throughout this time.

CHAPTER 1 - Literature Review: Responses of Corn to Changes in Plant Density

The largest share of cropland in the United States, 35 million hectares (86.5 million acres) in 2007, is dedicated to the production of corn, which yielded a total production of 13.1 billion bushels (NASS, 2008). The importance of this crop as grain, feed, and most recently as an energy source has continued to increase demand for the commodity. In Kansas, non-irrigated corn acres have increased dramatically since 1990, especially in western Kansas (Figure 1.1).

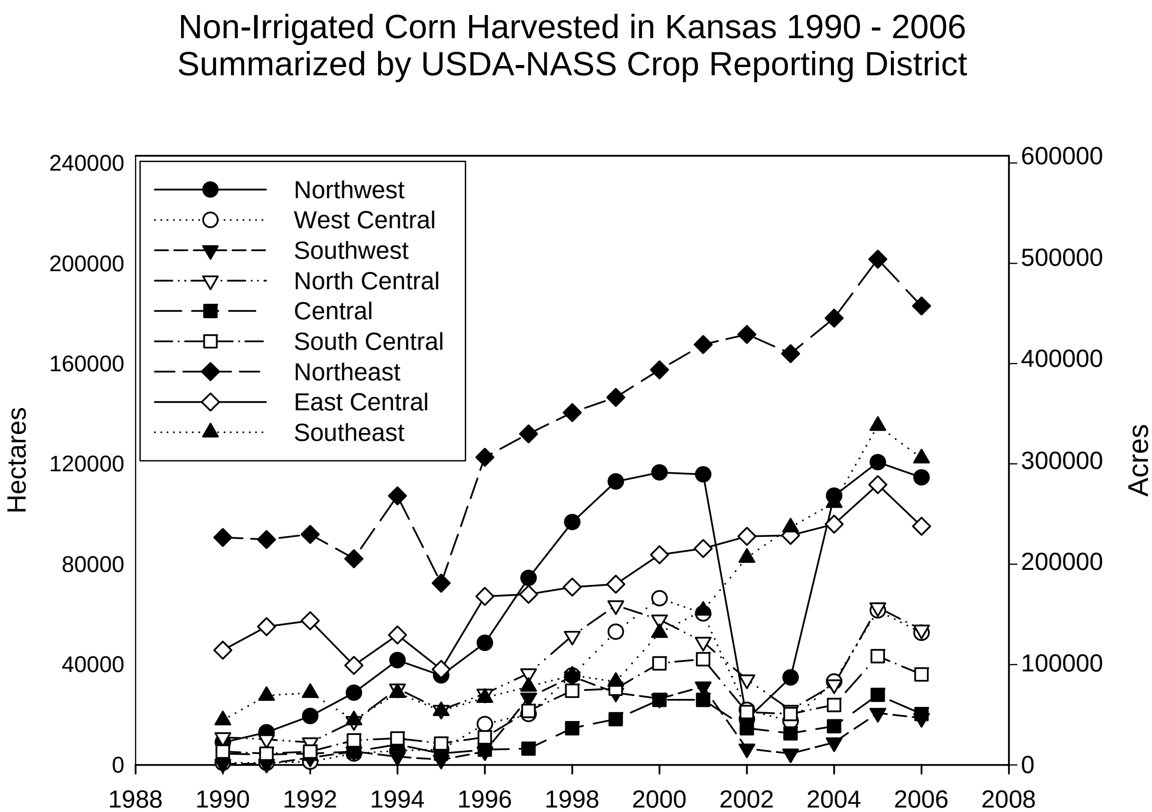

Figure 1.1 - Non-Irrigated Corn Harvested in Kansas 1990-2006

The adoption of no-till and intensified dryland rotations including corn has bolstered production in those areas. However, it is apparent that production in this region is not without risk. As evidenced in the Figure 1.1, harvest acres in 2001-2004 declined sharply due to repeated crop failures. Irrigated acres in Kansas remain stable (Figure 1.2), with some loss of acreage in southwest Kansas during the mid 2000's to cotton, a crop relatively new to the state.

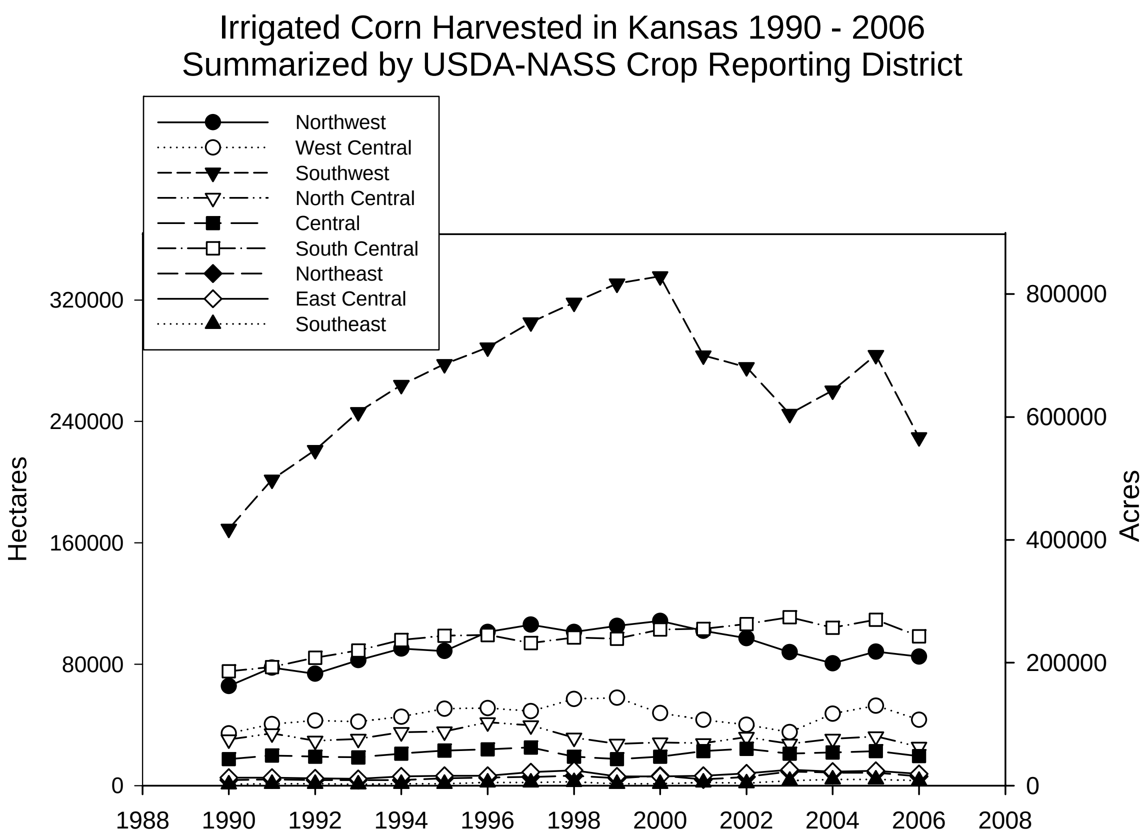

Figure 1.2 - Irrigated Corn Harvested in Kansas 1990-2006

The importance of corn both nationally and to Kansas has been the driving force behind agricultural research targeted at developing cultural practices aimed at maximizing corn grain yield.

Recent changes in production economics and advances in technology have resulted in new considerations for the application of cultural practices. One notable change is the dramatic rise in seed cost (Figure 1.3).

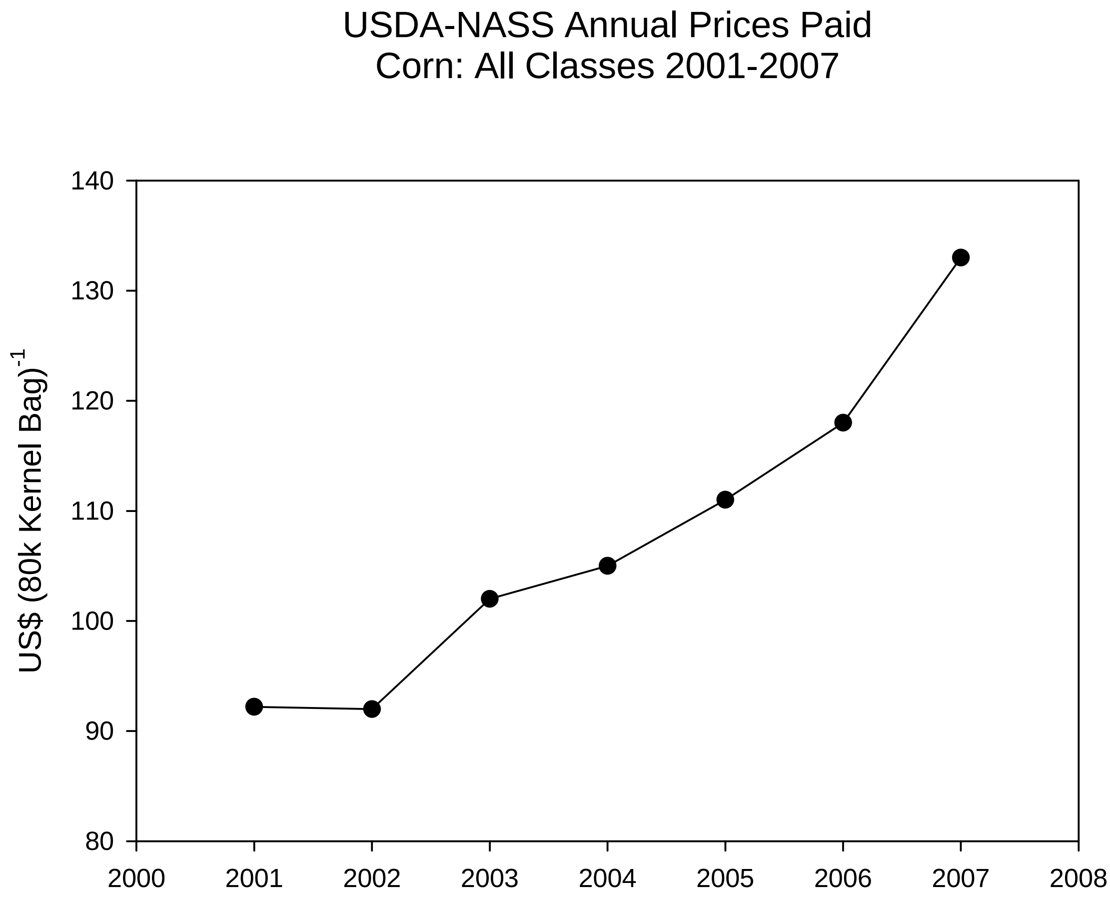

Figure 1.3 - Annual Prices Paid for Seed Corn 2001-2007

This rapid rise has been largely driven by the introduction of genetic traits, which have gained market adoption in spite of increased cost. While commodity prices for grain remain variable, inputs in corn production have risen with relative stability. It is important to recognize and understand the relationship between corn population and yield in order to maximize grain production and efficiently allocate crop inputs.

The Relationship Between Corn Population and Yield

Field Studies

Most field studies involving plant population have produced response curves linear in nature when the treatments were above or below the optimum population for a given site-year. Comprehensive studies over a wide range of densities have typically resulted in quadratic responses. Lang et al. (1956) reported a quadratic response to population in an evaluation of nine hybrids, three nitrogen rates, and densities ranging from 1.9 to 3.5 plants m^{-2} (4- to 24 000 plants ac^{-1}) in Illinois. Alessi and Power (1974) reported quadratic responses of grain yield to population in the Northern Great Plains. They noted that the optimal population varied tremendously with drought stress. Vanderlip (1968) reported quadratic responses to population for both irrigated and dryland trials in Kansas while using eight different hybrids at densities of 2 to 6.9 plants m^{-2} (8- to 28 000 plants ac^{-1}). Differences in hybrid and location led to variation in the optimal population. In Vanderlip's results, the optimum population was higher with higher yields, implying the validity of a yield-goal-driven seeding rate. Two dryland site-years in the study produced no response to population, and the use of the optimal population for a good year did not significantly impact yields in a stress year. The non-responsiveness at these location-years could be attributed to the use of hybrids characterized as intermediate in prolificacy (R.L. Vanderlip, personal communication). These hybrids typically produced multiple ears per plant at the lowest populations and offered some resistance to barrenness at higher populations. The hybrid characterized as a single-ear type, U.S. 523W, produced the lowest grain yields and highest percentage of barren plants at these locations. A two year study in western Kansas from 1973-1974 showed that yield declined with increasing population across densities of 4 to 6.9 plants m^{-2} (16- to 28 000 plants ac^{-1}). These plots were rain-fed after pre-plant irrigation was used to fill the soil profile (Anonymous, 1975). An adjoining study conducted in 1973-1974 evaluated populations under dryland conditions after one year of fallow. A quadratic response was observed with an optimum density of 3.4 plants m^{-2} (14 000 plants ac^{-1}).

It is well established that genetic advancement has improved corn hybrid performance. However, quadratic responses appear to remain relevant for more modern hybrids. Tollenaar (1992b) evaluated 4 hybrids introduced in 1959, 1962, 1983, and 1988, and reported distinct quadratic yield responses for all four hybrids when densities of 0.5 to 24 plants m^{-2} (2- to 97 000 plants ac^{-1}) were evaluated. Recent work by Sarlangue et al. (2007) produced grain yield response curves that were quadratic in nature when evaluated over plant populations ranging from 4 to 15 plants m^{-2} (16- to 61 000 plants ac^{-1}). Three hybrids were included in the study, ranging from short season and non-prolific to full season and prolific. Hashemi et al. (2005) presented response curves for both grain and total biomass production that were quadratic in nature, with a decline in yield above the optimal population most years. Nafziger (1996) evaluated plant populations in Illinois ranging from 4.4 to 7.4 plants m^{-2} (18- to 30 000 plants ac^{-1}). A quadratic response was evident with the optimal population being either the highest in the study or located just below it. Similar data was presented from Michigan by Widdicombe and Thelen (2002). A quadratic response led up to the highest population in the study, 9 plants m^{-2} (36 000 plants ac^{-1}). Although that population was optimal for the study, it is unknown whether it represented the true maximum grain yield that would have been attainable for that set of conditions. Cox (1997) reported quadratic responses to population for a variety of hybrids in both wet and dry years. Exceptions were linear responses from a fixed-ear type hybrid in the wet year and a semi-prolific type in the dry year. Optimal populations for grain yield, when averaged across hybrids, varied by 1.35 plants m^{-2} (5 500 plants ac^{-1}).

Non-quadratic responses have been noted in the literature as well. In two of the location X year X planting date combinations reported in the study by Ahmadi et al. (1993), yield increased in a positive linear or quadratic manner with respect to population, but remained the same at the two highest densities. This occurred at the earliest planting dates in the study with an optimum of approximately 12 plants m^{-2} (49 000 plants ac^{-1}). The authors made no explanation of the observed response. One could reason that the timing of stress or a genetic limitation induced a sink-limited situation which negated the impact of plant density on assimilate source availability and produced the observed results. Staggenborg et al. (1999) in northeast and north-central Kansas, evaluated 3 population densities: 1.9, 3.5, and 6.3 plants m^{-2} (14-, 20-, and 26 000 plants ac^{-1}), two hybrid maturities (102 day and 113 day), and three planting dates. They reported that grain yield generally increased with increasing plant density. Surprisingly, none of the six location-years resulted in a negative response to increasing plant population, even those with increased levels of stress. Some date X hybrid X population combinations produced a quadratic response to population. In other instances a linear response was significant between the lowest and middle population, with no difference between the middle and upper population treatment. The authors proposed that a linear or quadratic plateau may exist rather than a quadratic function. In one of the cases, a positive numerical trend existed up through the two upper populations, although no statistical difference was apparent. In the other case, a much more definite plateau was observed at the mid and high plant densities. This occurred for the short season (102 day) hybrid planted at the middle planting date (3 May). The earliest planting date (4 April) resulted in no population response, while the latest date (10 June) resulted in a quadratic response. It is possible that for this hybrid X environment condition, the tradeoff between decreasing kernels plant^{-1} and increasing plants unit area^{-1} resulted in basically unchanged total grain yield. Nafziger (1994) reported data from Illinois with a quadratic response to population over a range of 2.5 to 8.6 plants m^{-2} (10- to 35 000 plants ac^{-1}) under good environmental conditions. The estimated optimums were over 7.4 plants m^{-2} (30 000 plants ac^{-1}). Like Staggenborg et al. (1999) he reported that in a stress year no response to population was observed, which differs from observations of declining yield with increasing population under stress. Optimums in the stress environment were determined to be approximately 6.2 plants m^{-2} (25 000 plants ac^{-1}). The author speculated that the risk of maintaining high populations in Illinois is not as high as it might have been historically, as new hybrids appeared improved with regard to barrenness. Cox (1997) stated that for grain production in the well-drained soils of New York, high plant densities did not decrease grain yield in dry years. Lamm and Trooien (2001) reported that for subsurface drip irrigated corn in northwest Kansas there was little yield penalty for increased plant population over a range of 5.6 to 8.5 plants m^{-2} (23- to 35 000 plants ac^{-1}), even when irrigation was severely limited or eliminated. However, at the zero irrigation treatment, the lowest plant density always resulted in the highest yield.

Determining population responses can be further complicated by the climatic effects during the period of study. Polito and Voss (1991) evaluated plant densities ranging from 1.9 to 6.3 plants m^{-2} (20- to 36 000 plants ac^{-1}) in the western corn belt of Iowa from 1982 to 1984. This time period was characterized as extremely hot and dry. For 1983 and 1984 the authors reported stress index values almost two and three times the 24 year average, respectively. As may be expected, the lowest plant densities gave maximum yields in all experiments contained in the study.

The experiments of Norwood and Currie (1996) and Norwood (2001a) were also influenced by climatic extremes. In both experiments, population treatments ranged from 3 to 6 plants m^{-2} (12- to 24 000 plants ac^{-1}). Norwood and Currie (1996) found that dryland corn grain yields in southwest Kansas declined with increasing population in 1991, with losses being greater in reduced-till plots than the no-till. No-till yields declined from 2698 to 2259 kg ha^{-1} (43 to 36 bu. ac^{-1}) while reduced-till plots declined from 1506 to 1004 kg ha^{-1} (24 to 16 bu. ac^{-1}). Available soil water at planting in 1991 was less than 25% of capacity. Total rainfall was above average; however the distribution resulted in stress at the critical times of silking and grain fill. These factors played a role in the overall yield level and population response. In contrast, yield increased linearly with increasing population in 1992 with the optimal plant density being the highest under study. Conditions in 1992 were optimal with available soil water at planting above 94% in the no-till plots, well distributed seasonal precipitation totaling 7.6 cm (2.99 in) above normal, and below normal temperatures for most of the growing season. Yields in the no-till plots increased from 6964 to 10,164 kg ha^{-1} (111 to 162 bu. ac^{-1}) while yields in the reduced-till plots increased from 7278 to 9286 kg ha^{-1} (116 to

148 bu. ac^{-1}). These two years portray the stark extremes that exist in crop production on the semi-arid High Plains. A continuation of the previous study, Norwood (2001a) reported that dryland corn yields in southwest Kansas increased as population increased from 3 to 6 plants m^{-2} (12- to 24000 plants ac^{-1}) from1996 through 1999. The response to population was non-linear with increases of 13.5% between 3 and 4.5 plants m^{-2} (12- and 18 000 plants ac^{-1}) and 4.3% between 4.5 and 6 plants m^{-2} (18- and 24 000 plants ac^{-1}). This work was conducted in a time of above average precipitation and below average temperatures, which likely influenced the results.

These climatic impacts illustrate the need for long-term experiments documenting population response, or a system in which many environments could be documented in a single year by incorporating known variability in growing season water supplies. The integration of accurate climatic forecast may provide further improvement in producer selection of optimal plant populations.

Other work in the Great Plains has produced various results. Major et al (1991) evaluated densities of 2.9 to 14.8 plants m^{-2} (12- to 60 000 plants ac^{-1}) in the semi-arid plains of Alberta. They found 5.9 plants m^{-2} (24 000 plants ac^{-1}) to be the optimal density for most years, with responses typically quadratic in nature. However for location-years with higher drought stress, the lowest population, 4 plants m^{-2} (12 000 plants ac^{-1}) produced the highest grain yields. Increasing plant population at these location-years resulted in a linear decline in grain yield. Havlin and Lamm (1988) found no yield differences between corn populations of 2.1, 2.5, and 3.7 plans m^{-2} (8 500, 10 000, and 15 000 plants ac^{-1}) in northwest Kansas. Data collected over several years by Fjell (2005) showed drastic differences in population responses in northwest Kansas. In Wallace

County, responses varied tremendously across years when evaluated over a population range of 2 to 7 plants m^{-2} (8- 28 000 plants ac^{-1}). Plant densities that optimized yields ranged from 4.0 to 4.9 plants m^{-2} (16- to 20 000 plants ac^{-1}) in four of the seven years of the study. During this period, May through August rainfall varied between 114 and 153% of average for three of the years. Rainfall during the fourth year was below average, but was concentrated in July. During the three years when drought conditions were experienced, the optimal population was the lowest in the study with yields declining as plant density increased. Precipitation in May through August during the drought years ranged from 50 to 105%, with distribution also a challenge. Negative trends of yield with respect to population were also observed in Cheyenne County – 2000, Morton County – 2001, and Scott County – 2003.

Blumenthal et al. (2003) presented data from western Nebraska collected across 7 site-years. Population response curves were distinctly linear in nature but varied in direction by year and location. The authors employed the use of an environmental index for each site-year to characterize its yield potential. The environmental index was essentially the mean yield across populations for the site-year in question. Linear contrasts were utilized to determine breakpoints for yield responses. Several environment break points were identified. The first was at a yield goal of 1980 kg ha^{-1} (31.6 bu ac^{-1}). At yield levels below this point, increasing population from 1.73 to 2.72 plants m^{-2} (7- to 11 000 plants ac^{-1}) would result in decreased yield, whereas yield levels above this point would respond positively with increasing population across the aforementioned range. As observed in the data, yield decreases in environments less than the breakpoint were relatively small compared with the magnitude of yield increases in environments above. Another breakpoint was identified at 2480 kg ha^{-1} (40 bu. ac^{-1}). At yield potentials above this point, increases in yield were observed as population increased from 2.72 plants m^{-2} (11 000 plans ac^{-1}). At environments lower than the breakpoint, yield declines were observed as plant population exceeded 2.72 plants m^{-2}. Data collected in this study were used to validate the APSIM-maize model and produce probability analysis for various available soil water and plant population combinations in western Nebraska (Lyon et al., 2003).

Currently, population recommendations are general in nature and are specified based on geographical location. The Kansas Corn Production Handbook (Roozeboom, 2007) offers a range of recommendations for dryland corn, from 3.5 to 6.9 plants m^{-2} (14- to 28 000 plants ac^{-1}). Irrigated recommendations range from 5.9 to 8.9 plants m^{-2} (24- to 36 000 plants ac^{-1}). Dryland populations are recommended largely as a function of in-season precipitation, as water is typically the yield limiting factor in Kansas, especially as one moves west in the state. Irrigated recommendations are a function of relative maturity and water availability, ex. full vs. limited irrigation. Recommendations offered by the University of Nebraska attempt to take into account variability in residue levels, available soil water at planting, and hybrid maturity (Klein and Lyon, 2003). Various recommendations are offered for combinations of three geographic regions in the state, three residue or soil moisture levels, and for a mid-season or short-season hybrid. For example, the recommendations for western Nebraska include “Do Not Plant Corn”, 2.47, and 2.96 plants m^{-2} (0-, 10-, and 12 000 plants ac^{-1}). This approach attempts to offer producers some guidelines in selecting optimal seeding rates for a given farm or field situation.

Mathematical Relationships

The population and pattern in which corn is planted has been a continual subject of interest among producers and researchers alike. Changes in population or planting pattern change the distances between plants and thus influences interplant competition and individual plant yields. The ability to use mathematical models to predict these responses would prove valuable for researchers, seed companies, and producers. A great deal of work has been placed into developing quantitative relationships between plant population and yield (Willey and Heath, 1970). Duncan (1958) utilized a large dataset spanning multiple locations, years, hybrids, and populations to describe a mathematical relationship between plant population and grain yield. The logarithm of per plant grain yield declined in a linear manner as plant populations increased for all common planting patterns (r = 0.99). This relationship held true over a wide range of populations, between 1.5 and 6.2 plants m^{-2} (6- and 25 000 plants ac^{-1}). Duncan believed that a departure from the linear trend at a plant population on the lower end, possibly around 1.2 plants m^{-2} (5 000 plants ac^{-1}), was indicative of where individual plant yields were no longer influenced by interplant competition but limited by the genetically inherent productivity of the plant. Carmer and Jackobs (1965) further evaluated Duncan's relationship utilizing 8 hybrids over a range of populations from 2 to 7.9 plants m^{-2} (8- to 32 000 plants ac^{-1}). In their study, seven of the eight hybrids fit the model extremely well, the hybrid of exception departed from the model at the two lowest plant densities in the study. The grain yield per plant and kernels per ear for the hybrid were essentially equal across the two lowest populations, thus indicating the genetic potential of the plant had been reached and interplant competition was not a factor. This observation agreed with those of Duncan regarding the existence of a lower boundary at which the linear relationship driven largely by interplant competition was no longer valid. Williams et al. (1968) also found a pronounced linear trend when he evaluated the relationship over a larger range of plant densities in a study involving seven treatments with a range of 1.75 – 12.5 plants m^{-2} (7- to 50 000 plants ac^{-1}). Other mathematical forms of describing the relationship have since been proposed. Warren (1963) presented a linear relationship between individual plant yield and population as opposed to using the logarithm of individual plant yield. He reasoned that the resulting parabolic response would provide a better estimation of yield at population extremes than the exponential response derived from Duncan's equations. Further work was presented by Bleasdale (1967) and Fery (1971) who proposed methods that included recognition of the asymptotic relationship between total above ground biomass and population. They believed that these mathematical forms resulted in a relationship accurate over a wider population range and more robust across various spacing configurations than that originally proposed by Duncan (1958). Duncan (1984) further explained the aforementioned relationships in a theory relating the components of interplant competition. He termed these components as crowding and the effect of crowding. Crowding was defined as the sum of the independent crowding attributed to each plant located within an influential range of the target plant. A crowding value for any individual plant is as a function of its distance from the target plant. Thus through this calculation the crowding term (summation of individual plant crowding values) increases at an exponential rate as a function of plant population. In Duncan's relationship physical crowding or plant spacing in and of itself does not impact grain yield. The effect term is the slope at which the log of per plant grain yield declines as a function of crowding. This slope is a function of genotypes and environment, and thus significantly affects grain yield across varying populations.

Duncan believed that at plant densities lower than the optimal population the additional yield from an added plant is larger than the accompanying loss due to increased crowding. At plant densities above the optimum, the yield gained though the addition of another plant is less than the exponentially increasing loss due to interplant competition. Tollenaar (1989) conveyed a similar concept while identifying the physiological components of the relationship. Recognizing that dry matter accumulation increases and harvest index generally decreases with increasing plant population; he proposed that the optimal population is the point at which an increase in density would result in a smaller increase in dry matter per unit area than the dry matter lost through the corresponding decline in harvest index. For a reduction in population the inverse would then be true. These relationships fit into the “effect of the crowding” term described by Duncan (1958) and encompass the impact of additional plant density on light interception and thus dry matter accumulation, the division of available water and nutrient resources, subsequent plant stresses, and the corresponding negative impact on harvest index. Although most yield declines at populations above the optimum had been attributed to barren plants, Duncan (1984) argued that when the product of individual plant yield and plant population was evaluated over a range of plant densities, yield decreased in the region above the optimal population without any inclusion of assumptions regarding barren plants, thus possibly negating the impact that barren plants would have on per unit area yields. This is supported by recent data previously discussed where barrenness is not identified as a causal factor but yield still responds in a quadratic manner.

Physiological Impacts of Plant Density

Leaf Area, Light Interception, and Dry Matter Accumulation

The impact of plant population density on the physiological characteristics of corn has been evaluated in a wide array of research efforts. Investigations during vegetative growth and development have consistently found that total leaf area, rate of leaf area accumulation, and dry matter accumulation increase with increasing plant density. However various points at which the response becomes asymptotic or results in a plateau exist.

Both dry matter accumulation rates and intercepted photosynthetically active radiation (IPAR) have a significant impact on seed production (Kiniry et al., 2002). These relationships are somewhat nested as the interception and conversion of light into photosynthates is the driving factor behind dry matter accumulation rates. Williams et al. (1965) reported that leaf area production, light interception, and dry matter accumulation responded positively to an extensive range of plant populations from 0.67 to 70.0 plants m^{-2} (3- to 283 000 plants ac^{-1}). They found that essentially 100% light interception occurred at densities above 10.8 plants m^{-2} (43 600 plants ac^{-1}) when measured at ground level. The largest relative differences in dry matter accumulation, LAI, and light interception between densities occurred in the region below 10.8 plants m^{-2} (43 600 plants ac^{-1}) and above 2.7 plants m^{-2} (10 900 plants ac^{-1}). This is of particular interest as this range is inclusive of almost every practical plant population recommendation for grain production. Thus, plant density changes within this range pose the opportunity to significantly alter the light interception and dry matter accumulation characteristics of a corn plant community.

Further work reported by Williams et al. (1968) reiterated the relationships described in their previous study while focusing on a narrower range of plant populations ranging from 1.75 plants m^{-2} (7 100 plants ac^{-1}) through 12.5 plants m^{-2} (50 500 plants ac^{-1}). The results of this study showed that increasing plant density increased the rate of leaf area accumulation and reduced the time required for the crop canopy to reach an LAI of 3, the level normally believed to be the LAI above which 90% light interception occurs (measured at ground level), and thus approaching the asymptote of maximum photosynthetic production.

Tetio-Kagho and Gardner (1988) investigated how differences in plant population could impact canopy attributes and plant growth. Their data showed that corn at a density of 6.3 plants m^{-2} (25 500 plants ac^{-1}) reached the asymptote of light interception, near 95% interception, 14 days earlier than corn at a density of 3.5 (14 200) or 1.9 plants m^{-2} (7 700 plants ac^{-1}). This same general relationship was presented by Williams et al. (1968) where corn planted at a density of 12.5 plants m^{-2} (50 500 plants ac^{-1}) reached the upper asymptote of light interception over 15 days earlier than corn planted at 1.75 plants m^{-2} (7 100 plants ac^{-1}). Tetio-Kagho and Gardner (1988) also found that light interception varied with both plant density and canopy depth. At densities of 3.5 plants m^{-2} (14 200 plants ac^{-1}) and 6.3 plants m^{-2} (25 500 plants ac^{-1}) light interception at ear level was 83 and 93% respectively. For a density of 1.9 plants m^{-2} (7 700 plants ac^{-1}) light interception at ear level was approximately 50%, thus indicating that in high plant population environments light is captured primarily above the ear, and thus by younger and more efficient leaves. When leaf area per volume was evaluated through canopy depth and across the three populations it was apparent that the concentration of leaves at ear level, 0.9 m (2.95 ft), dramatically increased with increasing plant density. Leaf area was most evenly distributed across canopy depth at the lowest population evaluated, 1.9 plants m^{-2} (7 700 plants ac^{-1}). This was in agreement with Loomis et al. (1968) who found that the maximum leaf area was located at the ear stratum regardless of plant population and Williams et al. (1965) who noted that leaves were evenly distributed across height for plants at a density of 0.67 plants m^{-2} (2 700 plants ac^{-1}) and more concentrated towards the top as plant density approached 70.0 plants m^{-2} (283 000 plants ac^{-1}). Tetio-Kagho and Gardner (1988) further speculated that this distribution of leaves may explain the responsiveness of corn to increasing plant density. They attributed this to their observations of ear leaves being longer and wider than others, were relatively younger, and had the shortest pathway for assimilate transport to the grain.

Tollenaar (1989) reported an increase in LAI from 0.89 to 5.14 as population increased from 2.0 plants m^{-2} (8 100 plants ac^{-1}) to 13.0 plants m^{-2} (52 600 plants ac^{-1}), with newer hybrids generally having the largest gains in LAI as plant population increased. Data from additional site-years (Tollenaar, 1991), averaged across nine hybrids varying in time of introduction, showed a range of 0.85 to 4.18 as population density increased. The newest hybrid in the study had an LAI range of 1.0 up through 4.6 across the aforementioned plant population range. Cox (1996) reported 40% less leaf area at a plant density of 4.5 plants m^{-2} (18 200 plants ac^{-1}) when compared to a density of 9.0 plants m^{-2} (36 400 plants ac^{-1}) in the time period from mid-vegetative growth through grain filling. This resulted in lower rates of dry matter accumulation and 25% less dry matter at silking (R1 growth stage) for the lowest population. Crop growth rate was significantly higher for the denser plant population from stage V12 through R1.

However from R1 through R3 no differences in crop growth rates were observed among population treatments and relative differences in dry matter accumulation remained constant. Leaf area index from R1 through R3 remained above approximately 2.5 while either decreasing or remaining flat for all three plant populations. It has been shown that canopies with LAIs of 2 and 4.6 do not differ in the rate of dry matter accumulation (Tollenaar and Bruulsema, 1988), thus possibly explaining the observation of no differences in crop growth rate among the three population densities.

Williams et al. (1965) reported that the rate of dry matter accumulation increased as a function of plant density during the period of 27 to 42 DAP (shooting stage). This increase reached a plateau at a density of 10.8 plants m^{-2} (44 000 plants ac^{-1}) and a dry matter accumulation rate of 33.6 g (m^{-2}) day^{-1} (300 lb ac^{-1} day^{-1}). From 42 through 54 DAP, no such plateau was obvious. However the author speculated that the scatter in data points at the higher densities indicated a plateau existed, albeit at a much higher population than observed in the first sampling period. Williams et al. (1965) included some root mass in his dry matter accumulation values and noted that no differences across populations were observed in root mass to a depth of 25 cm (10 in). Williams et al. (1968), using a narrower range of plant populations, reported that dry matter accumulation was a direct function of plant population from 23 through 36 DOE after which the total dry matter accumulation differences remained relatively constant among the population treatments and increased at a similar rate.

Within population studies, dry matter accumulation has been shown as either linear or quadratic in response to plant population. In the data reported by Williams et al. (1968), total dry matter accumulation at physiological maturity as a function of plant density appeared to be quadratic in nature. A quadratic response was also reported by Hashemi et al. (2005). Within studies conducted by Cox (1996) at plant densities of 3, 6, and 9 plants m^{-2} (12-, 24-, 36 000 plants ac^{-1}), linear contrasts were always significant with quadratic contrasts being significant for single ear type hybrids in one year. In studies conducted by Tollenaar (1991) over plant populations of 2, 4, 8, and 13 plants m^{-2} (8-, 16-, 32-, and 52 500 plants ac^{-1}), dry matter appeared to respond in a linear plateau or quadratic fashion when averaged across all hybrids, or when evaluating the two newest hybrids in the study. Timing and rate of leaf senescence have been shown to be impacted by plant population, especially after the R3 stage (Tollenaar, 1992b). Stover losses as a percent of total dry matter at maturity were noted as 8.4, 13.2, and 16.7% for plant populations of 2, 4, 8, and 13 plants m^{-2} (8-, 16-, 32-, and 52 500 plants ac^{-1}) (Tollenaar, 1991). Late season senescence of leaves in higher plant populations is a likely cause for the appearance of a quadratic response; any environmental stresses present would be expected to amplify this phenomenon.

Aside from the physiological processes of plant growth, several phenological attributes have been mentioned in the literature. Tollenaar (1991 and 1992b) showed various phenological changes as well. Duration from planting to silking increased with increasing plant density, which is consistent with earlier work (Lang et al., 1956). This phenomenon has been indicative of stress effects on potential grain yield (Dow et al., 1984, Barnes and Woolley, 1969). Delayed tassel emergence has been observed as well (Hashemi-Dezfouli and Herbert, 1992). Conversely the duration from silking to physiological maturity declined by 50 and 120 heat units respectively when plant populations increased from 4 to 8 and 8 to 13 plants m^{-2} (16- to 32 000 and 32- to 52 500 plants ac^{-1}).

Physiological Yield Components

Intercepted light and subsequently produced dry matter is partitioned into yield components; the partitioning process and its resultant components are known to be responsive to changes in plant population. Yield components have exhibited differing levels of stability and impact on final grain yield. Stability of a given yield component is further complicated by interactions with genetic attributes of hybrids, prolificacy or ears $plant^{-1}$ being the most notable.

Changes in plant population typically alter the source:sink ratio and thus possess the ability to affect assimilate and sugar content in corn at specific time periods. Williams et al. (1968) evaluated stalk sugar concentration at various growth stages. A negative relationship between stalk sugar content prior to pollination and population density was observed. The largest difference in stalk sugar content occurred between the densities of 4.87 plants m^{-2} (19 700 plants ac^{-1}), which resulted in satisfactory kernel formation and 6.95 plants m^{-2} (28 100 plants ac^{-1}), which resulted in substantial kernel development failures. The author speculated that this relationship may be indicative of potential kernel set. Stalk sugar content at the dent stage had a negative correlation ($r = -0.91$) to grain yield. At populations below the optimum, the increased sugar content was attributed to reduced assimilate sink capacity due to fewer potential ears. Kernel formation failures at populations above the optimum reduced the sink size, resulting in sugar accumulation.

Dry matter partitioning into grain yield components has been shown to be time sensitive. Andrade et al. (1999) used population treatments of 2.2 through 16 plants m^{-2} (9- through 64 800 plants ac^{-1}) and reported a curvilinear relationship between kernel number m^{-2} and the dry matter accumulation rate for a time period of 10 days prior to 20 days post silking. This highly correlated relationship and results of various water stress studies (Denmead and Shaw, 1960) are explained by the findings Swank et al. (1982) and Simmons and Jones (1985) who showed that less than 10% of grain yield is attributable to assimilates produced prior to silking.

The impact of plant population on harvest index has been less clear across studies. DeLoughery and Crookston (1979) reported reductions in harvest index as plant population increased from 1.25 to 20 plants m^{-2} (5- to 81 000 plants ac^{-1}) and relative maturity increased from 75 to 135 days. The rate of decline became much larger as the water stress level of the environment increased. Tollenaar (1989) reported a decrease in harvest index from 0.537 to 0.434 as plant population increased from 2.0 plants m^{-2} (8 100 plants ac^{-1}) to 13.0 plants m^{-2} (52 600 plants ac^{-1}). Older hybrids had a lower harvest index at the highest plant population. Tollenaar (1992b) showed a decline in harvest index from 0.52 to 0.39 as plant population increased from 0.5 to 24 plants m^{-2} (2- to 97 000 plants ac^{-1}). Cox (1996) showed no differences in harvest index over two years for four hybrids planted at 4.5, 6.75, and 9.0 plants m^{-2} (18-, 27-, and 36 400 plants ac^{-1}). Tetio-Kagho and Gardner (1988b) noted, that although not statistically significant, harvest index declined numerically from 50 to 44% as plant density increased from 0.8 to 15.4 plants m^{-2} (3- to 62 300 plants ac^{-1}). Sinclair et al. (1990) reported Australian data with a relatively constant harvest index of 0.475. However, observations within the dataset at more intense levels of water stress were accompanied with harvest index values of 0 to 0.25. It is plausible that this observation would hold true for corn under water stress caused by increasing plant population. Although harvest index is typically believed to negative linear response with increasing plant population, observations of quadratic response have been noted. Cox (1997) reported that harvest index had no response to population in a wet year, but produced a quadratic response in a dry year. Work performed with three hybrids by Hashemi et al. (2005) produced quadratic responses in harvest index across a plant density range of 3 to 12 plants m^{-2} (12- to 48 600 plants ac^{-1}). In this study harvest index values ranged from 0.30 to approximately 0.53, with optimums occurring at 6 or 9 plants m^{-2} (24- or 36 400 plants ac^{-1}). The variability in harvest index response to changes in plant density may be partially explained in work conducted by Sarlangue et al. (2007). Their data showed differences among hybrid types and maturities on biomass plasticity, reproductive partitioning, and thus harvest index. Plant populations ranging from 4 to 15 plants m^{-2} (16- to 60 700 plants ac^{-1}) were used to produce a range of biomass per plant levels. They found that harvest index per plant increased with increasing population until the optimum was reached for a non-prolific, short season hybrid. This was attributed to the limited sink capacity of such a hybrid. In contrast, a longer season, more prolific hybrid had the largest per plant harvest index at the lowest population and then produced a very small linear decline with increasing population. For all hybrid types examined, harvest index dropped off sharply at the highest plant populations. This work supports a quadratic response, but also provides a basis for observed variability in harvest index studies conducted with a wide array of hybrids. Similar hybrid X density X per plant harvest index interactions were reported by Echarte and Andrade (2003) though an evaluation of Argentine hybrids varying in time of introduction.

It has been shown that the physiological components of yield differ greatly in contribution to adjustments in yield. Tollenaar (1992a) partitioned out dry matter accumulation and showed that every 10 g (0.35 oz) reduction in dry matter resulted in an 8.1% decrease in kernels plant^{-1}, 4.6% decrease in ears plant^{-1}, and a 1.6% decrease in kernel weight.

Kernel number has been shown to be the leading contributor to variation in grain yields. Staggenborg et al. (1999) reported that 85% of yield variability was accounted for by differences in kernel number per unit area in two plant population trials located in northeast Kansas. In a three year study, Norwood (2001a) reported in southwest Kansas that kernels ear^{-1} accounted for 58 to 64% of the variability in grain yields across a study involving 5 hybrids and 3 population treatments. Tollenaar (1992b) reported that kernel number contributed 86.6% to the decline in per plant grain yields as population increased from 0.5 to 24 plants m-2 (2- to 97 000 plants ac^{-1}). Tollenaar (1992a) showed kernels plant^{-1} decreased from 718 to 231 as plant population increased from 2 plants m^{-2} (8 100 plants ac^{-1}) to 13 plants m^{-2} (52 600 plants ac^{-1}) and explained the most variability for grain yields among hybrids and plant populations. Cox (1996) also reported negative linear relationships for kernels plant^{-1} with increasing plant population, across a two year study involving plant densities ranging from 4.5 to 9 plants m^{-2} (18- to 36 400 plants ac^{-1}). Hashemi-Dezfouli and Herbert (1992) reported a kernel row^{-1} decline of 43.5 to 23.9 as plant population increased from 3 to 12 plants m^{-2} (12- to 48 600 plants ac^{-1}). The decline was more dramatic in a shaded treatment, a decline of 38.4 to 8.7 kernels row^{-1}.

This was attributed to a reduction in photosynthetic capacity, induced in this study by artificial shading, but also representative of stress conditions. Tetio-Kagho and Gardner (1988b) reported the importance of kernel number in explaining yield variability, and further quantified kernel number into separate components. For a prolific type hybrid they concluded that yield was adjusted in the order of: kernel number per ear and kernel number per ear row, ear number per plant, kernel row number per ear, and kernel weight which remains relatively stable. Their data supported kernel number per ear or kernel number per ear row as being the most vulnerable yield component to assimilate competition. Hashemi et al. (2005) also reported that kernels row^{-1} was the most sensitive component as plant density increased from 3 to 12 plants m^{-2} (12- to 48 600 plants ac^{-1}) for three hybrids all considered single-ear and late maturity. Further adjustment in grain yield came from ears plant^{-1}, kernel weight, and kernel row number ear^{-1}, listed in order of importance.

Ears plant^{-1} contributes significantly less to variability in grain yields. Norwood (2001a) reported that ears per unit area accounted for 26 to 34% of the yield variability in a 3 year study involving multiple hybrids and populations. Though this yield component is a less significant contributor to yield variability, it is important to recognize its responsiveness to changes in plant density. In one year of the Norwood (2001a) study, ears ha^{-1} explained 65% of the variability, attributable to significant drought and heat stress at the V5 stage which is critical to ear formation (Ritchie et al., 1997). When ears ha^{-1} or ears plant^{-1} is limited by drought stresses the potential sink for grain fill is limited, thus negating any impacts of kernels ear^{-1} or kernel weight on yield adjustment if environmental conditions improve. Cox (1996) over a two year study found the effect of population on ears plant^{-1} to be highly significant as a negative quadratic in one year and insignificant the next. However, the numerical trend of decreasing ears plant^{-1} with increasing population remained constant. When ears plant^{-1} was statistically significant it was observed in the form of an ears plant^{-1} X hybrid interaction, with single ear hybrids showing a less dramatic decrease than prolific types. Norwood (2001a) showed a significant ears ha^{-1} X hybrid interaction for a drought stressed year. This was likely due to stress timing, as the decline increased with increasing hybrid maturity ratings. The longest season hybrid, 110 day, exhibited barrenness of approximately 40% at the highest population in the study, 6 plants m^{-2} (24 300 plants ac^{-1}). Tollenaar (1992a) showed ears plant^{-1} for the newest hybrid in the study decreasing from 2.05 to 0.94 as plant population increased from 2 plants m^{-2} (8 100 plants ac^{-1}) to 13 plants m^{-2} (52 600 plants ac^{-1}), indicating attributes of prolificacy and resistance to barrenness. Tetio-Kagho and Gardner (1988), while utilizing a fan design layout and a prolific hybrid, found that over a range of 0.8 through 15.4 plants m^{-2} (3- to 62 300 plants ac^{-1}) all plants produced 1 ear, with plants producing 2 and 3 ears up until populations of 4.3 and 2.8 plants m^{-2} (17 400 and 11 300 plants ac^{-1}) respectively. Hashemi-Dezfouli and Herbert (1992) reported decreases in ears plant^{-1} as population density increased from 3 to 12 plants m^{-2} (12- to 48 600 plants ac^{-1}). For plants in ambient light conditions, ears plant^{-1} declined from 1.0 to 0.85. A much higher decline was observed in plants subjected to an artificial shading treatment, 1.0 to 0.49 ears plant^{-1}.

Kernel weight has often been statistically significant in population studies; however its relative importance in grain yield adjustment is minor. Norwood (2001a) showed that kernel weight accounted for only 4 to 9% of the variability in grain yields in a population response study. Cox (1996) reported a negative linear relationships for kernel weight with increasing plant population, across both years. In some specific year x hybrid situations (typically involving a single eared hybrid) kernel weight showed a negative quadratic response. Tollenaar (1992a and 1992b) and Hashemi et al. (2005) observed that kernel weight declined with increasing plant population, but was of comparatively minor importance. Hashemi et al. (2005) speculated that adjustments in kernel number row^{-1} compensated for reduced assimilate reduction in high densities, thus allowing remaining kernels to grow at higher rates. This would result in kernel weight being of minor importance in yield adjustment.

Genotype X Population Interaction –

Age of Introduction, Prolificacy, and Flex

Although the physiological impacts of increasing plant density are generally applicable to all corn hybrids, a plant density by genotype interaction has been reported numerous times in the literature, and attributed to various sources. Some work has identified hybrid X population interactions that can be attributed to leaf structure (Hicks and Stucker, 1972). Several researchers have identified hybrid X population interactions that are representative of genetic progress in breeding over time. Tollenaar (1989) found highly significant population density X hybrid interactions for grain yield, LAI, and harvest index when nine hybrids introduced from 1959 through 1988 were planted at densities ranging from 2 to 13 plants m^{-2} (8- to 52 600 plants ac^{-1}). The interactions were attributed primarily to increased dry matter accumulation, made possible by increases in LAI and harvest index among the newer hybrids. These comparisons were made at each hybrids optimal population.

Changes in population response induced by genetic advancement through breeding are to be expected. Differences in response among hybrids common in time of introduction and environment are less simplistic. Sarlangue et al. (2007) showed optimal populations for three hybrids across two years ranged from 10 to 14.8 plants m^{-2} (40 500 to 60 000 plants ac^{-1}). They showed that hybrids differ in biomass plasticity, or how dynamic the reduction in per plant biomass is with respect to increasing plant population. The other component evaluated was reproductive partitioning, the ability of the plant to increase per plant grain yield with increasing per plant biomass.

As was mentioned in many studies, the largest source of hybrid X population interactions appears to be rooted in prolificacy, the ability of the plant to adjust ears $plant^{-1}$, and flex, the ability of the plant to adjust kernels ear^{-1}. These two methods of yield component self-adjustment by the plant are used to adjust assimilate sink size in response to the environmental impacts on assimilate availability. Differences in prolificacy and flex can result in starkly different yield responses to plant population among hybrids.

Prior and Russell (1975) evaluated 28 hybrids of varying classifications of prolificacy across a range of densities from 2.1 to 7.2 plants m^{-2} (8- to 29 200 plants ac^{-1}). They reported a narrower range in optimum density for elite, non-prolific hybrids than for prolific types. In environments with an average yield of approximately 6,300 kg ha^{-1} (100 bu ac^{-1}) both hybrid types responded in a quadratic manner with relatively similar optimal populations. However, in environments with an average yield of approximately 4,400 kg ha^{-1} (70 bu ac^{-1}) the prolific types exhibited a rather linear negative response with the optimal population being the lowest in the study. The elite, non-prolific hybrids continued to exhibit a quadratic response to population with the optimal approximately 1.2 plant m^{-2} (4 900 plants ac^{-1}) lower than that observed in the high yielding environments. However, the prolific type had a higher yield at its optimal population, the lowest in the study at 2.1 plants m^{-2} (8 300 plants ac^{-1}), than the non-prolific type at its optimal, approximately 4.6 plants m^{-2} (18 600 plants ac^{-1}). They stated that prolific hybrids could be beneficial in two environments; in high densities where resistance to barrenness is desired, and in marginal environments where low plant densities are required, but variability in yield potential requires selection of hybrids equally variable in yield potential. Barnes and Woolley (1969) reported that more prolific hybrids were more tolerant to moisture stress at pollination and blister kernel stages than single-eared types. It was also observed that the prolific variety extracted 1-2% more soil water when under stress. Utilizing newer genetics, Cox (1996) reported a linear response of grain yield to plant density for prolific hybrids and a quadratic response for non-prolific hybrids. In a drought stressed year of the study, a single-eared hybrid in the experiment showed no grain yield response to population, exhibited a comparatively low CO^2 exchange rate at all densities, a reduction in kernels per plant at a medium density, and increased barrenness at the highest density. Durieux et al. (1993) reported that prolific hybrids had greater yield potential than non-prolific types with increasing levels of nitrogen availability. One could speculate that the same would hold true for increasing levels of growing season water supply. Thomison and Jordan (1995) evaluated a prolific, semi-prolific, single-eared flex, and single-eared fixed hybrid at 5 locations across Ohio. Plant population treatments were 4, 6, and 8 plants m^{-2} (16-, 24-, and 32 000 plants ac^{-1}). They reported that the flex or prolific hybrid was the top yielder and the fixed hybrid was the lowest across locations and years. The optimal population for the prolific in an average year was 6 plants m^{-2} (24 000 plants ac^{-1}), all others were optimal at the highest density in the study. However, in a drought year the optimal population was 6 plants m^{-2} (24 000 plants ac^{-1}) for all hybrids. Location X population X hybrid interactions were common and attributed to differences in hybrid response to population as affected by soil moisture availability and temperature. Their study further confirmed earlier work (Lang et al., 1956) stating that prolific hybrids are adapted to a wider variety of environments, with greater ear prolificacy at low populations and resistance to barrenness at high plant populations.

The physiological aspect of prolificacy is not well understood. Prior and Russell (1975) stated that two types of prolificacy may exist; that which is sustained by upper leaf photosynthates to maximize production in high plant densities, and prolificacy sustained by lower leaf photosynthates thus resulting in production maximization in low plant densities.

Impact of Water Stress on Corn

It is well known that yield components of corn vary widely in sensitivity to water stress timing and duration. Most work has focused on water stress around silking, anthesis, and grain filling periods. Grant et al. (1989) evaluated seven stress intervals against a well watered control in a greenhouse study. The plants were well watered until the beginning of each treatment at which water was withheld until the well watered control treatment had used approximately two times the plant available water holding capacity. The pots were weighted every day and stress was considered to begin when the water use rate began to decline. The seven stress periods covered a span of 3 d prior to

37 d after the mean silking date. Two treatments, stress imposed from 3 d prior to 2 d post silking, and from 34 d through 37 d post silking, did not produce grain yields different than the control. Treatments that imposed stress from 1 d prior to 31 d post silking all reduced grain yields. The most drastic decline, 37% less compared with the control, was observed when stress was applied 1 d prior to 7 d after the mean silking date. The yield component most responsible for this decline was kernel number, which was reduced by 45% compared with the control. Kernel number then increased as the initiation of stress was moved further past silking. When stress was applied more than 22 d after silking kernel number was no different than the control. Kernel weight was reduced as the period of stress was placed further post silking. Kernel weight for stress starting 1 d prior and 22 d after silking was 80 and 51% of the control, respectively. These results reaffirmed that kernel number is very sensitive to water stress at silking and the sensitivity declines to 22 days after silking. Kernel weight was susceptible to water stress beginning at silking and increased in sensitivity as time progressed further into the grain filling period, up to 31 days post silking. These findings were in agreement with work conducted by Claassen and Shaw (1970b). They reported mean yield losses of 30 to 33% for three stress treatment periods applied over a 12 d post-silking period. A four day treatment period closest to the silking stage reduced yields 53%, while another stress treatment occurring at the end of silking (approximately 97% complete) reduced yield 29%. These yield adjustments were largely influenced by changes in kernel number. As the time of stress moved further past silking, its impact on kernel number decreased while the impact on kernel weight increased. The distribution of developed and partially

developed kernels per ear changed drastically as stress timing varied, with decreasing kernel weight being correlated to an increasing number of partially developed kernels.

These studies are in agreement with early work done on the topic. Robins and Domingo (1953) reported grain yield reductions of 22 and 50% with stress periods at pollination of 1 to 2 and 6 to 8 d, respectively. Work by Denmead and Shaw (1960) concluded that stress at silking was more harmful to grain yield than stress at any single growth stage. They reported yield reductions of 25, 50, and 21% for the vegetative, silking, and ear stages, respectively. Their results showed that the yield loss from stress in the vegetative stage was a direct result of reduced leaf area, while the yield loss from stress at silking resulted both from reduced leaf area and a critical timing interaction with reduced assimilate production. This conclusion was later supported by Swank et al. (1982) and Simmons and Jones (1985) who showed that less than 10% of grain yield is attributable to assimilates produced prior to silking.

Stress has been shown to impact dry matter partitioning. A reduction in assimilate sink capacity induced by reduced kernel number must result in changes to dry matter partitioning as assimilate continues to be produced. Non-grain biomass serves as a sink for assimilate as observed by Grant et al. (1989) and Claassen and Shaw (1970a). In these studies, stress applied at silking not only reduced kernel number but increased non-grain components of above ground biomass.

Discussion in stress research regarding non-receptive silks and non-viable pollen prompted further study. Herrero and Johnson (1981) focused on the reproductive system of corn across three water stress levels. The plants were kept in a well watered condition until tassel emergence at which watering regimes were instituted to maintain ear leaf water potential at -7 to -11 bars, -11 to -16 bars, and -16 to -18 bars for the three respective treatments. They concluded that water stress had much more of an impact on silk elongation and the subsequent timing of pollen shed and silk emergence than it did on pollen viability. A greater share of silk elongation occurred during the night hours for the drought stressed plant, as water potentials within the plant recovered. In their experiment water stress increased the time between the beginning of pollen shed and initial silking. Under the most severe stress treatment, silking was delayed until most all of the pollen had shed, thus resulting in barren and poorly filled ears and reducing the kernels per plant yield component.

While most work has focused on the effects of stress at silking, tassel, and grain fill, the impacts prior to tassel and silk have been evaluated as well. Claassen and Shaw (1970a) showed that stresses incurred 3 weeks before 75% silking resulted in dry matter reductions of 15 to 17% when compared with the control. Nesmith and Ritchie (1992) evaluated the impact of a pre-anthesis soil water deficit on plant growth and yield. Two treatments were evaluated, a control where PAW was kept at 80% or above, and pre-anthesis deficit, where at the emergence of the 9th leaf, water was withheld to within one week prior to tasseling of the control treatment. Both treatments were planted at a population of 7.9 plants m^{-2} (31 900 plants ac^{-1}). They found that leaf extension, measured relative to the well watered control, began to decline linearly at 85% of PAW and approached zero at 25% PAW. It was noted that the stress treatment did not affect the timing of leaf appearance, but did affect the rate of leaf area accumulation. A noticeable delay of 2 to 4 days was present in tassel emergence, silk emergence, and the beginning of the linear portion of grain fill. Grain yields were reduced 15 to 25% for the pre-anthesis deficit treatment when compared with the well watered control. The yield component most responsible for adjustment was kernel weight one year, and kernel number the next year. However, in further discussion the authors point out that kernel weight is often obtained by selecting a large number of seeds and calculating an average, thus assuming an equal distribution of seed size among treatments. Data presented in this study showed that the distribution of size among kernels varied by stress treatment, with grain from the pre-anthesis deficit treatment having a higher proportion of kernels below 150 mg (0.005 oz). Similar changes in kernel size distribution were observed by Claassen and Shaw (1970b), who graded kernels into three classes based on physical dimensions and performed kernel weight analysis by class. Nesmith and Ritchie (1992) further emphasized that the inclusion of all kernels when calculating kernel weight may lead to bias in the results, and thus stated that the leading component of yield adjustment was the number of well-developed kernels. This work showed that grain numbers are a sensitive yield component to water deficits occurring a week or more prior to anthesis.

Growing Season Water Supply and Optimal Corn Population

The aforementioned physiological impacts of increasing plant density; increases in light interception, crop growth rate, and dry matter accumulation; would naturally imply increased crop water use. Fulton (1970) showed that in Ontario, a plant population of 5.9 plants m^{-2} (23 900 plants ac^{-1}) resulted in 25 mm (1 in) more cumulative water use than a population of 3.9 plants m^{-2} (15 700 plants ac^{-1}). Yao and Shaw (1964) showed that increasing plant population from 3.5 to 6.9 plants m^{-2} (14- to 28 000 plants ac^{-1}) also increased rates of evapotranspiration measured from late May – early June through mid to late September. Timmons et al. (1966) reported that in years with adequate soil water, evapotranspiration was unaffected by plant populations ranging from 1.5 to 5.9 plants m^{-2} (6- to 24 000 plants ac^{-1}). However, in a site-year with dry conditions, evapotranspiration increased with population in a curvilinear manner from 1.5 up to 3.5 plants m^{-2} (6- to 14 000 plants ac^{-1}). This was observed over the time period encompassing plant growth from a height of 0.3 m (1 ft) tall up through tasseling. Chi-square analysis for site-years in the study indicated a consistent trend for increasing evapotranspiration with increasing plant density. In water limiting environments where stored soil moisture must be relied upon and rationed for successful grain production, this early consumption of water by denser plant stands may result in water stress later in the growing season. Alessi and Power (1976) found that increasing population from 2 to 7.4 plants m^{-2} (8- to 30 000 plants ac^{-1}) in the northern Great Plains increased water use during vegetative growth. This resulted in consistently lower available soil water at silking for higher plant populations.

In more recent studies, Cox (1996) showed a significantly lower soil water tension of -40 kPa at a density of 4.5 plants m^{-2} density (18 200 plants ac^{-1}) as compared to -56 kPa at 6.75 plants m^{-2} (27 300 plants ac^{-1}) and -58 kPa at 9.0 plants m^{-2} (36 400 plants ac^{-1}) when measured at the V11 growth stage. Norwood (2001b) reported that for dryland corn in southwest Kansas, water use generally increased with increasing plant population over a range of 3 to 6 plants m^{-2} (12- to 24 300 plants ac^{-1}). Soil water contents at harvest significantly differed by population for almost all depths across the four year study. Interactions with planting date and hybrid maturity were also observed.

In areas were in-season precipitation is insufficient to produce a crop; soil water in storage must be relied upon to meet the crop water needs for grain production. The importance of soil water was emphasized by Carlson (1990). Available soil water and heat stress were identified as the two most important weather-related variables. Holt et al. (1964) conducted studies at 9 locations across western Minnesota and eastern South Dakota from 1957-1962. This provided 75 site-years of available soil water at planting (ASW_p) data from which a distribution was devised. In three years of the study, corn grain yield was related to ASW_p in two of the years with R^2 values of 0.55 and 0.69. The non-related year ($R^2 = 0.09$) was attributed to above average precipitation during critical growth stages. Multiple regression was used to analyze ASW_p and precipitation data summarized by time intervals. The resulting models explained 64% of the yield variability encountered over a 4 year period. Benoit et al. (1965) used soil water content and temperature to predict dry matter accumulation at the time of ear formation. Alessi and Power (1965) evaluated the impact of moisture availability on dryland corn in Montana and North Dakota. Two available soil water conditions were imposed with pre-plant irrigation at the North Dakota location to provide additional variability in soil water conditions. Over the 6 year study, growing season water supply, the sum of available soil water and effective precipitation, explained 71% of yield variability. The sole use of available soil water at planting (ASW_p) explained 67.3% of the observed yield variability.

Leeper et al. (1974a) utilized four fields in Illinois, over 3 years, having spatial variability in soil depth, an estimated range of 30 to 120 cm (11.8 to 47.2 in). These changes in soil depth directly impacted water-holding capacity as well. Within each field, six different locations were selected to obtain a range of soil depths. At each location grain yields were measured with four replications. Plant available stored soil moisture was measured gravimetrically throughout the summer. Regression analysis was used to produce yield response curves for each field in relation to soil depth, water holding capacity, and available soil moisture through the summer. When used in a linear regression soil depth and water holding capacity explained 73 and 71% of yield variability, respectively. The more intense dataset, plant available stored soil moisture, only explained 55% of the yield variability. This was surprising as soil depth and water holding capacity only indicate the capacity of the soil, while plant available stored soil moisture is the amount actually available in the profile, and the weekly sampling involved allows inclusion of the seasonal stress pattern. Leeper et al. (1974b) combined the data to develop relationships that would be robust across variable climatic conditions. They accomplished this by combining the data from the previous analysis with rainfall and temperature data for each field. They found that in explaining yield variability, either the use of rooting depth (R^2=0.83) or available soil water at planting (R^2=0.81) resulted in a slightly better model than the use of weekly plant available stored soil moisture data (R^2=0.80). Models of this nature would be of immense value provided they prove robust through a variety of conditions.

It is intuitive that the optimal plant population would vary with both growing season water supply, and one of its components, ASW_p. Prior and Russel (1975) reported a lower optimal plant density at locations with stress and limited soil moisture.

Holt and Timmons (1968) identified this response in data collected at multiple locations in Minnesota and South Dakota. Plant populations in the study ranged from 1.98 to 5.93 plants m^{-2} (8- to 24 000 plants ac^{-1}). Available soil water measurements were taken when corn was approximately 30 cm tall (11.8 in). When soil water, plant density, and precipitation data for site-years with a yield response to population were used in multiple regression corn yield could be predicted with an $R^2 = 0.91$. Use of data from locations with no response to population, and all locations combined produced R^2 values of 0.78 and 0.71 respectively. The relatively high R^2 value for locations with no population response indicates that available soil water and in-season precipitation were primary factors. The authors showed that the yield responses to population changed in relation to growing season water supply. However, the response curves remained relatively flat such that only small decreases in estimated yields occurred with density changes of 0.5 plants m^{-2} (2 000 plants ac^{-1}).

The impact of growing season water supply on optimal plant populations has been observed in more recent work as well. Karlen and Camp (1985) observed different yield responses over two plant densities and three irrigation regimes. Polito and Voss (1991) stated that for their study, observed differences in population response can be attributed to a variety of factors, moisture availability being one of importance. Thomison and Jordan, (1995) found that differences in soil water availability influenced response to plant population across multiple locations for hybrids differing in ear type. It is evident however, that additional research is needed to evaluate the impacts of growing season water supply on modern hybrids.

Objective

Seeding corn at populations above the optimal increases the risk of encountering stress at critical growth stages and suffering yield reductions, while seeding at rates below the optimum increases the risk of not attaining the maximum yield potential for a given environment. Previous work has shown that the optimal plant population for corn is determined in part by growing season water supply. Growing season water supply has multiple sources of variation including those man-made such as residue management on evaporative losses, previous crop selection, and irrigation. Naturally occurring variability in soil texture, soil depth, and topography also impacts plant available water. Current corn population recommendations by K-State and others throughout the Great Plains are rather broad in nature and incorporate many generalizations. These recommendations are certainly appropriate for use at the regional scale. However, they were never intended for use at smaller spatial scales such as at the field or sub-field level. New technologies have provided opportunities in improving residue management, identification of spatial variability in plant available water with greater detail, and equipment capable of varying seeding rates spatially. With increasing input cost and declining technology cost, the economic implications of properly allocating resources continue to grow in importance.

The objective of this research was to identify causal factors of variability in growing season water supply for cropping systems in the Great Plains and develop appropriate plant population recommendations for corn with respect to spatial variability at both the field scale and sub-field scale through the use of site-specific management technologies.

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CHAPTER 2 - Accumulation of snow in stripper and conventionally harvested wheat residue – Field observation and potential impacts for the Central Great Plains

Abstract

Water is the most limiting factor in Great Plains crop production. Snowfall accounts for approximately 10-30% of the annual precipitation received throughout the central Great Plains region. Improvements in snow capture for stored soil water at planting could increase and/or stabilize crop yields, and may provide opportunities for further system intensification. This study was conducted to determine the impacts of wheat (*Triticum aestivum* L.) stubble height on snow catch and subsequent crops. Treatments consisted of unaltered stripper harvest with height of approximately 71 cm (28 in.), cut height of 25 cm (10 in.), and cut height of 10 cm (4 in.) Following a winter storm event, four subsample snow depth measurements were taken within each plot. Measured snow depths were significantly different among treatments ($p<0.0001$) with equivalent precipitation of 5.77 (2.27), 3.25 (1.28), and 1.73 cm (0.68 in.) for the stripped, 25 cm, and 10 cm heights respectively. Using an established yield-water production function, estimated grain sorghum [*Sorghum bicolor* (L.) Moench] production from captured snowmelt ranged from 1002 kg ha^{-1} (15.9 bu ac^{-1}) for the stripped stubble to 300 kg ha^{-1} (4.8 bu ac^{-1}) for the 10 cm cut height. Estimated probability of achieving a specified yield goal in stripped stubble was improved by 26% compared to 10 cm stubble and 16.6% over 25 cm stubble. Stubble height impacted snow catch available for soil water storage, thus providing opportunities for increases in grain yield, temporal yield stability, and economic returns.

Introduction

Water is the most limiting factor in Great Plains crop production. The high ratio of potential evapo-transpiration to precipitation has long influenced cropping systems and yield potentials throughout the Great Plains. Historically, the limited amounts of precipitation and its erratic patterns led to the implementation of the crop-fallow system to help stabilize crop yields. Advances in cropland productivity throughout the region have come largely through improving the precipitation use efficiency (PUE) of cropping systems and the precipitation storage efficiency (PSE) during these fallow periods. The success of a traditional wheat-fallow or more intense rotations requires the use of stored soil water by the plant, as not enough precipitation falls during the growing season to sustain any of the major crops grown throughout the region, thus PSE and PUE are of utmost importance. Precipitation storage efficiency has been improved through reducing tillage intensity and thus increasing surface residues; which decreases evaporative losses, improves infiltration, and reduces runoff (Nielsen et al., 2005). Precipitation use efficiency has been improved by replacing a summer fallow period with a summer crop, typically corn (*Zea mays* L.), grain sorghum, or proso millet (*Panicum miliaceum* L.), thus creating a wheat-summer annual-fallow rotation. The addition of a summer annual(s) improves PUE (Nielsen et al., 2005, Peterson et al., 1996) by utilizing water for transpiration that would have been lost to evaporation during the fallow period. Intensified rotations provide greater net returns while reducing economic risk (Dhuyvetter et al., 1996). Work by Schlegel et al. (2002) looked at further intensification by utilizing a wheat-wheat-sorghum-fallow or wheat-sorghum-sorghum-fallow rotation and found that potential existed to further improve economic returns over a single summer crop rotation. Such a cropping system would benefit from further improvements in PSE.

Opportunities through Snow Catch:

Within the central Great Plains, snowfall accounts for approximately 10-30% of the annual precipitation with depths ranging from 38 cm (15 in.) in portions of southwest Kansas to well above 102 cm (40 in.) in areas of eastern Wyoming and the Nebraska panhandle. Approximately 73% of snowfall precipitation occurs while soil is in a non-frozen state (Greb, 1980), thus minimizing precipitation losses to runoff. Although snowfall is a relatively small proportion of annual precipitation, the value of captured snowfall to crop production is estimated as 89% of stored soil water (Greb, 1979). The relative value of captured snowmelt, cool season rainfall, and warm season rainfall compared to stored soil water was estimated as 57, 25, and 22% respectively when evaporative losses were included (Greb 1979). From a summer crop production standpoint, the impact of captured snowmelt on plant available water is greater than summer precipitation due to the lower intensity of precipitation events, reduced evaporative losses from the soil surface, and little or no transpiration losses through weeds. Greb (1980) reported that the USDA-ARS station at Akron, CO typically experiences one blizzard and four strong drifting storms annually. These storm occurrences are typical across the central Great Plains region and provide opportunities for snow catch and soil water recharge through residue management.

Residue Effects on Snow Catch

Crop residue management has been observed to affect snow catch and resulting soil water storage. Work conducted as early as 1914 at the Colby, KS Branch Experiment Station showed improved over-winter soil water storage in undisturbed standing wheat stubble compared with plots that were listed or plowed in the fall (Kuska and Mathews, 1956). An adjoining 18 year study found overwinter gains in soil water of 3.86 (1.52), 2.72 (1.07), and 7.95 cm (3.13 in.) for corn stubble, fall-plowed wheat stubble, and standing wheat stubble respectively, with an average precipitation of 13.84 cm (5.45 in.). Studies involving wheat residue throughout the central Great Plains region are summarized in Table 2.1 and indicate an average overwinter PSE of 83.6%.

Table 2.1 - Reported values for overwinter precipitation storage efficiency, PSE, in wheat stubble throughout the west-central Great Plains

Location	Wheat Residue	Years	PSE %	Reference
Colby, KS	Undisturbed	25	78.5	Kuska and Mathews, 1956
	Undisturbed	4	77.0	
North Platte, NE	Undisturbed	4	98.9	Smika and Whitfield, 1966
	Incorporated		-15.4	
Akron, CO	Undisturbed	11	80	Smika et al., 1986
	Stubble-mulch		57	

Standing residue increases surface roughness and drag, thus increasing the total shear stress necessary to move a particle and reducing wind speeds immediately above the residue (Tabler and Schmidt, 1986). Increasing residue height also increases boundary layer height, providing more capacity for the deposition of snow and increasing resistance against blowing and drifting of snow. Lyles and Allison (1976) determined that the critical friction-velocity ratio (CFVR), a measure of protection from wind erosion, for 30 cm (11.8 in.) stubble was more than double that of 15 cm (5.9 in.) stubble. Aase and Siddoway (1980) confirmed that increasing stubble height reduced wind velocity and increased friction velocity. These attributes make it possible for additional snow capture with taller residues. The importance of capturing snow during initial deposition is imperative as Tabler and Schmidt (1986) estimated that in Wyoming over half of a winter's drifting snow is lost to evaporation when transported a distance of 3 km (1.9 mi.) and 22% at a distance of 1 km (3281 ft.).

Various impacts of stubble height have been evaluated in the northern Great Plains (Table 2.2). Experiments have generally shown that snow catch and change in soil water increases with stubble height.

Table 2.2 - Reported snow depth measurements, soil water change, and PSE for various heights of wheat stubble

Location	Stubble Height	Snow Depth	Change in Soil Water	PSE %	Reference
	cm (in.)				
Mandan, ND	5 (2)	-	5.3 (2.1)	50	Bauer and Tanaka, 1986
	20-25 (8-10)	-	6.7 (2.6)	70	
	33-38 (13-15)	-	8.0 (3.1)	93	
Saskatoon, SK	30.3 (11.9)	20.8 (8.2)	-	-	Nicholaichuk et al., 1986
	47.9 (18.9)	27 (10.6)	-	-	
Sidney, MT†	0	6 (2.4)	1.3 (0.5)	-	Black and Siddoway, 1977
	15 (5.9)	12 (4.7)	2.6 (1.0)	-	
	28 (11)	20 (7.9)	4.3 (1.7)	-	
	38 (15)	26 (10.2)	5.6 (2.2)	-	
Sidney, MT	0	9 (3.5)	-	-	Aase and Siddoway, 1980
	15-19 (5.9-7.5)	17 (6.7)	-	-	
	30-35 (11.8-13.8)	34 (13.4)	-	-	
Swift Current, SK	15-20 (6-8)	18 (7)	13 (5.1)	34	Campbell et al., 1992
	40-60 (16-24)	28 (11)	31 (12.2)	50	

† Changes in soil water were not measured in the Sidney, MT study. Values presented are precipitation value of snow accumulation.

Bauer and Tanaka (1986) found at Mandan, ND in 3 of the 14 comparisons, the overwinter change in soil water was greater than the precipitation received, indicating capture of blowing snow, although this could not be confirmed as snow depth measurements were not recorded. Campbell et al. (1992) utilized a deflector on a modified windrower to obtain strips of taller stubble spaced every 6 m (19.7 ft.). Stubble in the areas between strips was representative of typical harvest. Differences in soil water were only significant in 3 of 10 years. The low PSE and soil water increases were attributed to frozen soil conditions and soil profiles with little remaining storage capacity.

Attempts have been made to imitate taller residue to improve snow catch. Barrier strips of wheat grass (*Agropyron elongatum*) have been used in both the northern (Black and Siddoway, 1976) and central Great Plains (Greb 1979). These living snow fences were effective at increasing snow catch and subsequent grain yield but require maintenance and negatively impact machinery efficiency. The impact of residue height has been observed in corn (Sharratt, 2002) and sunflower (*Helianthus annuus* L.) residue (Nielsen, 1998). In both cases, increasing residue height improved snow catch. Nielsen (1998) also noted that differences in snow catch among stalk heights increased as the average wind speed during the snow event increased.

Stripper Headers and Stubble Properties

Stripper headers reduce harvest cost by increasing machine field capacity (Haag et al., 2004) while maintaining acceptable harvest losses (Wilkins et al., 1994). These operational advantages and perceptions regarding improved soil moisture storage have resulted in increased adoption of stripper headers. The use of stripper headers in harvesting small grains creates unique residue properties following harvest.

Smika (1983) examined wheat stubble 61 cm (24 in.) in height and showed that a wind velocity of over 6 m s^{-1} (13.4 mph) was required before wind could be detected at the soil surface compared to 2.4 m s^{-1} (5.4 mph) for stubble 30 cm (11.8 in.) in height. McMaster et al. (2000) found that when wind velocity was measured at heights below 1 m (39.4 in.) stripped stubble measuring 55 cm (21.7 in.) tall had a lower scaled wind velocity than conventionally harvested stubble 38 cm (15 in.) tall. The taller stubble provided compensation for sparse stands, those with < 280 stems m^{-2} (26 stems ft^{-2}), resulting in a wind profile similar to dense stands harvested with a conventional header. This would allow areas with lower levels of productivity (i.e. more arid regions of the central Great Plains) to receive similar conservation benefits as a result of stripper header use. They projected large reductions in relative friction velocity and potential evaporation with increasing stubble height. Displacement height for the stripped stubble was determined to be 29 cm (11.4 in.) compared to 23 cm (9 in.) and 19 cm (7.5 in.) for cut stubble.

Baumhardt et al. (2002) quantified the effects of two stubble heights, 59.4 cm (23.4 in.) stripped stubble and 39.4 cm (15.5 in.) cut stubble on wind profile, irradiant energy interception, and evaporation. They found that irradiant energy at the soil surface was reduced 12% by the stripped stubble and evaporation measured over a 4-day period was 26% less. They also found that the displacement height of the wind profile in taller stubble was 22.4 cm (8.8 in.) compared with 16.5 cm (6.5 in.) in the cut stubble. They demonstrated that the stripped stubble impacted wind velocity up through the highest point of measurement, 2 m (80 in.)

Little is known about the ability of contiguous areas of tall stubble, such as those resulting from stripper header harvest, to catch snowfall, even though the effect of stubble height on the wind profile and particle transport is recognized. The objectives of this research were to quantify the snow trapping potential of stripped wheat stubble and two heights of conventionally harvested wheat stubble following a winter storm event, and evaluate the potential impact of wheat stubble height on subsequent crop yield.

Materials and Methods

A production field of hard red winter wheat in Red Willow County, NE was selected for studies evaluating the impact of wheat stubble height on soil water dynamics and grain yields of subsequent corn crops. The site is located in southwest Nebraska (40°07’07” N, 100°17’28” W) at an elevation of 792 m (2598 ft.) above sea level. The experiment was located on a Holdrege-Keith soil association with approximately 60% Holdrege (fine-silty, mixed, superactive, mesic Typic Argiustolls) and 40% Keith silt loams (fine-silty, mixed, superactive, mesic Aridic Argiustolls) with 1 to 3 percent eroded slopes. Average climatic data (HPRCC, 2007a) for the area are 549 mm (21.6 in.) of annual precipitation, with 19.3% occurring Nov. through Mar., 10.8° C (51.4° F) mean annual temperature, and 1447 mm (57 in.) of open pan evaporation occurring in April through Oct. The cropping system at this site is entirely no-till with a winter wheat–corn–fallow rotation.

The field was seeded 28 September 2005 with a medium-short semi-dwarf variety of hard red winter wheat (‘Jagalene’, AgriPro Wheat Genetics, Berthoud, CO). Seeding was performed at a rate of 78 kg ha^{-1} (70 lb ac^{-1}) in 19 cm (7.5 in.) rows with a no-till drill (Model 9432, AGCO-Sunflower Mfg., Beloit, KS). The wheat was harvested 23 June 2006 with a commercial combine using a small grains stripper header (Model CVS32, Shelbourne-Reynolds Engineering, Colby, KS). The grain yield over the plot area averaged 3.6 Mg ha^{-1} (53 bu. ac^{-1}) as recorded by a properly calibrated yield monitor (Model YM2000, AgLeader Technologies, Ames, IA) equipped with a WAAS enabled GPS receiver (Model 18OEM, Garmin Intl., Olathe, KS).

Three stubble height treatments were assigned in a randomized complete block design with four replications. Treatments consisted of unaltered stripper harvest with stubble height of approximately 71 cm (28 in.), cut height of 25 cm (10 in.), and cut height of 10 cm (4 in.) A commercial combine equipped with a small grains platform was used to create the stubble height treatments on 21 July 2006. The operation was performed in such a manner to maximize travel in existing tire tracks and minimize the amount of stubble laid over. Plot dimensions were 15.2 x 15.2 m (50 x 50 ft.) Two alleys measuring 3.8 m (12.5 ft.) in width were placed lengthwise across blocks in-between plots. This allowed the cooperator to reach across all plots with a ground applicator for herbicide application during the fallow period. Areas of the field adjacent to the plot area were left in unaltered stripped stubble condition.

A significant snowfall event occurred across the High Plains region on 30-31 Dec. 2006 with snow depths up to 86.4 cm (34 in.) in some locations. Wind velocities during storm are characterized as maximum 9.1 m s^{-1} (20.4 mph), minimum 3.3 m s^{-1} (7.4 mph), average 5.9 m s^{-1} (13.2 mph), and SD 1.4 m s^{-1} (3.1 mph) as summarized from hourly weather data collected at McCook, NE (HPRCC, 2007b). Snowfall depth of 43.2 cm

(17 in.) was recorded approximately 4.8 km (3 mi.) from the experiment site. A core of snow 10.2 cm (4 in.) in diameter was removed and allowed to melt at a room temperature of 21° C (70° F). Precipitation was measured as 6.65 cm (2.62 in) or 15.4% of snow depth. The experiment site was unreachable due to blizzard conditions until 8 January 2007. During that time the average temperature at McCook, NE was -5.4° C (22.3° F), maximum daily temperature was 5.4° C (41.7° F), which occurred while snow depth measurements were being taken. The possibility for melting or sublimation due to soil and air temperature exists, however no efforts were made to quantify these losses. On 8 Jan. 2007, snow depth was measured at four locations within each plot. The four subsampling sites were randomly selected and generally represented quadrants of the plot. Care was taken to avoid selecting locations where combine tire tracks had altered the standing wheat stubble. Drifting effects from adjacent plots were minimal in length and were avoided for sampling purposes. Foot traffic was confined to existing tracks and alleys to minimize residue disturbance for future experiments. Snow depth measurements were also collected from the stubble that had been driven over within the alleys during herbicide application. Two measurements were taken from within the trafficked alley area between each set of plots. Multiple measurements of wheat straw diameter were taken within each plot, at the top of the straw, with a digital caliper. Wheat straw diameter was typically 3 mm (0.12 in.) regardless of stubble height. This is in agreement with the measurement presented by McMaster et al. (2000).

The data were analyzed as a randomized complete block design with subsampling. The statistical analysis was performed using the PROC GLM procedure in SAS 9.1.3. Means separation for treatments was performed using the LSD option within

PROC GLM. Yield predictions were performed using the yield-water relationship for grain sorghum developed by Stone and Schlegel (2006) and historical weather data for McCook, Nebraska (HPRCC, 2007b).

Results and Discussion

Snow Depth

Stubble height significantly effected snow depth (Table 2.3). Snow depths increased as stubble height increased (Table 2.4). Snow water equivalent was calculated for each stubble treatment using the obtained water content of 15.4%. The snow depths collected from within the trafficked alleys had a mean of 33.8 cm (13.3 in.) and standard deviation of 2.8 cm (1.1 in) (Data not shown).

Table 2.3 - ANOVA for snow depth in three stubble height treatments collected January 2007 in Red Willow County, NE.

Source	Df	P > F
Rep	3	0.4165
Stubble	2	<0.0001
Error	6	0.1205

Table 2.4 - Average snow depths and calculated equivalent precipitaiton for three stubble height treatments collected January 2007 in Red Willow County, NE.

Harvest Method	Stubble Height	Snow Depth	Water Equivalent
	------------------------- cm (in) -------------------------		
Stripped	71 (28)	37.4 (14.7) [a†]	5.8 (2.3)
Cut	25 (10)	21.1 (8.3) [b]	3.3 (1.3)
Cut	10 (4)	11.2 (4.4) [c]	1.7 (0.7)

† Means within a column followed by a different letter differ at $P < 0.01$.

The stripped treatment trapped an equivalent precipitation of 334% of the shortest stubble height, with the intermediate height retaining 189% of the shortest stubble height. It is likely that the cut stubble treatment plots were affected by the increased height of the boundary layer caused by both the stripped plots in the study as well as the surrounding field of stripped stubble. It is anticipated that had the plots been constructed of sufficient scale to provide adequate fetch, resulting differences in snow depth would have been more contrasting than reported. Tabler and Schmidt (1986) stated that reductions in wind velocity can be observed as far as 100 times height downstream, and the reduction in surface shear stress, as relevant to snow deposition, is between 10-30 times height depending upon porosity of the barrier.

Potential Impact on Available Soil Water, Crop Yield, and Dryland Crop Stability

The estimated changes in soil water, grain sorghum yield, and the probabilities of achieving a 5017 kg ha^{-1} (80 bu ac^{-1}) yield are presented in Table 5.

Table 2.5 - Estimates of change in available soil water at emergence, grain sorghum yield, and yield level probability for three stubble height treatments collected January 2007 in Red Willow County, NE.

Harvest Method	Stubble Height Treatment	Estimated Change in ASW_e	Estimated Grain Sorghum Yield Attributed to Change in ASW_e	Probability of ISP to achieve 5017 kg ha^{-1} (80 bu. ac^{-1}) yield goal
	------ cm (in) ------		-- kg ha^{-1} (bu ac^{-1}) --	
Stripped	71 (28)	4.8 (1.9)	1002 (15.9)	46.5%
Cut	25 (10)	2.7 (1.1)	565 (9.0)	29.9%
Cut	10 (4)	1.4 (0.6)	300 (4.8)	20.5%

The estimated change in available soil water at emergence (ASW_e) was calculated assuming an overwinter PSE of 83.6%, the average of reported values for standing no-till wheat stubble in the central Great Plains (Table 2.1). We assumed that no change in storage occurred for the two-month period between overwinter and crop emergence. In order to evaluate the potential impact on crop yield we chose to use a grain sorghum yield-water supply relationship developed in the central Great Plains region by Stone and Schlegel (2006). Their relationship (Equation 1) is based on 30 years of data from Tribune, KS where Y is grain yield (kg ha^{-1}), ASW_e is available soil water (cm) to a depth of 183 cm (6 ft), and ISP is precipitation received (cm) between 15 June – 14 Sept.

Equation 1 - Yield-Water Relationship for Grain Sorghum at Tribune, KS

$$Y = -1131 + 207.87 ASW_e + 2.715 ISP^2 \qquad [1]$$

Although a production function for corn was desired for evaluation, efforts in creating yield-water relationships for corn have proven difficult due to the extreme temporal variability inherent in central Great Plains dryland corn production.

Estimated grain sorghum yield attributed to snow catch was calculated using the estimated change in ASW_e. The partitioning of yield potential into the components of ASW_e and ISP allows yield probability prediction for a given ASW_e condition and rainfall distribution. Historical precipitation data for McCook, NE from 1909 – 2006 (HPRCC, 2007b) were summarized to obtain total precipitation for 15 June – 14 Sept. for each year. Figure 2.1 shows the probability of receiving ISP values from 0 to 40 cm (0-15.7 in.)

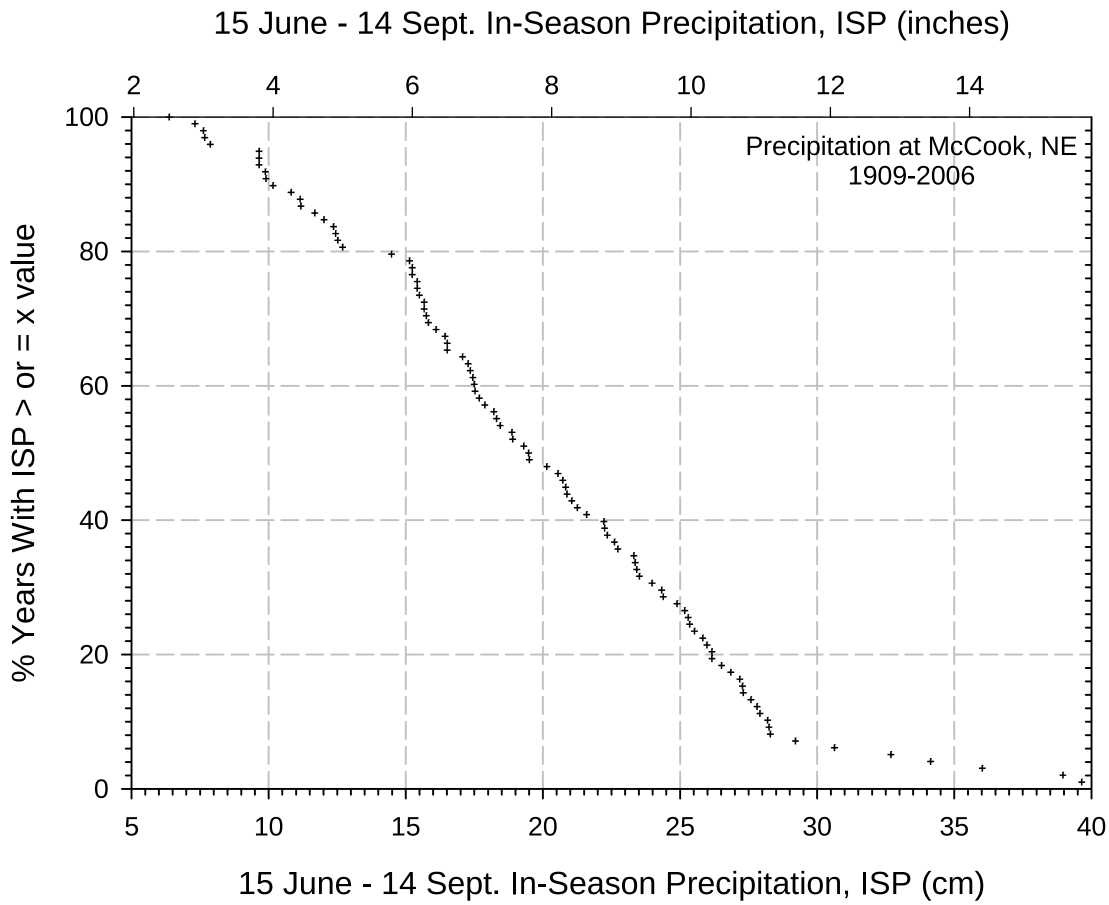

Figure 2.1 - Percent of years at McCook, NE (1909-2006) with ISP (15 June – 14 Sept.) > or = a selected ISP value.

As an example, we calculated the probability of achieving a 5017 kg ha^{-1} (80 bu ac^{-1}) yield with a base ASW_e of 19.2 cm (7.56 in.), 50% field capacity for a Holdrege-Keith silt loam with profile depth of 183 cm (6 ft). This value is essentially equal to 19.3 cm (7.6 in.), the mean value observed by Stone and Schlegel (2006). The estimated change in ASW_e due to snow catch was added for each treatment to obtain ASW_e for use in the production function (Figure 2.2).

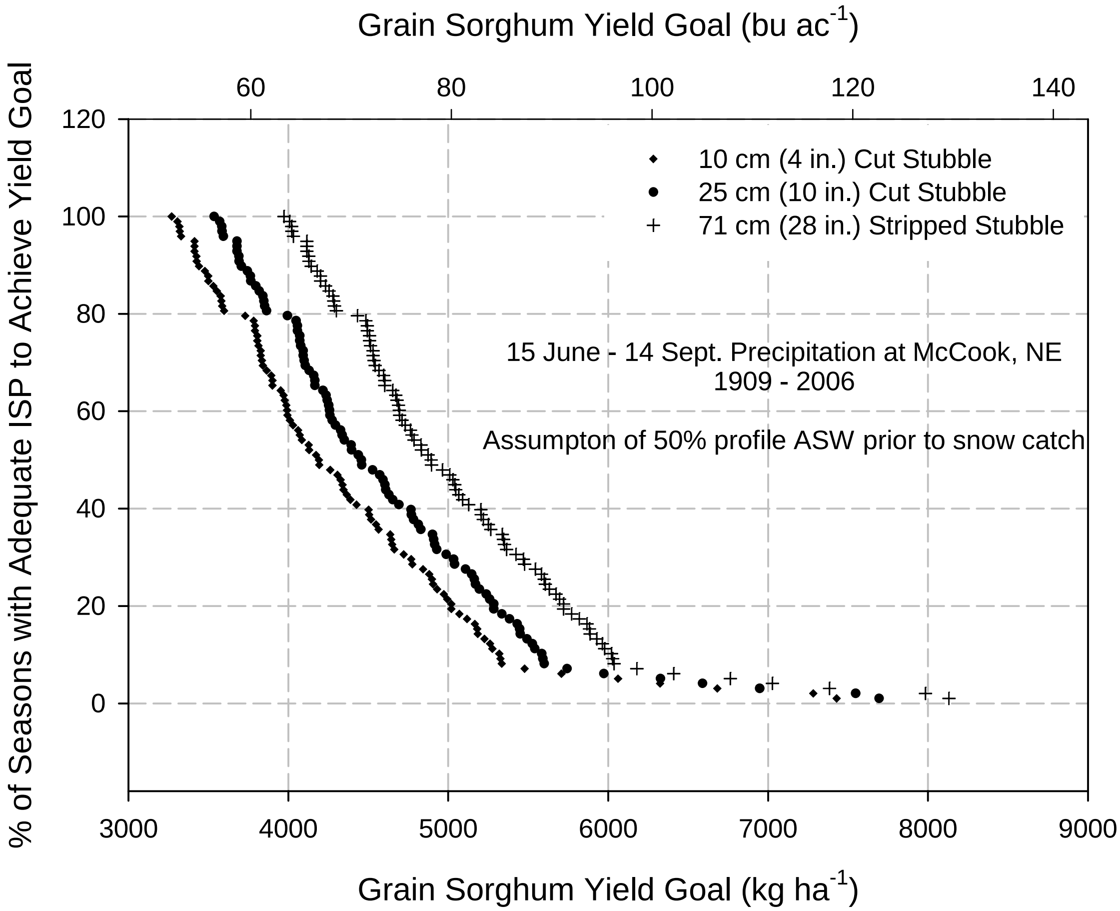

Figure 2.2 - Percent of seasons with adequate ISP to support a selected yield level and stubble treatment.

At the 5017 kg ha^{-1} (80 bu ac^{-1}) yield level, the moisture gained from snow catch in the stripped treatment improves the probability of receiving adequate ISP 28% over the 10 cm (4 in.) treatment and 17% over the 25 cm (10 in.) treatment. This is extremely important from a producer's perspective, as the probability of producing at or above an economic break-even yield of approximately 5017 kg ha^{-1} (80 bu ac^{-1}) (Dumler and Thompson, 2006) is greatly improved by taller residue and associated improvements in snow catch.

Limitations

It is important to note that the ability of taller stubble to trap and transform snowfall into stored soil water is dependent upon the occurrence and characteristics of snowfall events throughout the winter season. The ability of the taller stubble to maintain its architecture throughout the winter season will impact its ability to capture snow. Anecdotal evidence suggests occurrences where most of the standing stubble is laid over. This is often the result of weather conditions or the physical properties of the straw resulting from biological decomposition. The selection of cultivars that exhibit excellent straw quality, strength, and appropriate architecture for stripper header harvest are management decisions that can affect available soil water at emergence. It is also likely that in some years, any potential yield benefit gained by capturing additional snowfall will either be masked by above normal spring precipitation, or overcome by below normal in-season precipitation.

Conclusions

Our results further demonstrate that harvesting practices which increase the standing height of wheat stubble, such as the use of stripper headers, create the potential to capture additional snowfall and increase the effective precipitation available for soil water storage.

Increases in stored soil water may increase subsequent summer crop yields and improve the probability of attaining an economically critical yield goal. Therefore, producers should select harvesting strategies that result in the tallest stubble possible. Using stripper headers may offer producers the opportunity to restrict harvest losses at an acceptable level while capitalizing on the improved soil and water conservation opportunities afforded by taller wheat stubble.

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CHAPTER 3 - Effect of Wheat Stubble Height on Available Soil Water at Planting and Optimum Population for Subsequent Dryland Corn

Abstract

Water is the most limiting factor in Great Plains crop production. Summer annual crops have been adopted into the traditional wheat-fallow rotation to create a wheat-summer annual-fallow rotation that improves precipitation use efficiency and producer profitability. A critical component to the success of this intensified rotation is the presence of adequate residue from the proceeding wheat crop. The adoption of stripper headers has improved harvest efficiency and results in taller wheat stubble. Taller wheat stubble should improve capture and storage of over winter precipitation and reduce evaporative losses, thus increasing available soil water at planting. Additional soil water would typically result in higher grain yields and require higher optimal seeding rates. This study was conducted to determine the optimal seeding rate for two hybrid maturities (97 day and 108 day) seeded into stubble measuring 10, 25, and 71 cm (4, 10, and 28 in) in height. Seeding rates ranged from 2.47 to 5.43 plants m^{-2} (10 to 22 000 plants ac^{-1}). Three site-years of data were collected from plots located in the High Plains of northwest Kansas and southwest Nebraska. Climatic conditions during the study produced corn yields at relative extremes. Corn planted into taller wheat stubble produced higher yields in extremely dry years and produced yields no different than corn planted into shorter stubble in extremely wet years. In the dry year, grain yield of the long season hybrid responded positively to increasing population in tall stubble and negatively in short stubble. Yield of the short season hybrid increased with increasing stubble height and was mostly unresponsive to population. Grain yields of both hybrids responded positively to increasing plant population in a wet year, with the longer season hybrid being more responsive. The yield components of yield $plant^{-1}$, kernel weight, and kernels

plant^{-1} were also affected by hybrid, stubble, and population treatments. Available soil water at planting increased 24% as stubble height increased from 10 to 71 cm (4 to 28 in) in one year of the study.

Introduction

Water is the most limiting factor in Great Plains crop production. The high ratio of potential evapotranspiration (ET) to precipitation has long influenced cropping systems and yield potentials throughout the Great Plains. Historically, the limited amounts of precipitation and its erratic patterns led to the implementation of the crop-fallow system to help stabilize crop yields. Advances in cropland productivity throughout the region have come largely through improving the precipitation use efficiency (PUE) of cropping systems and the precipitation storage efficiency (PSE) during the remaining fallow periods (Farahani et al., 1998). The success of a traditional wheat-fallow or more intense rotation requires the use of stored soil water by the plant, as not enough precipitation is received during the growing season to sustain any of the major crops grown throughout the region, thus PSE and PUE are of utmost importance. Precipitation storage efficiency has been improved through reducing tillage intensity and thus increasing surface residues; which decreases evaporative losses, improves infiltration, and reduces runoff (McGee et al., 1997, review article by Nielsen et al., 2005). Precipitation use efficiency and water use efficiency of the cropping system, has been improved by replacing a summer fallow period with a summer crop (Nielsen et al., 2005, Peterson et al., 1996, Schlegel et al., 2002). Crops typically used include corn (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], or proso millet (*Panicum miliaceum* L.), thus creating a wheat-summer annual-fallow rotation. The addition of a summer annual(s) improves PUE by utilizing water for transpiration that would have been lost to evaporation during the fallow period. Intensified rotations provide greater net returns while reducing economic risk (Dhuyvetter et al., 1996, Schlegel et al., 2002).

A critical component to the success of a summer annual in this rotation is the amount and longevity of residue produced by the proceeding wheat crop. It has been shown that residue reduces runoff (Russell, 1939), reduces evaporation (Unger and Parker, 1976, Steiner, 1989), reduces weed growth (Wicks et al., 1994), and when standing retains snow (refer to Chapter 2 of this work for a complete discussion). Increasing surface residue levels has been shown to improve infiltration rates. Baumhardt and Lascano (1996) applied 65 mm h^{-1} (2.6 in hr^{-1}) over a one hour time period. They reported that infiltration was lowest for bare soil, 28.7 mm (1.13 in), increased with residue in a curvilinear manner up to a plateau of 44 mm (1.73 in). The plateau point occurred at a residue level of approximately 2.4 Mg ha^{-1} (2140 lb ac^{-1}). Unger (1978) reported that precipitation storage efficiency and available soil water at sorghum planting increased as surface residue levels increased from 0 to 12 Mg ha^{-1} (10,700 lb ac^{-1}) in the southern High Plains. Similar increases in precipitation storage efficiency have been observed in the central and northern Great Plains (Greb et al., 1967). In the northern plains of Montana and eastern High Plains of Colorado, PSE increased from 16 to 28 percent and 26 to 33%, respectively, as residue increased from 0 to 6.7 Mg ha-1 (6,000 lb ac^{-1}). In western Nebraska, PSE increased from 29 to 34% as residue increased from 0 to 10 Mg ha-1 (9,000 lb ac^{-1}).

Increasing the amount of standing or surface residue, often accomplished though no-till practices, has been shown to be superior for a variety of subsequent crops. Norwood and Currie (1997) reported 28% higher grain yields for corn and 11% higher for sorghum when grown under no-till conditions in southwest Kansas. Unger and Wiese (1979) reported increases in precipitation storage, available soil water at sorghum planting, grain yields and water use efficiency as tillage system progressed: disk, sweep, and no-till in the southern High Plains. Cotton lint yield increased 35% when grown in standing wheat stubble as compared with conventional tillage (Lascano et al., 1994). Planting into standing stubble also improved the transpiration to evaporation ratio 19%.

Unger (1978) reported that grain sorghum grown in the southern High Plains increased in yield as wheat straw mulch increased from 0 to 12 Mg ha^{-1} (10,700 lb ac^{-1}). The yield advantage was more significant as available soil water at planting decreased, however, water use efficiency improved with increasing residue level under most all conditions (Unger and Jones, 1981). The yield response was explained with a linear relationship to available soil water at planting, which has shown to be useful in estimating sorghum yields (Jones and Hauser, 1974, Stone and Schlegel, 2006). Hoefer et al. (1981) reported that corn in western Nebraska produced 17% less grain when wheat stubble was removed immediately after planting. Corn grown in stubble resulted in higher brace root penetration, higher tillering, and lower lodging. Early season growth was slower for corn planted in stubble, with plant height lower at 28 DAP. The author speculated that this slowed growth resulted in more soil water available later in the season. Wicks et al. (1994) applied residue treatments immediately before planting at two locations in western Nebraska and one location in southeast Nebraska, thus negating the impacts of residue level during the fallow period. Despite the timing of changing residue levels, corn grain yield generally responded positively as the level of applied wheat straw residue increased from 0 to 6.8 Mg ha^{-1} (6 069 lb ac^{-1}). Using data pooled from six site-years, available soil water at depths of 0 to 15 cm (0 to 6 in) and 30 to 150 cm (12 to 60 in) 30 DAP could be explained with a linear regression on residue level with

R^2 values of 0.90 and 0.99. Corn root density at the North Platte location increased linearly with increasing residue level (R^2=0.92).

Stripper headers reduce harvest cost by increasing machine field capacity (Haag et al., 2004) while maintaining acceptable harvest losses (Wilkins et al., 1994). These operational advantages and perceptions regarding improved soil moisture storage have resulted in increased adoption of stripper headers. The use of stripper headers in harvesting small grains creates unique residue properties following harvest. Smika (1983) examined wheat stubble 61 cm (24 in.) in height and showed that a wind velocity of over 6 m s^{-1} (13.4 mph) was required before wind could be detected at the soil surface compared with 2.4 m s^{-1} (5.4 mph) for stubble 30 cm (11.8 in.) in height. McMaster et al. (2000) found that when wind velocity was measured at heights below 1 m (39.4 in.) stripped stubble measuring 55 cm (21.7 in.) tall had a lower scaled wind velocity than conventionally harvested stubble 38 cm (15 in.) tall. Displacement height for the stripped stubble was determined to be 29 cm (11.4 in.) compared with 23 cm (9 in.) and 19 cm (7.5 in.) for cut stubble. Baumhardt et al. (2002) quantified the effects of two stubble heights, 59.4 cm (23.4 in.) stripped stubble and 39.4 cm (15.5 in.) cut stubble on wind profile, irradiant energy interception, and evaporation. They found that irradiant energy at the soil surface was reduced 12% by the stripped stubble and evaporation measured over a 4-day period decreased 26%. They reported the displacement height of the wind profile in taller stubble was 22.4 cm (8.8 in.) compared with 16.5 cm (6.5 in.) in the cut stubble and that stripped stubble impacted wind velocity up through 2 m (80 in), the highest point measured.

Previous work has made apparent that differences in residue level and condition affect growing season water supply. It is reasonable to assume that different stubble heights may result in different levels of growing season water supply by reducing wind at the soil surface, reducing evaporation, and improving snow catch. Unknown however, is the impact that taller and more erect wheat stubble, such as that left by a stripper header, has subsequent on crop production. The objectives of this study were to evaluate the impact of wheat stubble height and hybrid maturity on corn grain yield and optimal plant density.

Materials and Methods

The plots were located in adjacent counties, located in southwest Nebraska and northwest Kansas in the semi-arid west central Great Plains (Table 3.1). All locations were in a no-till cropping system consisting of a wheat-corn-fallow or wheat-corn-sorghum-fallow rotation. The previous wheat crop in all locations was seeded at approximately 78 kg ha^{-1} (70 lb ac^{-1}) in 19 cm (7.5 in.) or 25 cm (10 in.) rows with a no-till drill (Model 9432, AGCO-Sunflower Mfg., Beloit, KS). The wheat was harvested in late June with a commercial combine using a small grains stripper header (Model CVS32, Shelbourne-Reynolds Engineering, Colby, KS).

Table 3.1 - Geographic Locations and Attributes of Corn - Stubble Experiments

Location	Latitude	Longitude	Elevation
			m (feet)
Decatur 2006	40°00’04” N	100°15’24” W	774.5 (2541)
Rawlins 2007	39°55’51” N	100°53’27” W	885.1 (2904)
Red Willow 2007	40°07’07” N	100°17’28” W	792 (2598)

Two hybrids were used for the study based upon their familiarity to the author and past performance in High Plains dryland conditions. Garst '8812YG1/RR' is a 97 day hybrid (2250 heat units to black layer) with good early vigor and growth, and is considered to be semi-determinate in ear flex. It is best adapted to medium to high plant populations and is of medium height. Under Midwest conditions it does not exhibit prolific tendencies, however it may under low enough plant populations. Garst '8534YG1/RR' is a 108 day hybrid (2560 heat units to black layer) of tall height. It is considered well adapted to medium and low plant populations. It has good ear flex and is not prolific under any conditions. Both hybrids were considered to have good drought stress tolerance and both possessed semi-upright leaf architectures. YieldGuard (Cry 1Ab – MON810) and RoundUp Ready (Nk603) genetically modified traits were present in both hybrids. Hybrid characteristic data are from personal observation, seed company materials (Anonymous, 2006), and breeders notes (Kris Nyhus, personal communication, 2008). Seed of both hybrids was treated with a seed applied insecticide (Cruiser250, Syngenta, Greensboro, NC). Plant densities selected for the study were intended to contain the optimum population for the environment, while covering a range in which a quadratic response could be observed under normal environmental conditions.

Plots were planted in 76.2 cm (30 in) rows using a vacuum planter with true v double-disk openers (Model 6100, AGCO-White, Hesston, KS). Nitrogen was applied at planting as a (32-0-0) solution placed approximately 5 cm over from the row and 5 cm below the soil surface (2 x 2 in). The nitrogen rate used for all locations was 101 kg N ha^{-1} (90 lb N ac^{-1}). The planter was equipped with a variable rate hydraulic drive (Model PRC, Veris Technologies, Salina, KS), thus providing the ability to rapidly change the desired seeding rate. Cooperators provided effective weed control through the use of pre-emergence herbicides.

Decatur County– 2006

Plots were placed at three locations in a production field of hard red winter wheat stubble in Decatur County, KS. The locations are designated Decatur County east (DCE), Decatur County west (DCW), and Decatur County monitored (DCM). These designations simply relate to plot location within the field and identify the plot that was used for a soil water evaporation study. The soil is classified as a Holdrege silt loam (fine-silty, mixed, superactive, mesic Typic Argiustolls) with 1 to 3 percent slope. Average climatic data (HPRCC, 2007a) near the site are 549 mm (21.6 in.) of annual precipitation, with 56% occurring May through Aug., 10.8° C (51.4° F) mean annual temperature, and 1447 mm (57 in.) of open pan evaporation occurring in April through Oct. The field was seeded in late September 2004 with a tall semi-dwarf variety of hard red winter wheat (‘TAM111’, AgriPro Wheat Genetics, Berthoud, CO). The field was harvested in June 2005. Corn plots were planted 16 May, 2006.

Red Willow County - 2007

The experiment was placed at one location in a production field of hard red winter wheat stubble in Red Willow County, NE. The experiment was located on a Holdrege-Keith soil association with approximately 60% Holdrege and 40% Keith silt loams (fine-silty, mixed, superactive, mesic Aridic Argiustolls) with 1 to 3 percent eroded slopes. Average climatic data are identical to those previously mentioned for the Decatur County location. The field was seeded 28 September 2005 with a medium-short semi-dwarf variety of hard red winter wheat ('Jagalene', AgriPro Wheat Genetics, Berthoud, CO). The grain yield over the plot area averaged 3.6 Mg ha^{-1} (53 bu. ac^{-1}) as recorded by a properly calibrated yield monitor. Corn was planted 18 May, 2007.

The experimental design implemented was common to both the Decatur 2006 and Red Willow 2007 locations and was a split-split-split block arrangement. Main plots were three stubble height treatments assigned in a randomized complete block design with four replications. Treatments consisted of unaltered stripper harvest with stubble height of approximately 71 cm (28 in.), cut height of 25 cm (10 in.), and cut height of 10 cm (4 in.) A commercial combine equipped with a small grains platform was used to create the stubble height treatments on 21 July 2006. The operation was performed in such a manner to maximize travel in existing tire tracts and minimize the amount of stubble laid over. Plot dimensions were approximately 15.2 x 15.2 m (50 x 50 ft.) Two alleys measuring 3.8 m (12.5 ft.) in width were placed lengthwise across blocks in-between plots. This allowed the cooperator to reach across all plots with a ground applicator for herbicide application during the fallow period. Areas of the field adjacent to the plot area were left in unaltered stripped stubble condition. Sub plots of plant population treatments were four rows wide, applied in a split-block manner and randomized within replications. Sub-sub plots of hybrid treatments, two rows wide, were also applied in a split-block manner with respect to replications. Planting order and direction was randomized so that hybrid position was randomized within each population. Corn was seeded at 3.0, 3.8, 4.5, and 5.3 plants m^{-2} (12 200, 15 300, 18 200, and 21 500 plants ac^{-1}).

Rawlins County - 2007

The plot was located on soil classified as a Keith silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustolls) with 0 to 1 percent slope. Average climatic data (HPRCC, 2007b) near the site are 545 mm (21.4 in.) of annual precipitation, with 56% occurring May through Aug., and a mean annual temperature of 10.3° C (50.6° F). The proceeding wheat crop had been harvested with both conventional and stripper headers. The plot was located where the two resulting stubble heights, approximately 33 cm (13 in) and 71 cm (28 in), were adjacent to each other. Eight rows of border were centered over the stubble height transition. Corn was planted across the entire area at a population of 6.9 plants m^{-2} (28 000 plants ac^{-1}) on 17 May, 2007. Two row plots of the hybrid treatment were strip applied within each stubble height and across replications. Planting order and direction were randomized so that hybrid position was randomized. Population treatments were assigned in a randomized complete block, with each stubble height having 5 replications. Plant density treatments were applied as four row plots, thus including two hybrid subplots within each population plot. At approximately the V4 stage, population treatments were obtained by hand thinning the stand using templates in an effort to attain uniform spacing. Stands were thinned to 2.5, 3.2, 4.0, 4.7, and 5.4 plants m^{-2} (10, 13, 16, 19, and 22 000 plants ac^{-1}). All doubles were thinned to one plant. The plots were 10.7 m (35 ft) in length with 1.5 m (5 ft) alleys located between blocks.

Soil Water

Soil cores were taken at planting in 2006 for the Decatur County plots to determine gravimetric water content and bulk density. Cores measuring 41 mm (1.61 in) in diameter were taken to a depth of 122 cm (48 in) using a hydraulic soil probe (KSU Ag

Engineering, Manhattan, KS.). Cores were taken at 15.2 cm (6 in) intervals up until 61 cm (24 in) and 30.5 cm (12 in) intervals from 61 cm (24 in) to 122 cm (48 in). Cores were placed in sealed bags and wet weights were obtained within 6 hours of sampling. Cores were dried at 105 °C (221 °F) for a minimum of 72 hours. Data using time domain reflectometry were also collected using a portable unit (TDR300, Spectrum Technologies, Plainfield, IL.) equipped with 12 cm (4.8 in) probes in the Decatur plots in 2006 at the time of corn seeding. Soil cores were not taken at the Red Willow or Rawlins locations in 2007. Above normal precipitation in the months before planting (Figures 3.10 and 3.15) and measurements taken with a ball rod support the assumption of a full soil water profile at planting.

Harvest

Stand counts were randomly taken throughout the plots at harvest, and an average percent emergence was calculated. Harvest stands were calculated by multiplying a plots seeding rate by average emergence. All plots were mechanically harvested with a plot combine. Samples were sieved to remove foreign material and broken kernels using a 12/64 round-hole sieve according to USDA procedures (Anonymous, 1996) and analyzed for moisture content and test weight. All plot yields were adjusted to 15.5% moisture content. In 2006 kernel weight was obtained by randomly selecting 100 seeds that were dried at 105 °C (221 °F) for a minimum of 72 hours. In 2007 the same procedure was used with 200 randomly selected seeds for analysis. Yield plant^{-1} and kernels plant^{-1} were calculated for each plot using the collected data.

Statistical Analysis

Statistical analysis for all plots was carried out using the Proc GLIMMIX procedure within SAS version 9.1.3. The GLIMMIX procedure provides a modeling environment that allows both fixed linear and mixed models and was appropriate for the plot designs used in this study. Denominator degrees of freedom were obtained using either the Containment or Kenward-Roger method. Variance component estimation was performed with the restricted maximum likelihood technique (REML). In instances where variance components were estimated as near zero or negative the NOBOUND option was invoked to attempt completion of a G matrix that was positive definite. Invoking NOBOUND in these situations provides better control of the Type I error rate and better power in estimates of whole-plot error variances (Littell et al., 2006). Means separation output was obtained using the PDMIX800 macro application (Saxton, 1998).

The three Decatur 2006 plots were combined due to their close physical location, the physical loss of some plots in the field, and as an effort to combat extreme variances created by harsh climatic conditions. Means separation by LSD was performed at the 0.10 significance level. Analysis was conducted with a treatment structure treating population x stubble and hybrid x stubble as split-block plots and hybrid as a subplot (split-plot) of population. The source table was constructed in the normal way with the only exception being the use of replication x hybrid(population) as the error term for the hybrid and population x hybrid effects. This was necessary as hybrid was only randomized within each population, thus the use of this error term allowed proper allocation of the split-plot and whole-plot variances.

The Rawlins 2007 plots present a difficult analysis situation as no true replications existed of the A level, stubble height. The strip application of hybrid treatments across replications rather than within replications prevented a split-block analysis and thus added additional complications. After consultation with a statistician (L. Murray, personal communication, 2008) an analysis was performed on the data as though the stubble height, was randomized. Only the stubble x hybrid effect was extracted from this analysis. This was believed to be a viable option due to five replications of hybrid within stubble via the experimental structure. Analysis of a split-split plot design was then performed within each stubble height. Although comparisons across stubble treatments cannot be made, statistical evaluation of results can be performed within stubble treatments and presented with interpretation left to the reader. Means separation for all 2007 data was conducted using the LSD method with significance of 0.01.

Soil water at planting values for the Decatur 2006 plots were collected on the stubble whole-plot experimental unit. This allowed for a conventional RCBD analysis to be performed using Proc GLIMMIX. Means separation was conducted with a significance of 0.01, except where noted. Depth values used in the analysis, and reported herein are the mean depth for sampling. Soil water data from the DCM location were observed to have a tremendous amount of inherent spatial variability, possibly a latitudinal trend. Several techniques were attempted to recover the intra- and inter-block data using covariate analysis as described by Milliken and Johnson (2002) and Federer (2003). These techniques were rendered ineffective due to the structure of the variability, the location of treatments within the plot, and the lack of data points necessary to create meaningful regressions on the covariate. As a result, the DCW and DCE locations were combined for analysis with the DCM location to be evaluated independently.

Results

Soil Water

Soil water content was affected by stubble treatment at every depth of study in the combined analysis of the DCE and DCW locations (Table 3.2). No differences were seen among stubble treatments at the DCM location (Table 3.2).

Table 3.2 – Decatur 2006 ANOVA – Effect of Stubble Treatment on Soil Water by Depth

	p > F				
	Sampling Depth cm (in)				
Site	7.6 (3)	22.9 (9)	45.7 (18)	76.2 (30)	106.7 (42)
DCM / DCE Combined	0.0991	0.0067	<0.0001	0.0080	0.0027
DCM	NS	NS	NS	NS	NS

The impact of stubble treatment on soil water was evaluated at each depth and is shown in Figure 3.1. Vertical lines represent the permanent wilting point (PWP) and field capacity (FC) volumetric water contents for a Holdrege silt-loam soil at water potentials of –15 and –1/3 bar, respectively. The 71 cm (28 in) stripped and 25 cm (10 in) cut stubble treatments typically had higher levels of soil water than the 10 cm (4 in) cut treatment. At the 7.6 cm (3 in) depth, soil water in the stripped was greater than the 10 cm (4 in) stubble, with the intermediate being no different than the other two stubble heights. At all depths other than 7.6 cm and 1.2 m, the 10 cm (4 in) stubble was lower than the other two stubble treatments. At the 1.2 m (42 in) depth soil water in the short cut and stripped treatments were lower than intermediate height, and were basically at permanent wilting point.

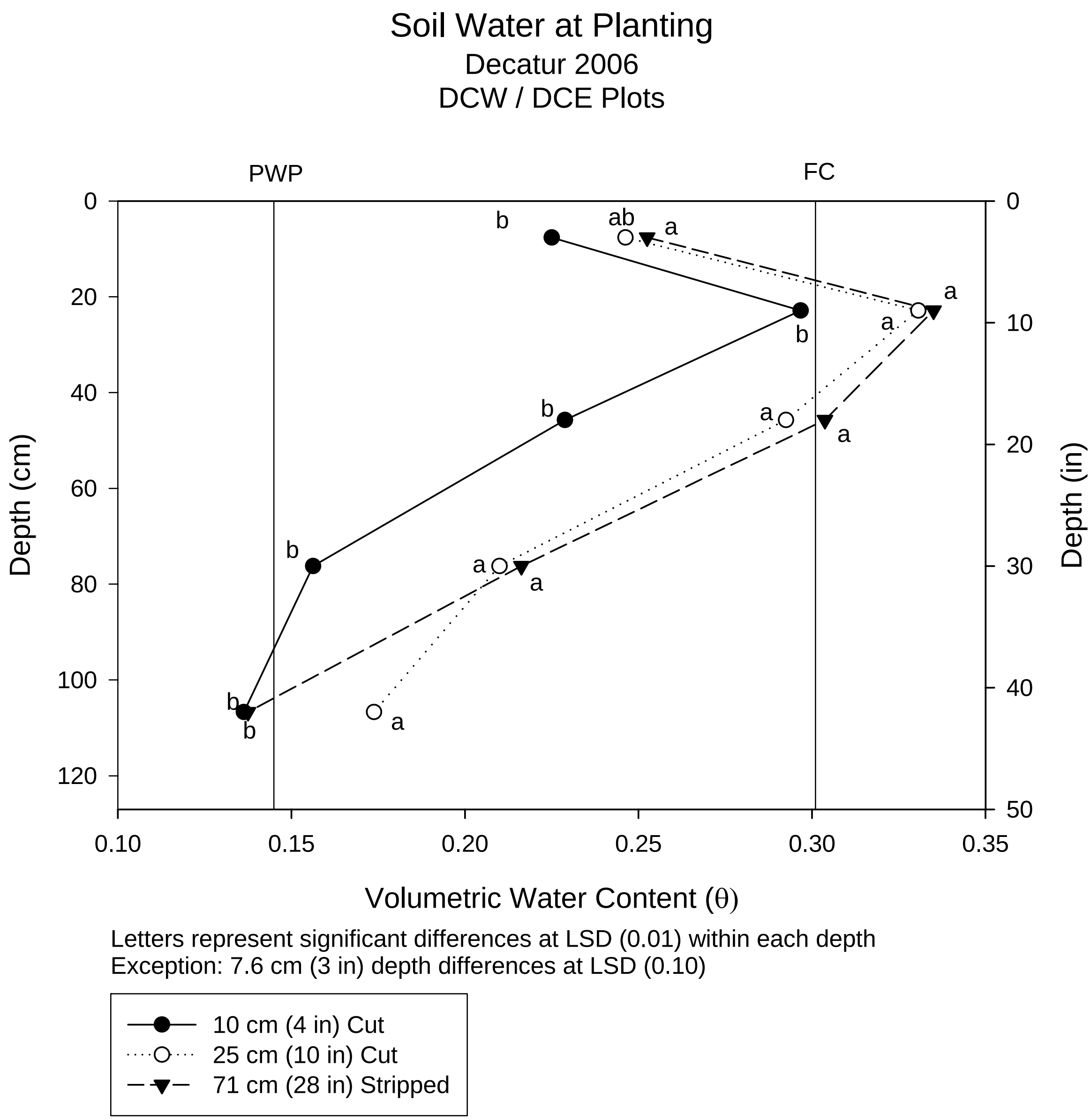

Figure 3.1 - Decatur 2006 Soil Water at Planting by Depth

Of particular interest is the difference in soil water at the 45.7 cm (18 in) and 76.2 cm (30 in) depth. This depth is important, as studies involving corn with little or no irrigation have found seasonal soil water depletion is maximized around a depth of 61 cm

(2 ft) (Stone et al., 1978, Hattendorf et al, 1988, Russell and Danielson, 1956). Throughout this critical depth region, the two taller stubble treatments have almost twice the soil water present in the short cut stubble treatment.

Total profile soil water at planting was evaluated for depths of 0.6, 0.9, and 1.2 m (2, 3, and 4 ft). Stubble treatments had a significant impact on profile soil water for each of the profile depths evaluated in the DCW/DCE locations (Table 2). No statistical differences were observed at the DCM location, the arithmetic means are presented for informational purposes.

Table 3.3 – Decatur 2006 Effects of Stubble Treatment on Profile Soil Water

Stubble Treatment	Profile Soil Water at Planting						
	Plot Location and Profile Depth m (ft)						
	1.2 (4)		0.9 (3)		0.6 (2)		DCM - 1.2 (4)
	cm (in)						
71 cm (28 in) Stripped	29.0 (11.4)	a	24.8 (9.8)	a	18.2 (7.2)	a	29.6 (11.7)
25 cm (10 in) Cut	28.6 (11.3)	a	23.4 (9.2)	a	17.0 (6.7)	ab	27.1 (10.7)
10 cm (4 in) Cut	23.4 (9.2)	b	19.2 (7.5)	b	14.4 (5.7)	b	24.5 (9.6)
ANOVA p-value	0.0031		0.0027		0.0079		NS
LSD 0.01	4.5 (1.75)		4 (1.59)		3.1 (1.24)		-
LSD 0.05	3.2 (1.26)		2.9 (1.15)		2.3 (0.89)		-
LSD 0.10	2.6 (1.04)		2.4 (0.94)		1.9 (0.73)		-

Letter groupings within a column represent no differences at LSD (0.01)

Work by Gordon et al. (1995) has shown that most soil water depletion occurs in the top 61 cm (2 ft) of the soil profile with almost no depletion at depths below 91 cm (3 ft). As shown in Table 3.3, differences exist between the two taller stubble treatments and the short cut treatment at these depths, as well as the 1.2 m (4 ft) depth. When the depth under study is reduced from 1.2 m (4 ft) down to 61 cm (2 ft) the tall stripped stubble and intermediate stubble height treatments begin to separate, likely due to the previously discussed water content differences at the 1.07 m (42 inch) depth.

Grain Yield and Yield Components

Extreme differences in growing season water supply and yield level were clearly evident between the 2006 and 2007 data, and as a result will be discussed separately. No attempt was made to combine the results from the 2007 trials because of the aforementioned issues of experiment design at the Rawlins 2007 location.

Decatur 2006

The year 2006 continued a multi-year drought in the west-central Great Plains region. Precipitation received from 1 July, 2005 (wheat harvest) through 30 Sept., 2006 with respect to normal is shown in Figure 3.1 for the Decatur County location in 2006.

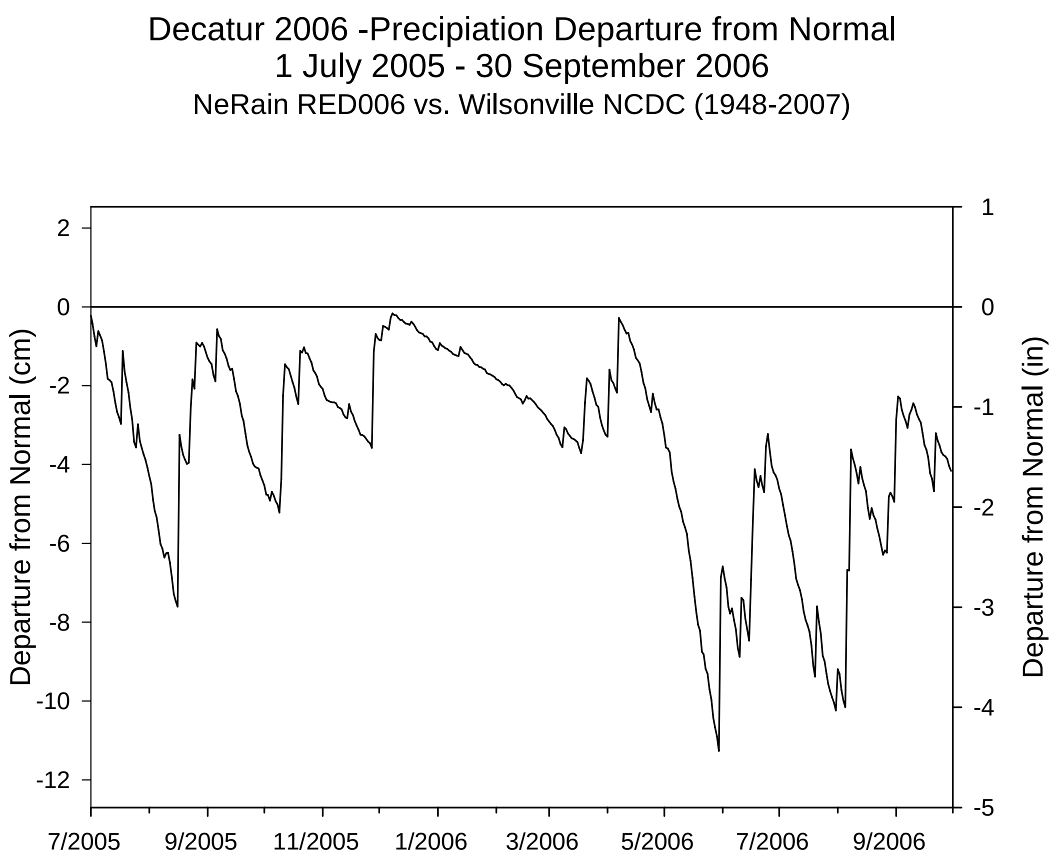

Figure 3.2 - Decatur 2006 Cropping Period Precipitation

As evident in the chart, the cropping period started with below normal precipitation, a dry fall resulted in deviations as large as 7.62 cm (3 in) below normal. Some recovery was experienced with winter precipitation, however the normal level of precipitation was never attained during the time of this study. Precipitation levels declined rapidly throughout the end of April and beginning of May reaching their lowest around 1 June, 2006. At the time of planting (16 May, 2006) cumulative precipitation was 6.9 cm (2.7 in) below normal. Rainfall events in mid and late June provided some recovery throughout the vegetative growth stages until precipitation levels again declined to approximately 10 cm (4 in) below normal in mid July through early August, a critical time in terms of pollination, kernel set, and grain fill. The conditions, especially during the critical grain development stages, were reflected in the average grain yield across treatments of 2.96 Mg ha^{-1} (47.2 bu ac^{-1}).

Analysis of variance results are presented in Table 3.4. The significant stubble X population X hybrid interaction was common for yield and yield components, except kernel weight, which exhibited a stubble X hybrid interaction. No effects involving population were significant for kernel weight.

Table 3.4 – Decatur 2006 ANOVA for Yield and Yield Components

	Grain Yield	Yield $Plant^{-1}$	Kernels $Plant^{-1}$	Kernel Weight
Source		P > F		
Rep	<.0001	<.0001	<.0001	0.0533
Stubble	<.0001	<.0001	<.0001	0.0002
Population	0.4611	<.0001	<.0001	0.1816
Hybrid	0.0001	0.001	<.0001	0.4110
Pop x Hybrid	0.4521	0.5836	0.524	0.2087
Stubble x Population	0.0234	0.9052	0.422	0.5120
Stubble x Hybrid	0.0114	0.0304	0.098	**0.0004**
Stubble x Population x Hybrid	**0.0358**	**0.0136**	**0.044**	0.1611

The three-way interactions will be discussed as two-way interactions at the treatment level in the study of least interest (Milliken and Johnson, 1984). The hybrid effect is of least interest in this study, and numerous examples can be found in the literature where hybrids responded differently to stresses, therefore discussion of three-way interactions will be sliced by hybrid. Grain yield for 8812YG1/RR was different between the short cut stubble treatment and the two taller stubble treatments at all levels of plant population (Figure 3.3). At the lowest population all three stubble treatments were different. No population response was evident for the 71 cm (28 in) stripped and 10 cm (4 in) cut stubble treatments with the hybrid maintaining essentially the same yield across all levels of plant population. The source of the stubble X population interaction is a positive response to population for the 25 cm (10 in) cut stubble as population increases from 2.8 to 4.2 plants m^{-2} (11 400 to 16 950 plants ac^{-1}). Grain yields for the 71 cm (28 in) stripped, 25 cm (10 in) cut, and 10 cm (4 in) cut treatments averaged 3.66, 3.49, and 2.07 Mg ha^{-1} (58.3, 55.6, and 33.0 bu ac^{-1}), respectively.

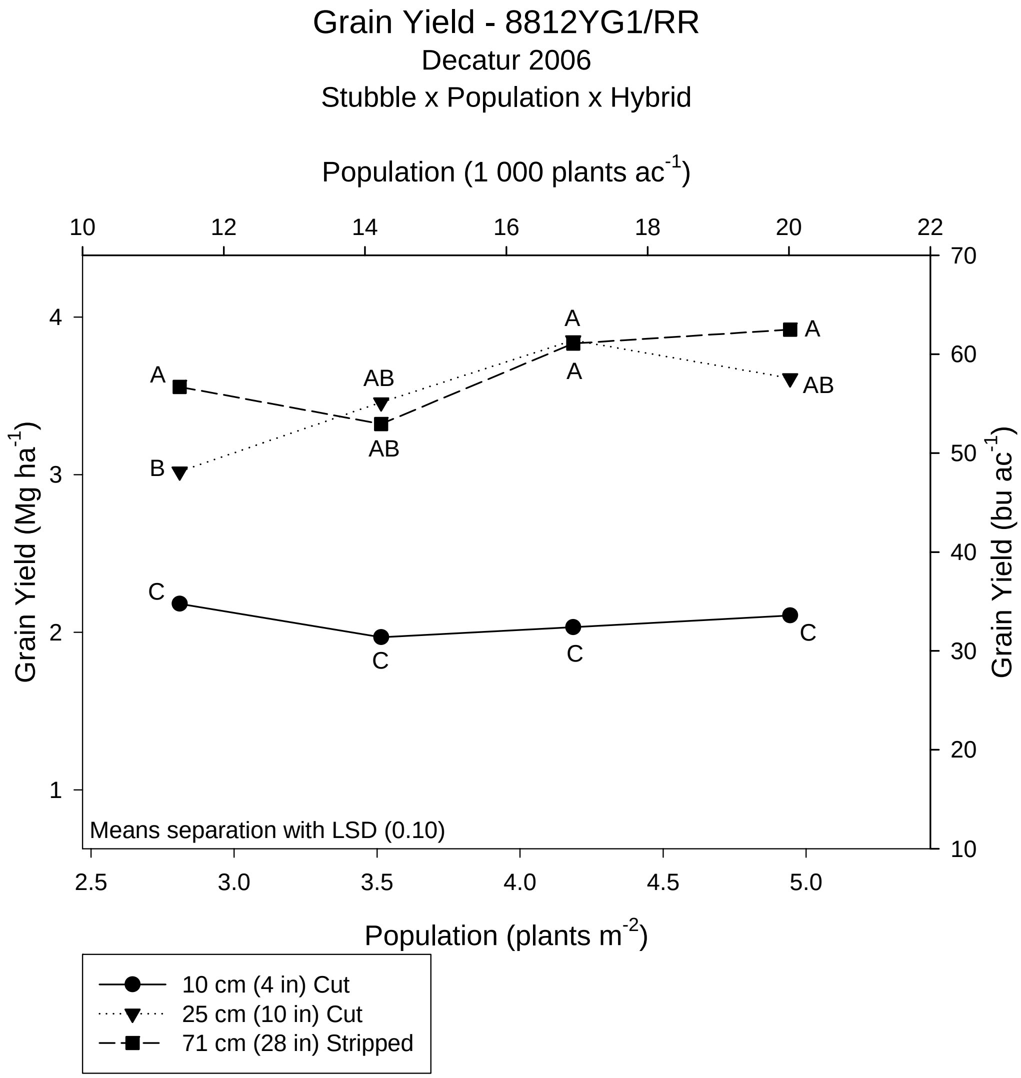

Figure 3.3 - Decatur 2006 Grain Yield - 8812YG1/RR - Stubble x Population

A yield response to population was more evident with 8534YG1/RR and the response varied with stubble height (Figure 3.4). Both the 25 cm (10 in) and 71 cm (28 in) stubble treatments resulted in grain yield responding positively to increasing levels of plant population. For the 71 cm (28 in) stripped stubble treatment grain yield increased from 2.96 to 3.79 Mg ha^{-1} (47.1 to 60.4 bu ac^{-1}). Yield declined for this hybrid in the 10 cm (4 in) treatment from 1.94 to 1.33 Mg ha^{-1} (30.9 to 21.1 bu ac^{-1}) as plant population increased from 2.8 to 3.5 plants m^{-2} (11 400 to 14 200 plants ac^{-1}). Yield was unresponsive at populations above this level.

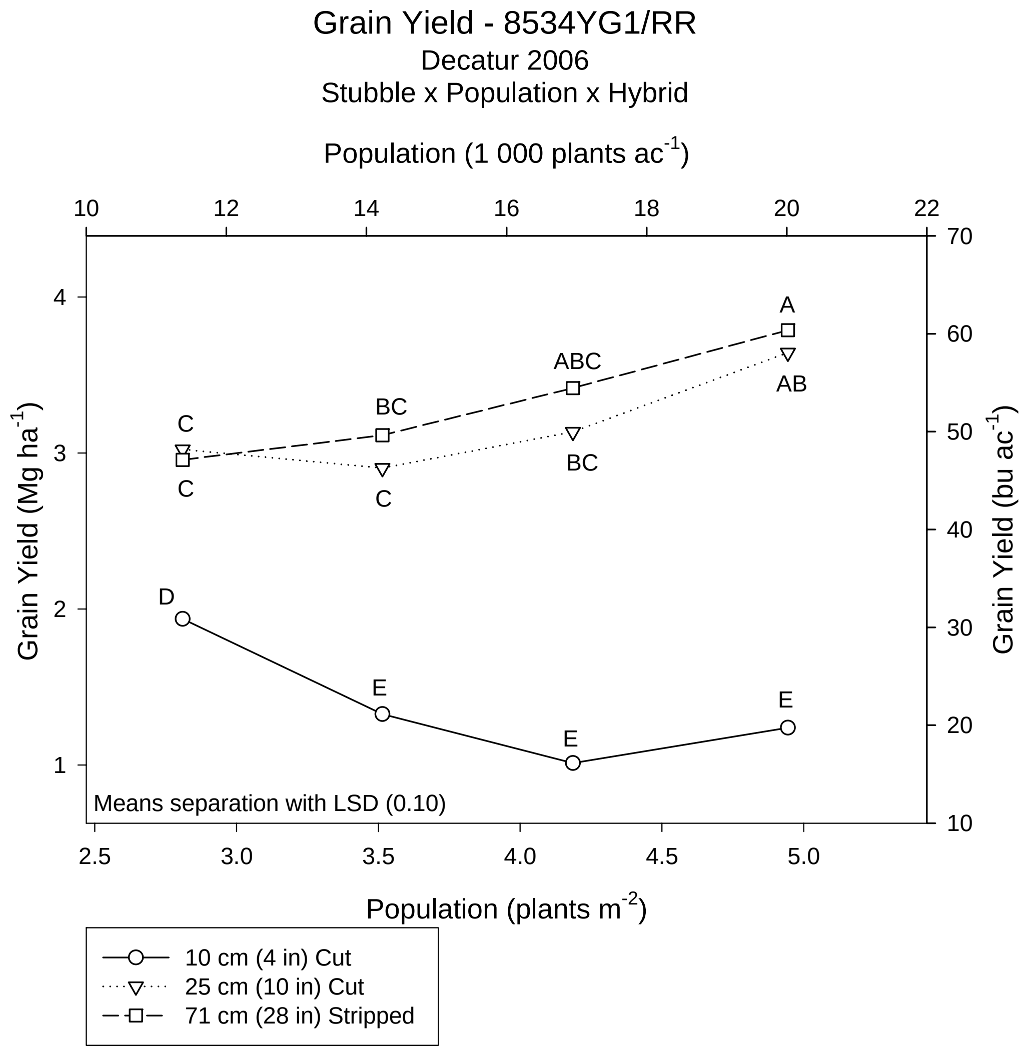

Figure 3.4 - Decatur 2006 Grain Yield – 8534YG1/RR – Stubble x Population

Overall the grain yield of 8534YG1/RR was less than that of 8812YG1/RR. Only at the highest populations and in the taller stubble treatments did the yield of 8534YG1/RR approach that of the other variety.

Grain yield $plant^{-1}$ declined in a linear manner as plant population decreased for 8812YG1/RR (Figure 3.5). The three stubble treatments were different at the lowest plant population. As population increased the two tallest stubble treatments trended together but remained higher than that of the short cut stubble. The largest change in grain yield plant^{-1} for the 71 cm (28 in) stripped and 10 cm (4 in) cut treatments occurred as plant population increased from 2.8 to 3.5 plants m^{-2} (11 400 to 14 200 plants ac^{-1}). The slope over this range in population for the 25 cm (10 in) cut treatment did not vary from the balance of points with a clear linear trend.

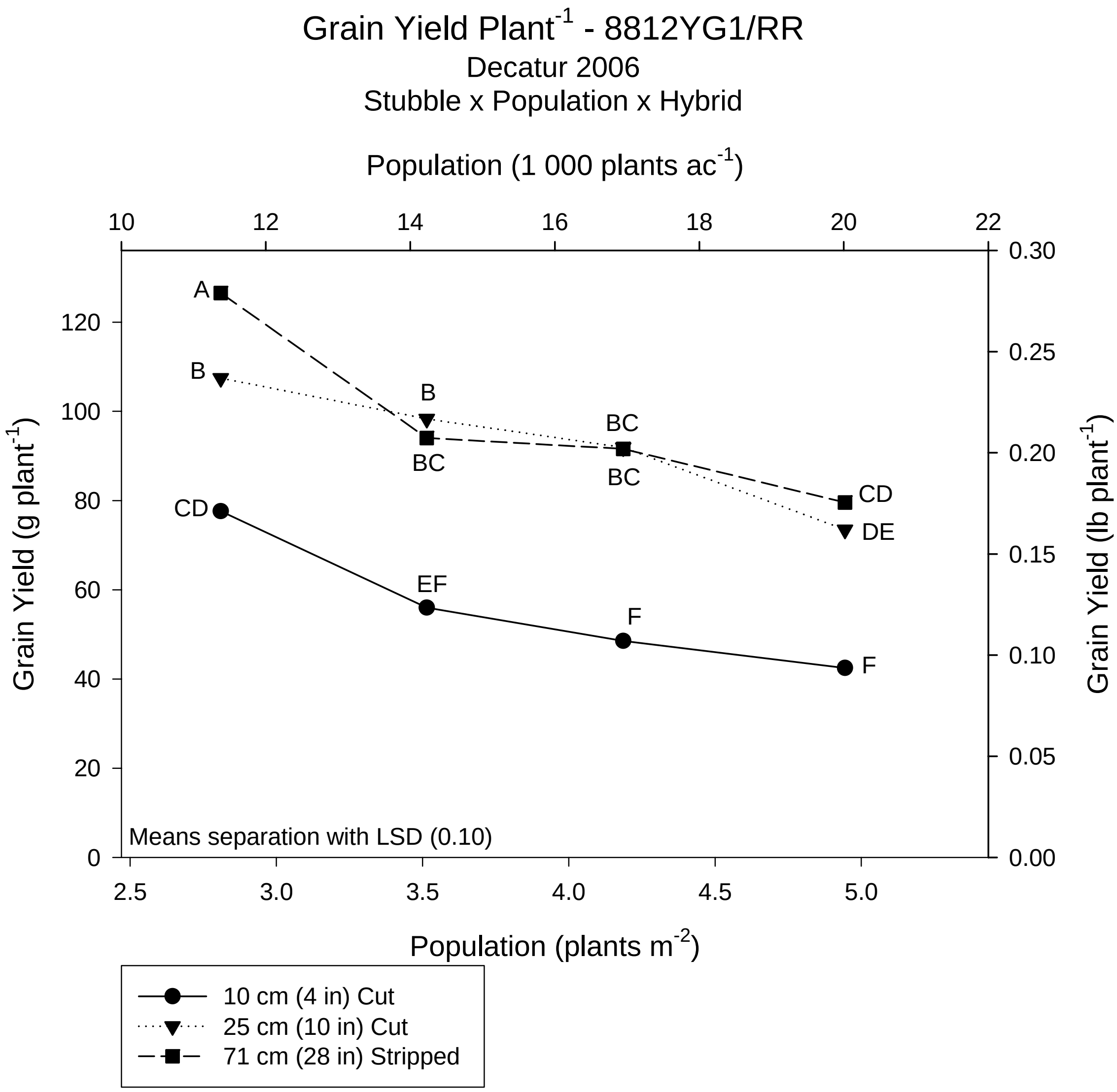

Figure 3.5 - Decatur 2006 Grain Yield Plant^{-1} – 8812YG1/RR – Stubble x Population

Grain yield plant^{-1} for 8534YG1/RR declined as plant population increased (Figure 3.6). The two taller stubble plants maintained higher levels of grain yield plant^{-1} over the entire range of plant densities. The two taller stubble treatments trended together and were less responsive to increasing plant population. Grain yield plant^{-1} for the shortest stubble height declined the most as plant population increased from 2.8 to 3.5 plants m^{-2} (11 400 to 14 200 plants ac^{-1}). After this rapid decline grain yield plant^{-1} continued to approach an asymptote of approximately 22.7 g plant^{-1} (0.05 lb plant^{-1}).

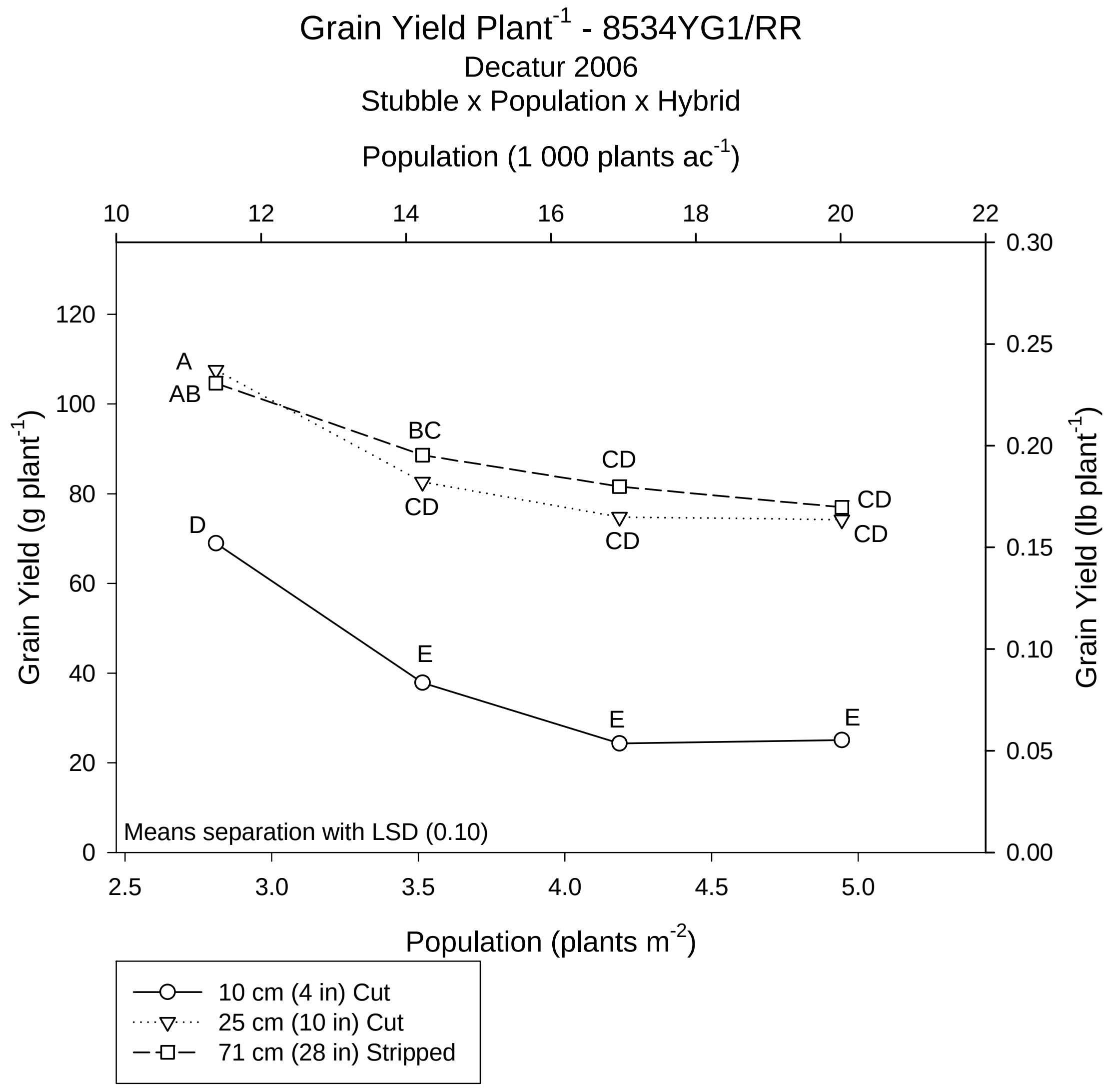

Figure 3.6 - Decatur 2006 Grain Yield Plant^{-1} – 8534YG1/RR – Stubble x Population

The relative importance of kernel number plant^{-1} as compared to kernel weight is evidenced by the similarity between the responses seen for kernel number plant^{-1} and grain yield plant^{-1}. For both 8812YG1/RR (Figure 3.7) and 8534YG1/RR (Figure 3.8) kernels plant^{-1} declined with increasing population. Kernel number plant^{-1} were different for each of the three stubble treatments at the lowest plant population of 2.8 plants m^{-2} (11 400 plants ac^{-1}). However, the intermediate and tall stubble treatments were not different at higher plant populations while maintaining a clear advantage over the short cut stubble treatment.

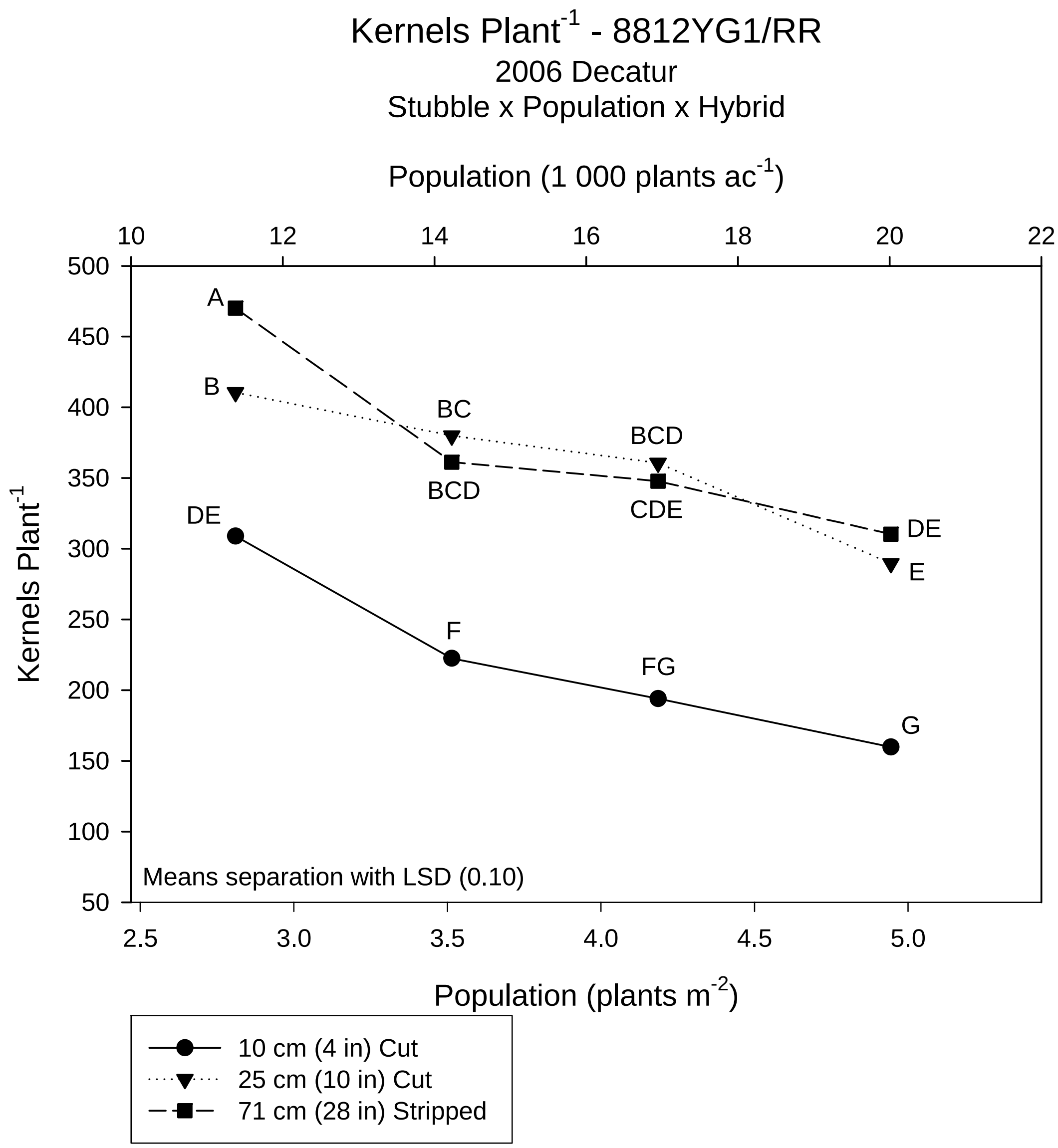

Figure 3.7 - Decatur 2006 Kernels Plant^{-1} - 8812YG1/RR - Stubble x Population x Hybrid

Kernels plant-1 for 8534YG1/RR at the intermediate and tall stubble treatments were equal across the range of plant populations. The short cut stubble treatment always resulted in the lowest kernels plant^{-1} regardless of plant population. The response of kernel number to population for the short cut stubble resembled that of a exponential decay curve, with the largest decline occurring between 2.8 to 3.5 plants m^{-2} (11 400 to

14 200 plants ac^{-1}). After this rapid decline kernels plant^{-1} continued to approach an asymptote of approximately 95 kernels plant^{-1}.

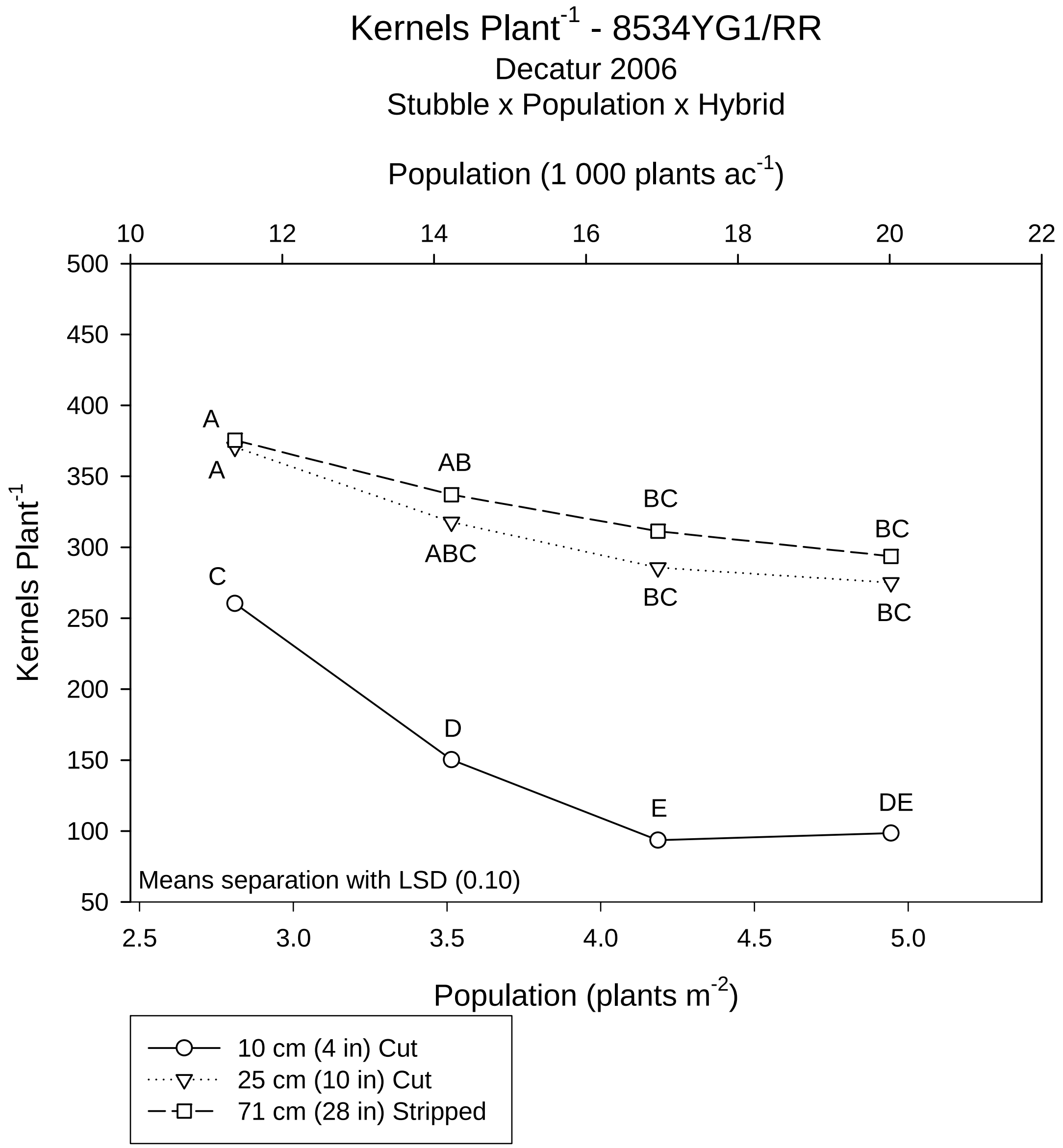

Figure 3.8 - Decatur 2006 Kernels Plant^{-1} - 8534YG1/RR - Stubble x Population x Hybrid

A stubble x hybrid interaction was evident in kernel weights (Figure 3.9). For both hybrids, kernel weight remained relatively constant for both the 71 cm (28 in) and

25 cm (10 in) stubble treatments. At the 10 cm (4 in) stubble treatment kernel weights were reduced drastically for both hybrids. Kernel weight loss was most evident at this stubble height in 8534YG1/RR. Although no difference was detected between hybrids at the two taller stubble treatments, the numerical trend for 8812YG/RR kernel weight was noticeably more linear in nature than the linear plateau response of 8534YG1/RR.

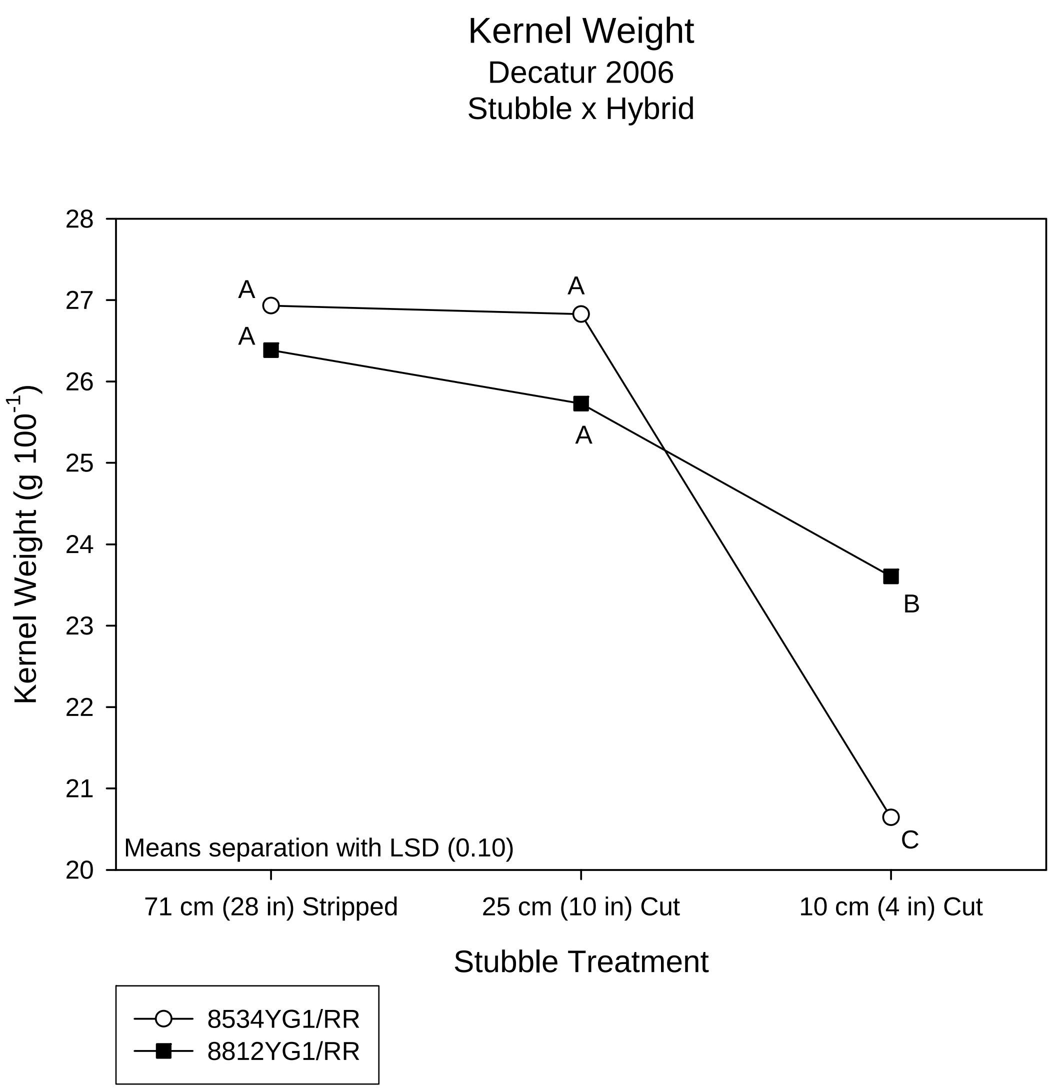

Figure 3.9 - Decatur 2006 Kernel Weight - Stubble x Hybrid

Red Willow 2007

Environmental conditions in 2007 at the Red Willow County location were vastly different than those experienced at the Decatur County plots in 2006. For approximately the first two months of fallow following wheat harvest cumulative precipitation was as much as 5 cm (2 in) below normal (Figure 3.10). However, after about the 1st of October precipitation rose above normal and remained that way throughout the crop year. At the time of planting (18 May, 2007) the cumulative precipitation for the crop period (starting 1 July, 2006) was 23.2 cm (9.15 in) above normal. Favorable growing conditions continued throughout the year as reflected in an average grain yield of 7.61 Mg ha^{-1} (121.4 bu ac^{-1}) across all treatments. Cumulative precipitation ranged from a low of 18.7 cm (7.37 in) above normal on 3 July, 2007 to 27.1 cm (10.66 in) above normal on 14 July, 2007. Temperatures and relative humidity were also favorable for much of the growing season (data not shown).

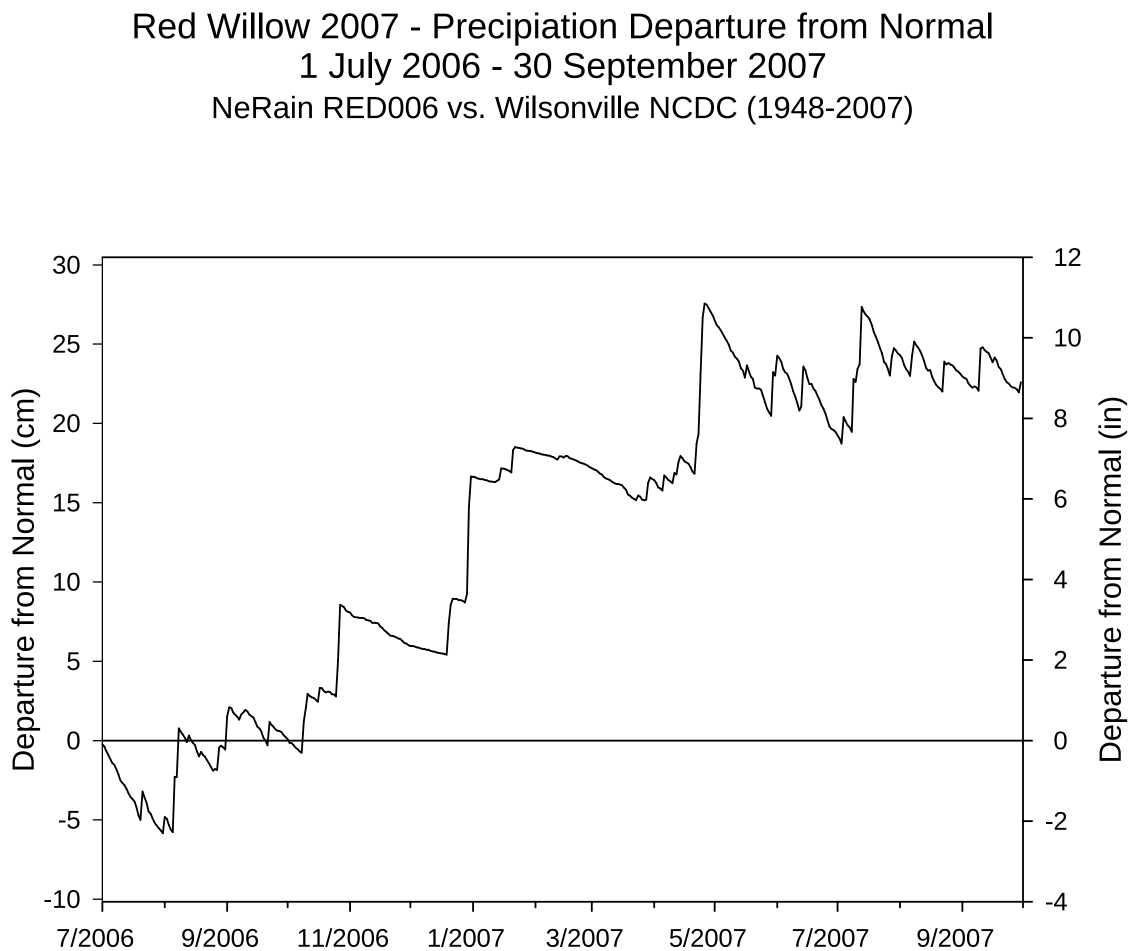

Figure 3.10 - Red Willow 2007 Cropping Period Precipitation

Stubble treatments did not affect grain yield or any yield component at Red Willow 2007 as indicated by significant population and hybrid interactions and main effects (Table 3.5).

Table 3.5 - Red Willow 2007 ANOVA for Yield and Yield Components

	Grain Yield	Yield Plant^{-1}	Kernel Weight	Kernels Plant^{-1}
Source	P > F			
Rep	0.99	0.9814	0.4962	0.8511
Stubble	0.6186	0.6468	0.8224	0.5687
Population	<.0001	**<.0001**	**0.0381**	**0.0001**
Hybrid	<.0001	**<.0001**	**<.0001**	**0.0258**
Pop x Hybrid	**0.0835**	0.1602	0.2678	0.1165
Stubble x Population	0.1753	0.5563	0.5977	0.1737
Stubble x Hybrid	0.1488	0.1535	0.4366	0.1364
Stubble x Population x Hybrid	0.9701	0.9843	0.8925	0.9769

Corn grain yield responded positively to increasing plant population in a linear manner. A significant hybrid x population interaction is evident as 8534YG1/RR was more responsive to increasing plant populations (Figure 3.11).

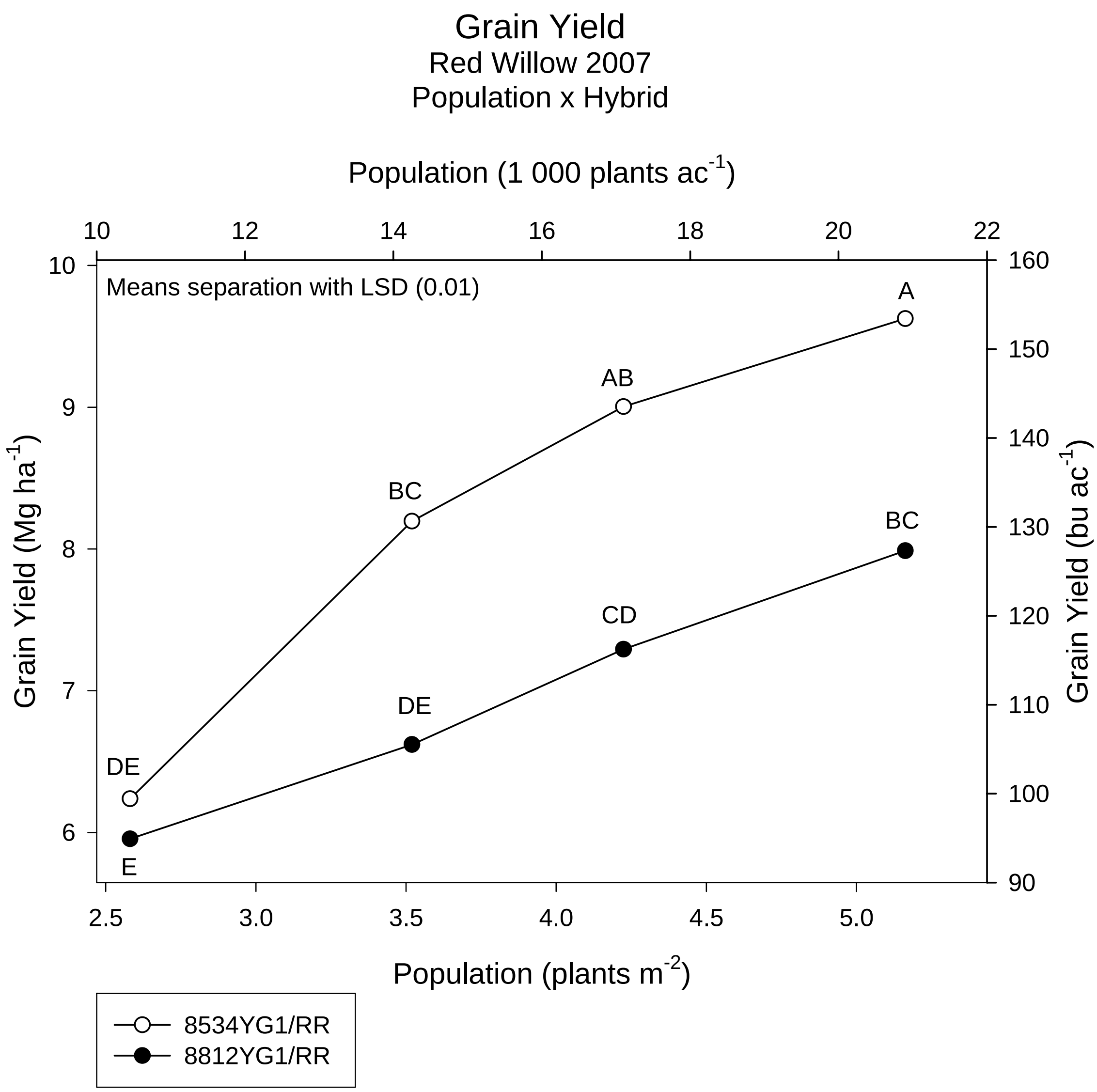

Figure 3.11 - Red Willow 2007 Grain Yield - Population x Hybrid

Yields between the two hybrids were equal at the lowest plant population of 2.8 plants m^{-2} (11 400 plants ac^{-1}). As plant population increased, the different response rates resulted in a grain yield difference of 1.64 Mg ha^{-1} (26 bu ac^{-1}) at the highest population of 4.9 plants m^{-2} (20 000 plants ac^{-1})

Yield $plant^{-1}$, kernel weight, and kernels $plant^{-1}$ were also impacted by hybrid, with higher values for each yield component produced by 8534YG1/RR (Table 3.6).

Table 3.6 - Red Willow 2007 Effect of Hybrid on Yield Plant^{-1}, Kernel Weight, and Kernels Plant^{-1}

Hybrid	Yield Plant^{-1}		Kernel Weight		Kernels Plant^{-1}	
	g (lb.) plant^{-1}		g (oz) 100^{-1}			
8534YG1/RR	477.3 (1.05)	a†	33.1 (1.17)	a	656.5	a‡
8812YG1/RR	413.8 (0.91)	b	30.4 (1.07)	b	610.2	b

† Within column means separation by LSD (0.01)
‡ Kernels Plant^{-1} means separation by LSD (0.05)

Population affected grain yield plant^{-1} (Figure 3.12) and kernels plant^{-1} (Figure 3.13). As population increased both yield components declined in a linear fashion.

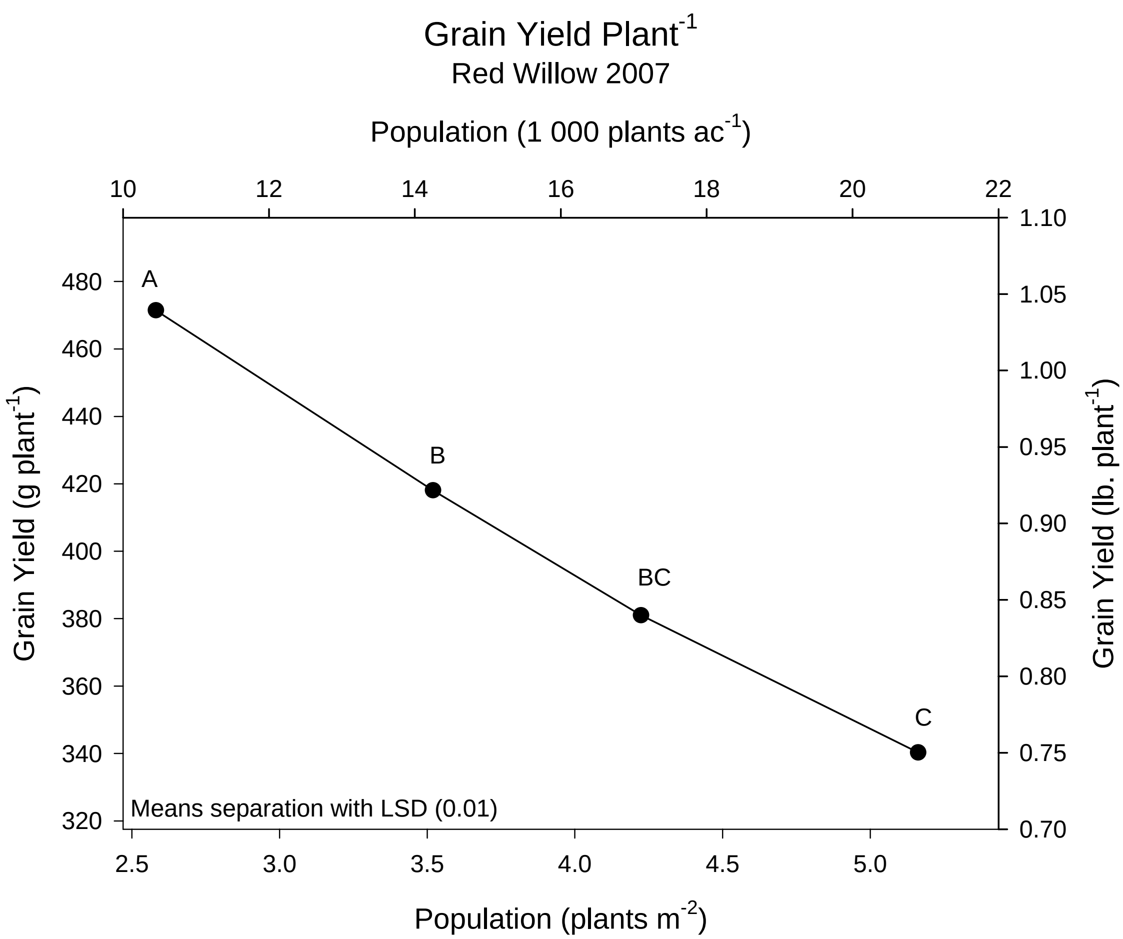

Figure 3.12 - Red Willow 2007 Grain Yield Plant^{-1} – Population

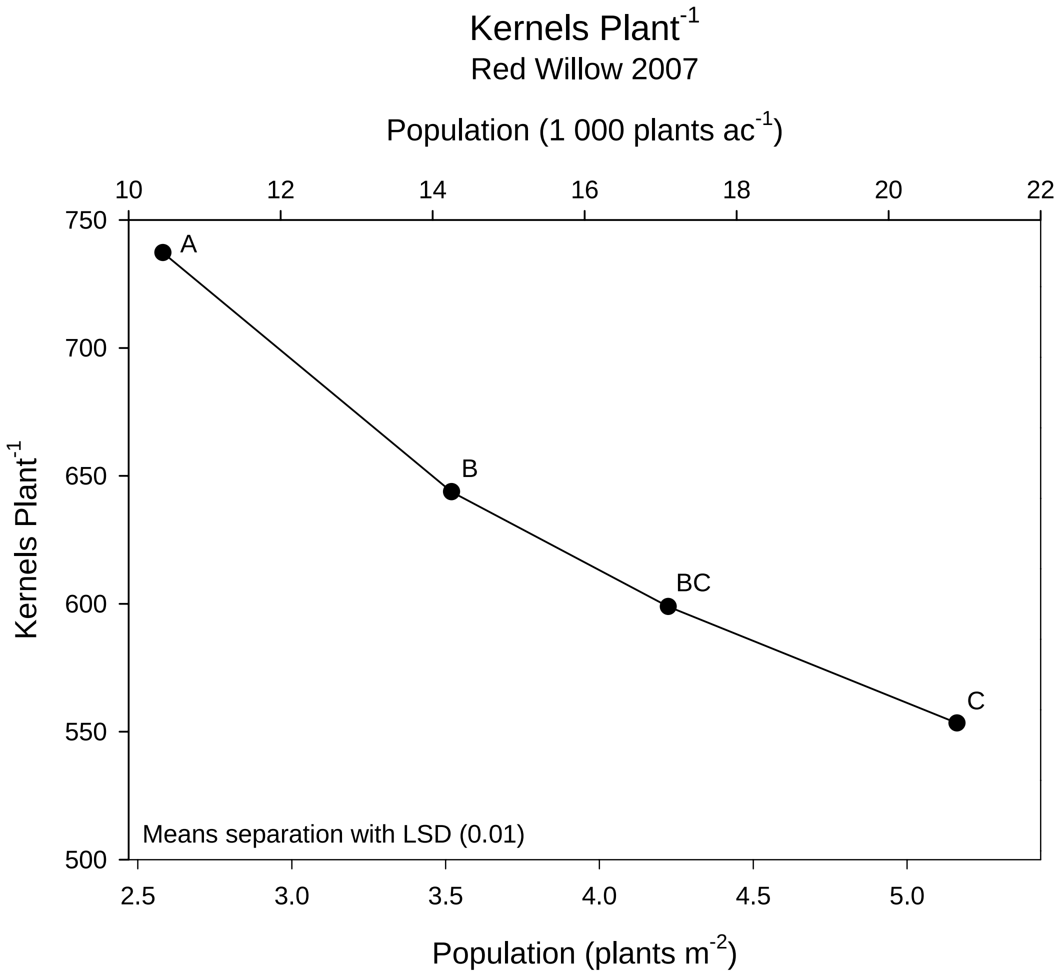

Figure 3.13 - Red Willow 2007 Kernels Plant^{-1} - Population

Kernel weight responded in a quadratic manner to increasing plant population (Figure 3.14). The first derivate was evaluated with the optimal found at 3.5 plants m^{-2} (14 290 plants ac^{-1}).

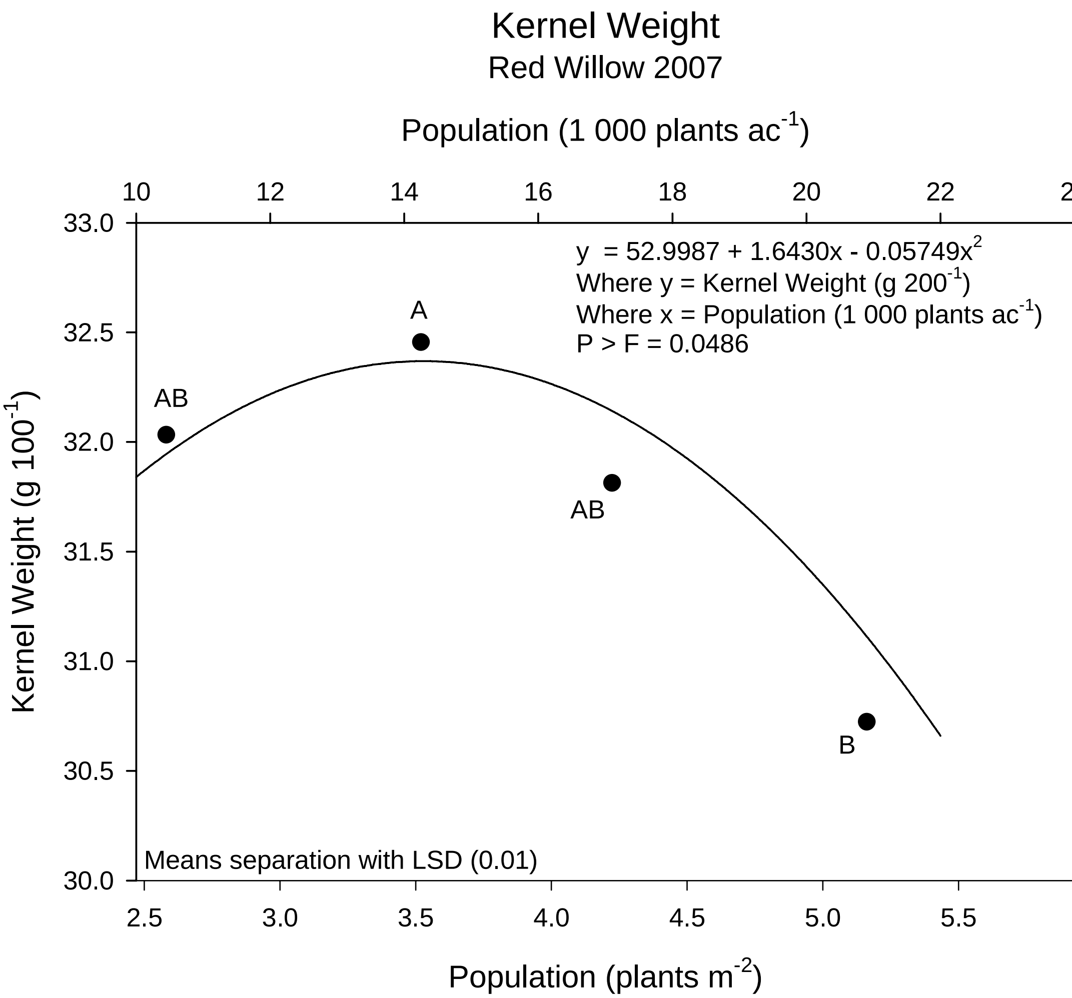

Figure 3.14 - Red Willow 2007 Kernel Weight

Rawlins 2007

Conditions at the 2007 Rawlins County plot were similar to those experienced at the Red Willow County plot. For approximately the first two months of fallow period following wheat harvest cumulative precipitation was as much as 5 cm (2 in) below normal (Figure 3.15). However, after the first part of October precipitation rose above normal and remained that way throughout the crop year. At planting (17 May, 2007), the cumulative precipitation for the crop period and proceeding fallow period (starting 1 July,

2006) was 16.9 cm (6.65 in) above normal. Favorable growing conditions continued throughout the year as reflected in an average grain yield of 6.2 Mg ha^{-1} (98.8 bu ac^{-1}) across all treatments. Cumulative precipitation varied from the high observed at planting to a low of 6.65 cm (2.62 in) above normal on 8 July, 2008. Temperatures and relative humidity were also favorable for much of the growing season (data not shown).

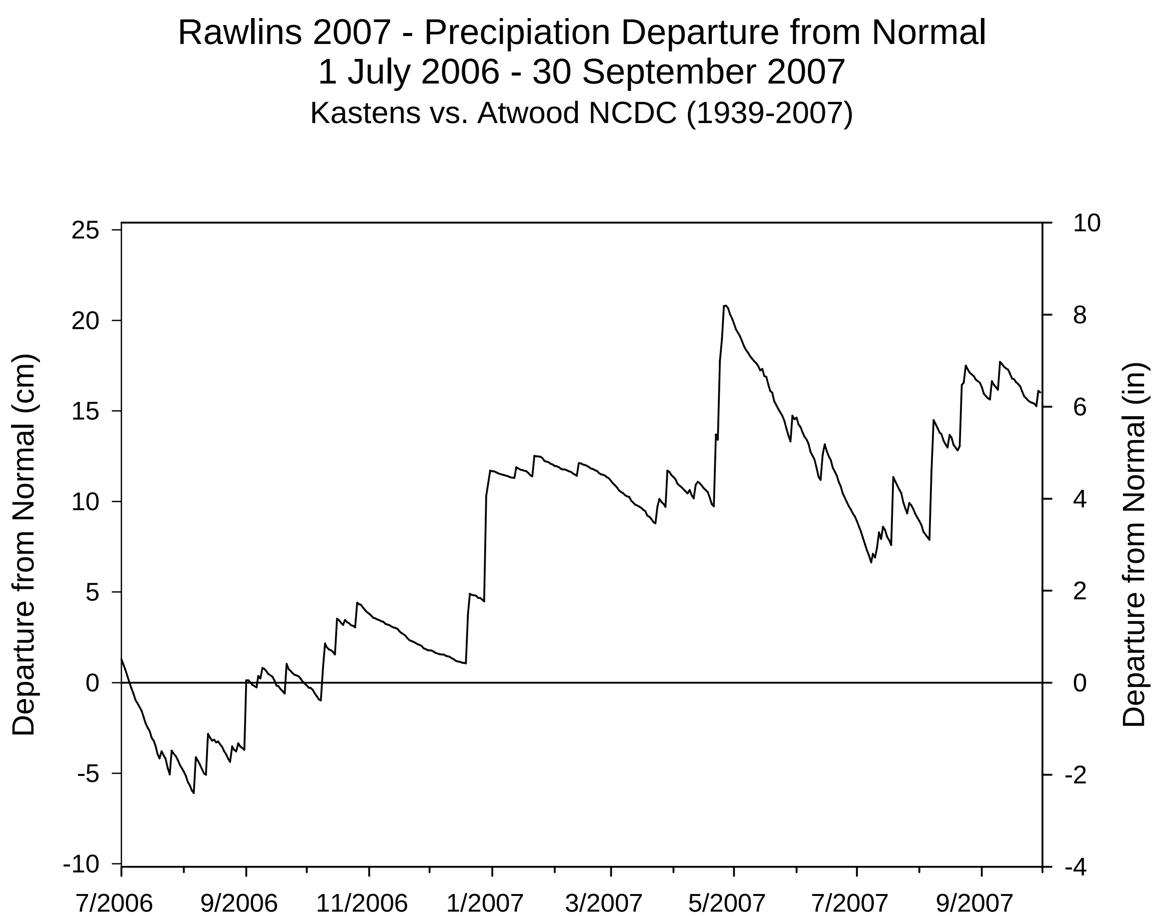

Figure 3.15 - Rawlins 2007 Cropping Period Precipitation

As previously discussed, experiment design issues at the Rawlins 2007 location preclude a tradition ANOVA across the entire study. An analysis was performed (Table 3.7) as through stubble treatments were randomized at the A level of the Split-plot design. The grain yield means for the 71 cm (28 in) stripped and 33 cm (13 in) stubble were 6.5 and 5.9 Mg ha^{-1} (103.6 and 94.4 bu ac^{-1}) respectively. Although the stubble main effect was significant in the analysis, no valid comparisons can be made and the means are provided for information only. The only source of variation that was potentially valid for analysis and significant is stubble x hybrid, which affected grain yield, yield plant^{-1}, and kernels plant^{-1}.

Table 3.7 – Rawlins 2007 ANOVA for Yield and Yield Components – Including Stubble Main Effect

	Grain Yield	Yield Plant^{-1}	Kernel Weight	Kernels Plant^{-1}
Source		P > F		
Rep	0.0057	0.0046	0.6902	0.0008
Stubble	0.0222	0.0139	0.3608	0.0041
Population	0.0326	<.0001	0.1751	<.0001
Stubble x Population	0.2149	0.2041	0.8337	0.1241
Hybrid	<.0001	<.0001	<.0001	0.0032
Population x Hybrid	0.9916	0.727	0.0022	0.9173
Stubble x Hybrid	**0.0003**	**0.0002**	0.4857	**0.0012**
Stubble x Population x Hybrid	0.914	0.7487	0.6884	0.7672

The stubble x hybrid interaction resulted from the performance of 8534YG1/RR in the stripped stubble treatment. Grain yield (Figure 3.16), yield plant^{-1} (Figure 3.17), and kernels plant^{-1} (Figure 3.18) were all greater for this hybrid x stubble combination. All other treatment combinations resulted in approximately equal responses.

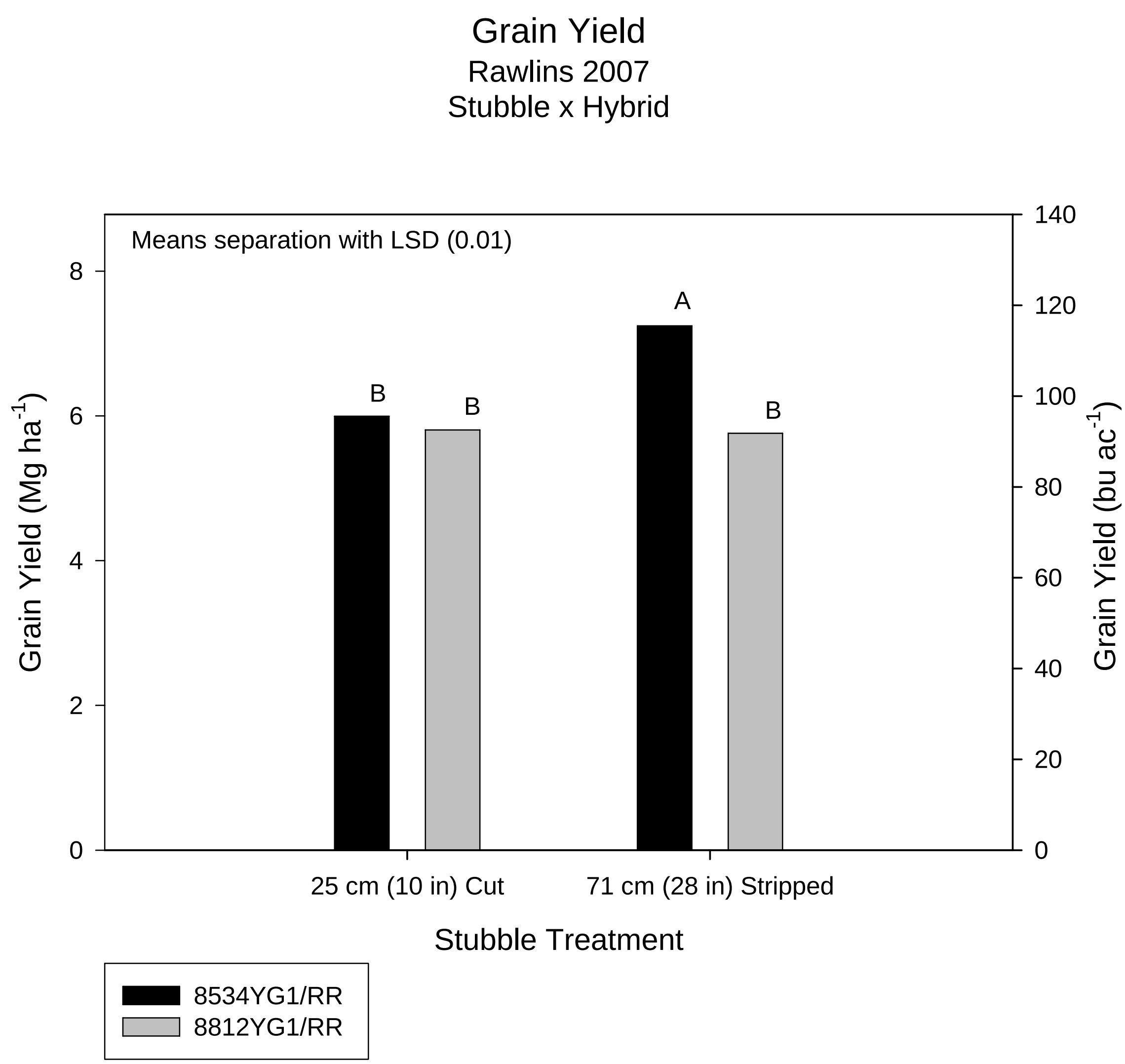

Figure 3.16 - Rawlins 2006 Grain Yield - Stubble x Hybrid

Grain yield for 8534YG1/RR in the stripped stubble treatment was 7.25 Mg ha^{-1} (115.5 bu ac^{-1}) compared with yields of 6.0 Mg ha^{-1} (95.5 bu ac^{-1}) for the same hybrid in the cut stubble and an average yield of 5.8 Mg ha^{-1} (92.2 bu ac^{-1}) for 8812YG1/RR across stubble treatments.

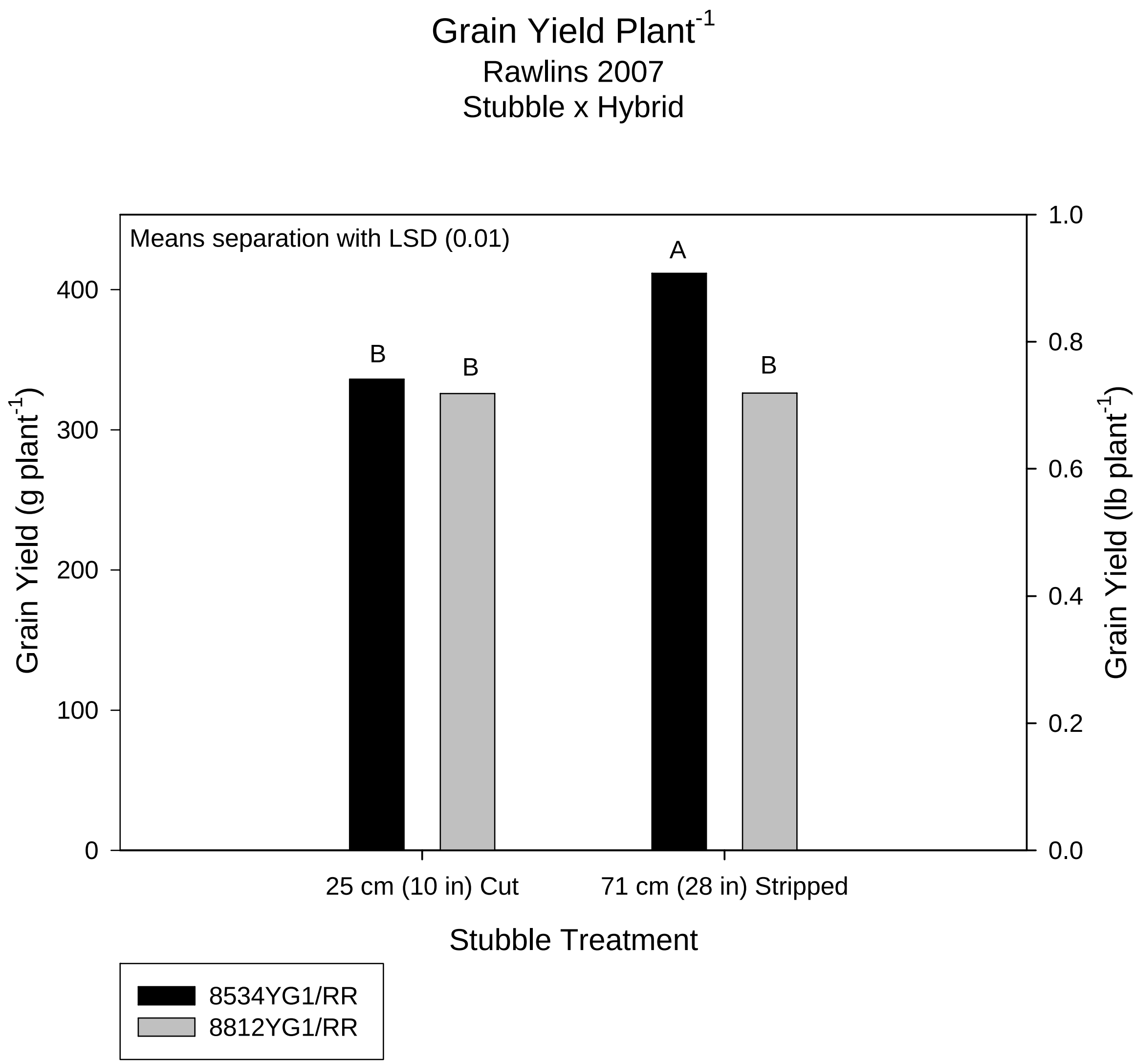

Figure 3.17 - Rawlins 2007 Grain Yield Plant^{-1} - Stubble x Hybrid

Grain yield plant^{-1} for 8534YG1/RR in stripped stubble was 412.8 g plant^{-1} (0.91 lb plant^{-1}) compared with 335.7 g plant^{-1} (0.74 lb plant^{-1}) for the same hybrid in the cut stubble. Grain yield plant^{-1} for 8812YG1/RR regardless of stubble treatment was 326.6 g plant^{-1} (0.72 lb plant^{-1}).

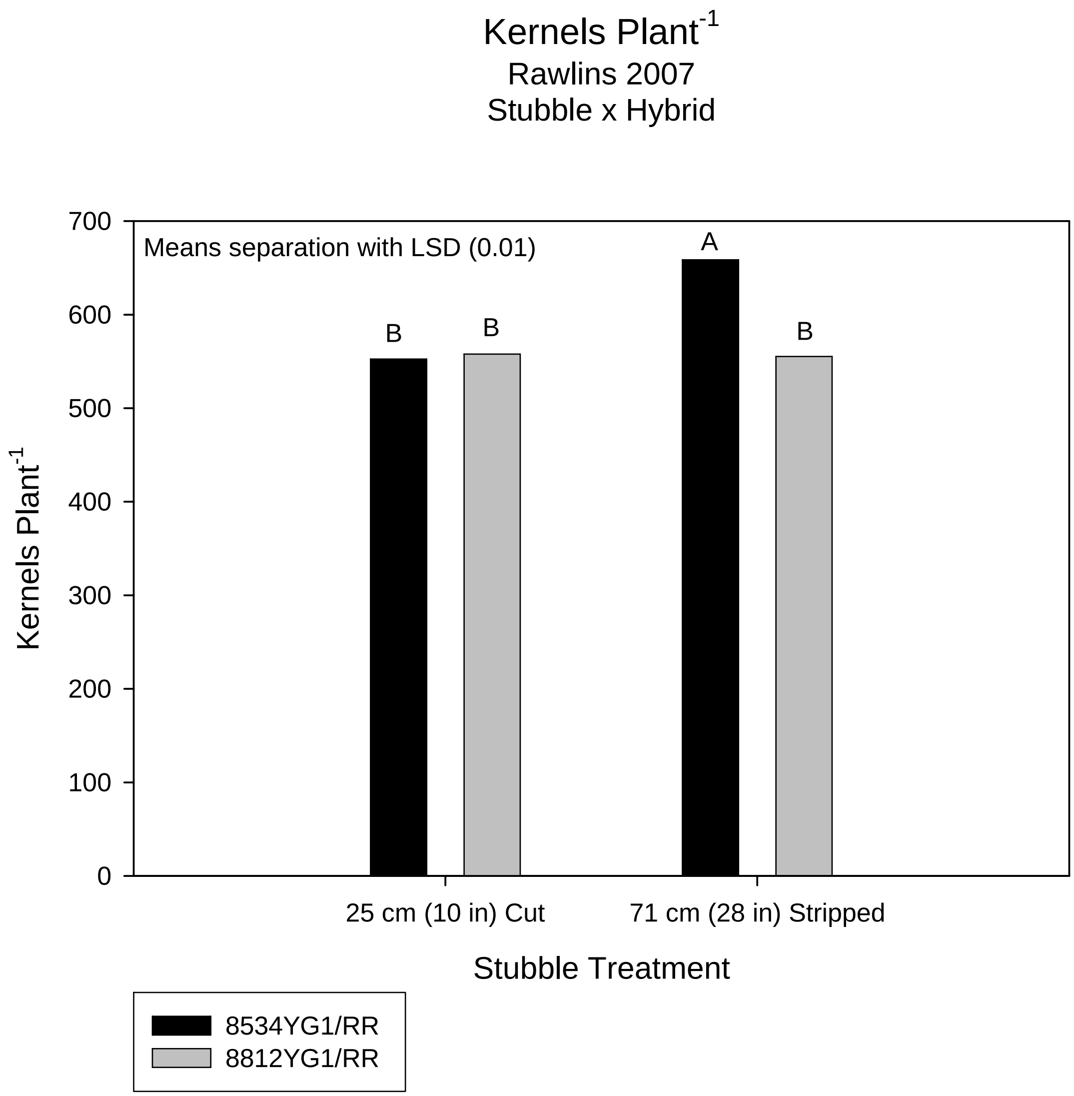

Figure 3.18 - Rawlins 2007 Kernels Plant^{-1} - Stubble x Hybrid

Hybrid 8534YG1/RR produced more kernels plant^{-1} in stripped stubble at 659 kernels compared with 552, 555, and 558 kernels for the same hybrid in cut stubble, and 8812YG1/RR in stripped and cut stubbles respectively.

A proper analysis could be conducted on population and hybrid evaluated with the respective stubble treatments as described in the methods and materials section. Results of ANOVA for each stubble treatment are presented in Tables 3.8 and 3.9.

Table 3.8 - Rawlins 2007 ANOVA for Yield and Yield Components - Stripped Stubble

	Grain Yield	Yield Plant^{-1}	Kernel Weight	Kernels Plant^{-1}
Source		P > F		
Rep	0.0184	0.0501	0.0875	0.0660
Population	0.4749	**0.0004**	0.4703	**0.0004**
Hybrid	**<.0001**	**<.0001**	<.0001	**0.0002**
Population x Hybrid	0.9913	0.5736	**0.0570**	0.9680

Table 3.9 - Rawlins 2007 ANOVA for Yield and Yield Components - Cut Stubble

	Grain Yield	Yield Plant^{-1}	Kernel Weight	Kernels Plant^{-1}
Source		P > F		
Rep	0.0239	0.0249	0.9420	0.0109
Population	**0.009**	**<.0001**	0.4069	**<.0001**
Hybrid	0.3998	0.4116	0.0102	0.8086
Population x Hybrid	0.8969	0.9441	**0.0516**	0.6712

The hybrid main effect on grain yield, yield plant^{-1}, and kernels plant^{-1} in the 71 cm (28 in) stripped stubble treatment were previously discussed and are graphically presented in Figures 3.16, 3.17, 3.18). The affect of plant population on grain yield in the cut stubble was significant (P>F = 0.009). The response is shown in Figure 3.19. Although the population main effect was not significant for the stripped stubble, and no cross stubble treatment comparisons can be made, the means are plotted in Figure 3.19 for informational purposes and reader interpretation.

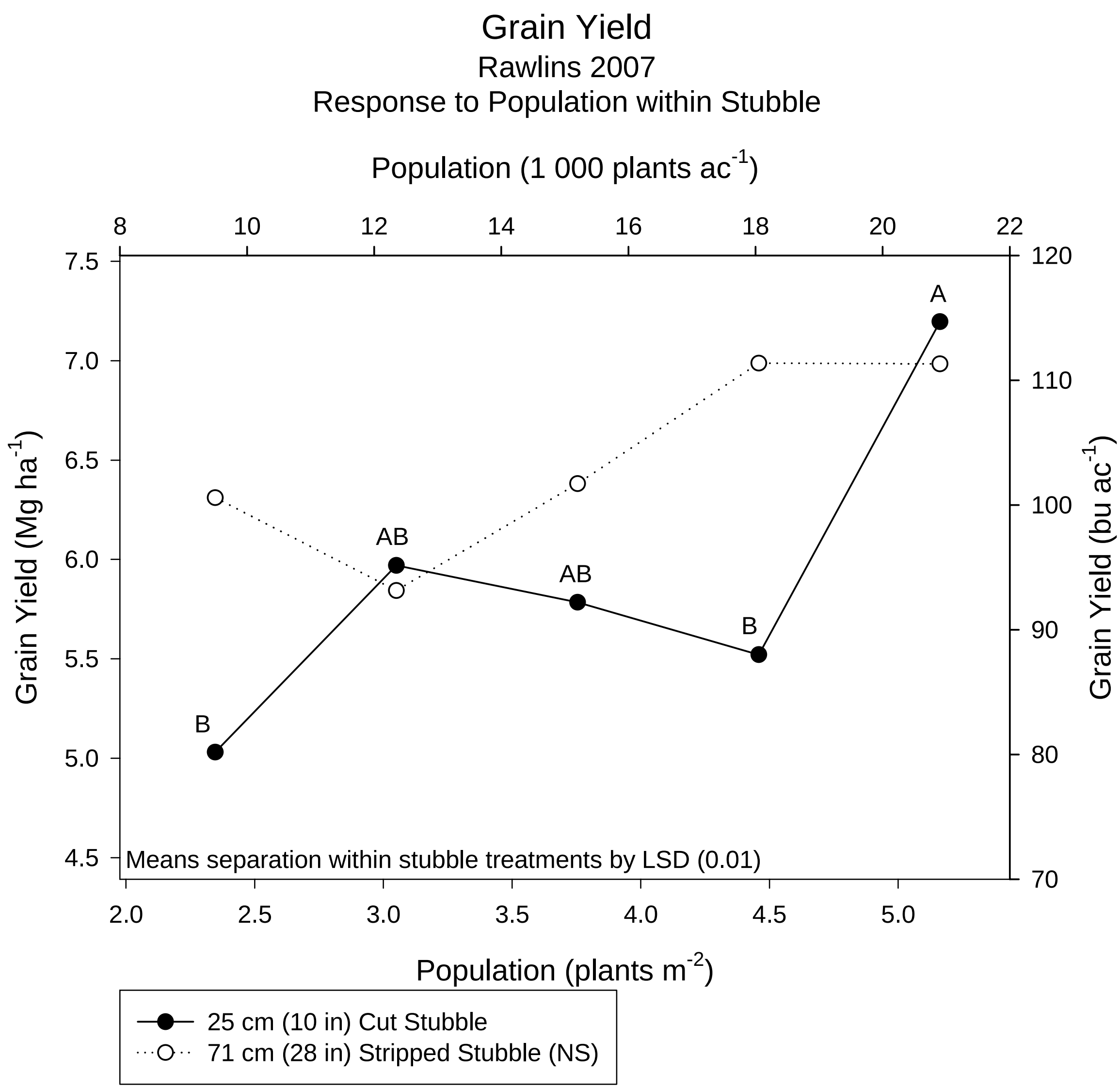

Figure 3.19 - Rawlins 2007 Grain Yield - Population within Stubble

Grain yields were maximized at the highest population in the study 5.2 plants m^{-2} (20 900 plants ac^{-1}). Below this population level the response was somewhat erratic. However the lowest grain yield occurred at the lowest population in the study 2.4 plants m^{-2} (9 500 plants ac^{-1}).

Plant population affected yield $plant^{-1}$ in both stubble treatments (Figure 3.20). Letter groupings presented are only valid within stubble treatments.

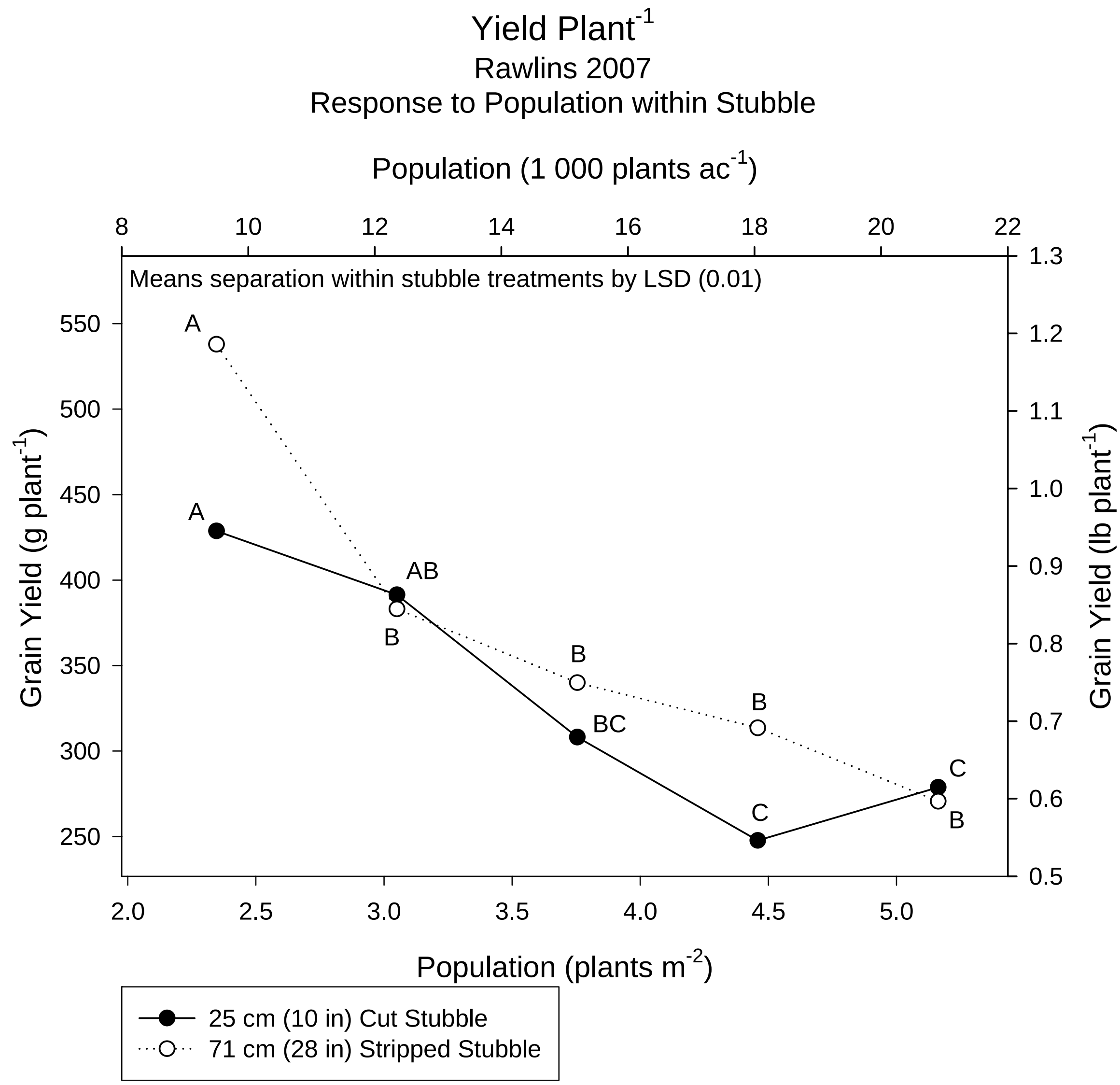

Figure 3.20 - Rawlins 2007 Yield Plant^{-1} - Population within Stubble

The largest single decline in yield plant^{-1} occurred in the stripped stubble treatment. As plant population increased from 2.4 plants m^{-2} (9 500 plants ac^{-1}) to 3.1 plants m^{-2} (12 350 plants ac^{-1}) grain yield plant^{-1} declined from 539.8 g plant^{-1} (1.19 lb plant^{-1}) to 381 g plant^{-1} (0.84 lb plant^{-1}). Yield plant^{-1} in the cut stubble treatment declined in a linear manner as plant population increased.

Kernels plant^{-1} responded in a fashion similar to that of yield plant^{-1} (Figure 3.21). The largest single decline in kernels plant^{-1} occurred in the 71 cm (28 in) stripped stubble treatment. As plant population increased from 2.4 plants m^{-2} (9 500 plants ac^{-1}) to 3.1 plants m^{-2} (12 350 plants ac^{-1}) kernels plant^{-1} declined from 871 to 634.

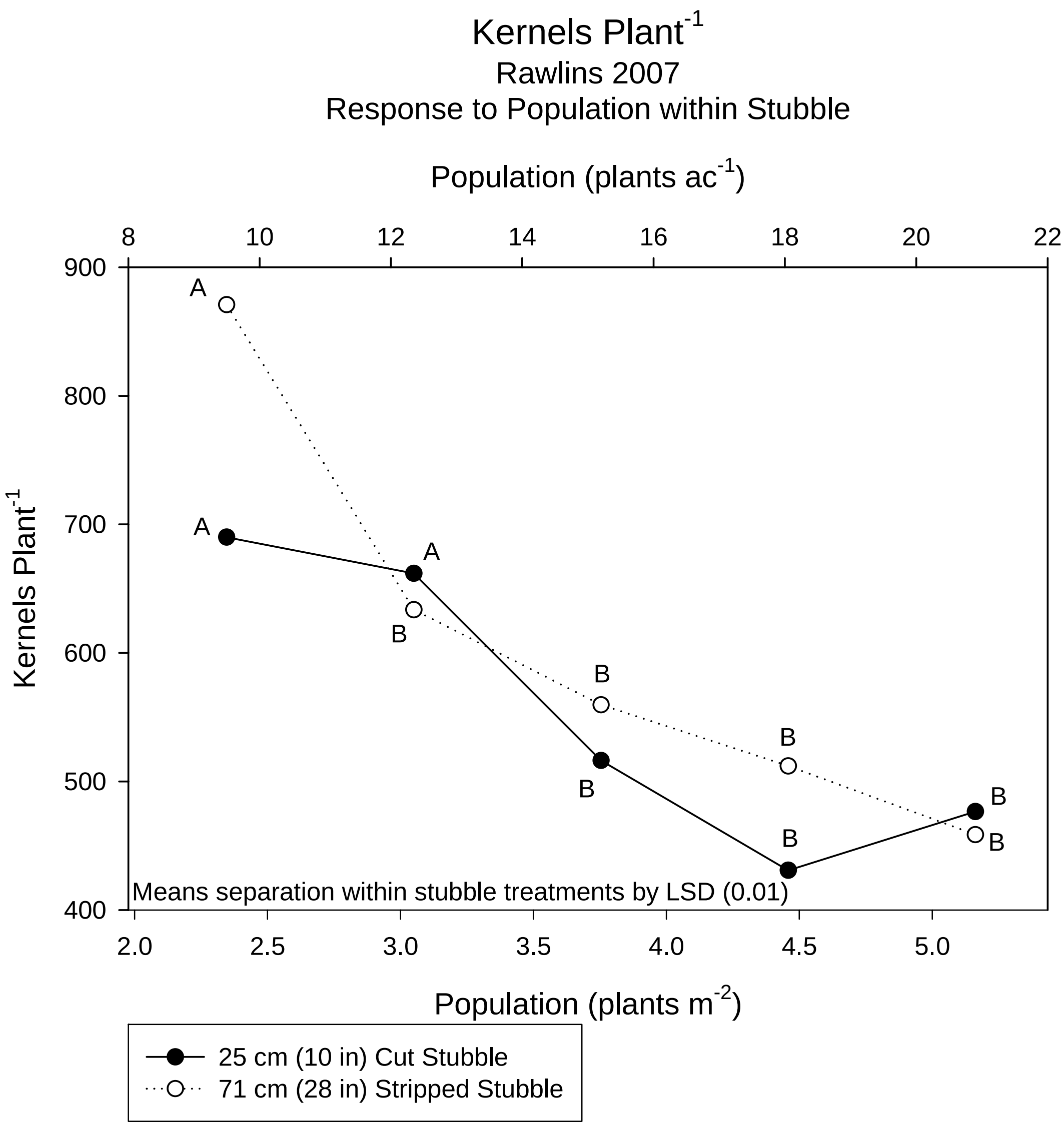

Figure 3.21 - Rawlins 2007 Kernels Plant^{-1} - Population within Stubble

A population x hybrid interaction affected kernel weight (Figure 3.22). Kernel weight for 8812YG1/RR was relatively stable with no differences evident across the entire range of plant populations. The response of 8534YG1/RR kernel weight to plant population was much more dynamic. As also observed with kernels plant^{-1} and grain yield plant^{-1} the largest single decline in kernel weight occurred in the stripped stubble treatment as plant population increased from 2.4 plants m^{-2} (9 500 plants ac^{-1}) to 3.1 plants m^{-2} (12 350 plants ac^{-1}) kernel weight declined from 32.9 to 29.9 g 100^{-1}.

Discussion

The impacts of stubble treatment on Decatur 2006 soil water at planting are important for a variety of reasons. The increases in soil water storage attributed to stubble treatments occur at depths important in the plant water extraction process. Water stored at these depths is also better protected to evaporative losses, especially in a no-till system with surface residue cover. Differences of approximately 50% the plant available range at both the 46 and 76 cm (18 and 30 in) depths are of importance when estimating the probability of success or failure for a grain crop. The ability to consistently impact soil water storage at these depths through changes in residue management could open opportunities for more intensified and dynamic cropping systems. The trend of increasing soil water with stubble height at the 7.6 cm (3 in) depth is noteworthy, however this region can be quickly influenced by evaporative losses and small precipitation events, thus making it extremely dynamic and of lesser relative value in cropping systems decisions. The difference in soil water at the 122 cm (48 in) depth between the intermediate stubble height, and the stripped and short cut stubble heights is somewhat perplexing. It is possible that this difference is representative of the sum of numerical differences present between the stripped and intermediate cut stubbles at shallow depths and that this water has not yet moved down through the soil profile.

Regardless of cause, the effect of such a situation is relatively unimportant when compared to differences at shallower depths, as this depth is of minor importance for soil water extraction by most crops.

In the dry year of the study, the two taller stubble treatments, 25 cm (10 in) cut and 71 cm (28 in) stripped resulted in higher grain yields across all populations and for both hybrids in the study (Figures 3.3 and 3.4). All yield components decreased with increasing population and shorter stubble height. Higher levels of soil water at planting in the taller stubble treatments undoubtedly impacted the performance of corn and the response to plant population.

Differences among hybrids were clear among the environments (years). The short season hybrid, 8812YG1/RR, outperformed the long season hybrid, 8534YG1/RR, despite its relatively lower ratings for ear flex at Decatur 2006. Under the highest stress condition, 10 cm (4 in) cut stubble with increasing plant populations, the short season hybrid maintained grain yields at approximately 2 Mg ha^{-1} (32 bu ac^{-1}). The long season hybrid under the same conditions declined from 1.9 Mg ha^{-1} (30.8 bu ac^{-1}) to as low as 1.0 Mg ha^{-1} (16.1 bu ac^{-1}). This certainly was a timing issue as tasseling, silking, and grain fill in the short season hybrid occurred earlier in the season, with higher levels of soil water than the long seasoned hybrid. Trooien et al. (1999) confirmed that shorter season hybrids consumed less water than long season hybrids. The water use rate however did not differ between hybrids, so any benefit to a short season hybrid in a drought year results from simply having more water still available in the profile for the critical reproductive stages. Stubble height, and subsequent soil water at planting, impacted both the response and overall yield level of the long season hybrid at the higher populations. In the shortest stubble, grain yield decreased with increasing plant population, while in the intermediate and tall stubble, grain yield increased. The short season hybrid, 8812YG1/RR, did not respond to changes in plant population, but yield level was affected by stubble height as average grain yield for the short stubble treatment was 42% less than that of the intermediate or tall stubble heights. Differences in response to increasing plant population were evident in the calculated "effect of crowding". Following the procedure outlined by Duncan (1958) the log of grain yield $plant^{-1}$ was plotted as a function of population, linear equations were fit and contrast regarding the slopes were made for both 8534YG1/RR (Figure 3.22) and 8812YG1/RR (Figure 3.23).

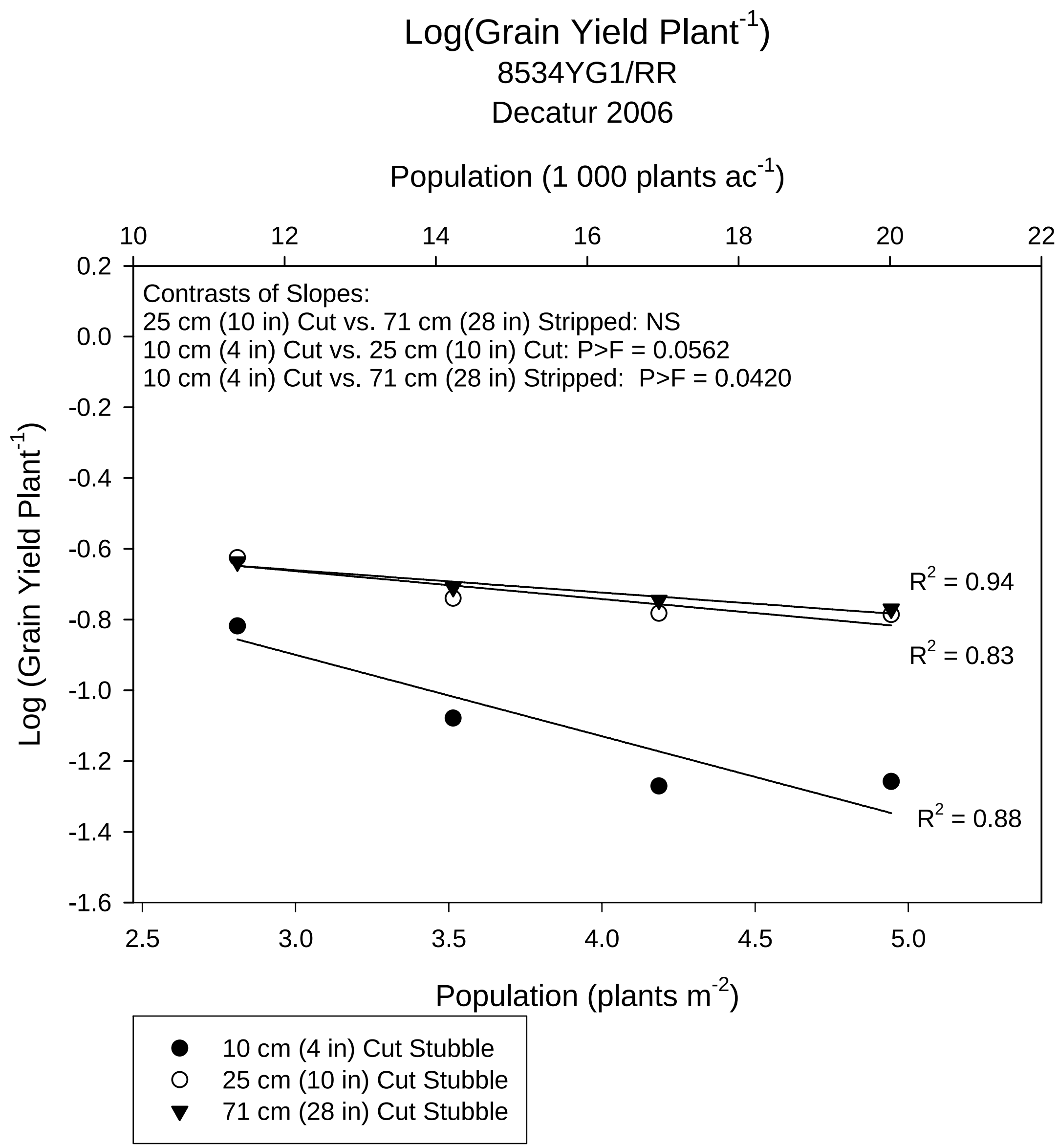

Figure 3.22 - Decatur 2006 Log(Grain Yield Plant^{-1}) - 8534YG1/RR - Stubble x Population

The effect of crowding term, or slope of the linear regression, was different for each of the two taller stubble treatments when compared with the short cut stubble. The two taller treatments were not different from each other.

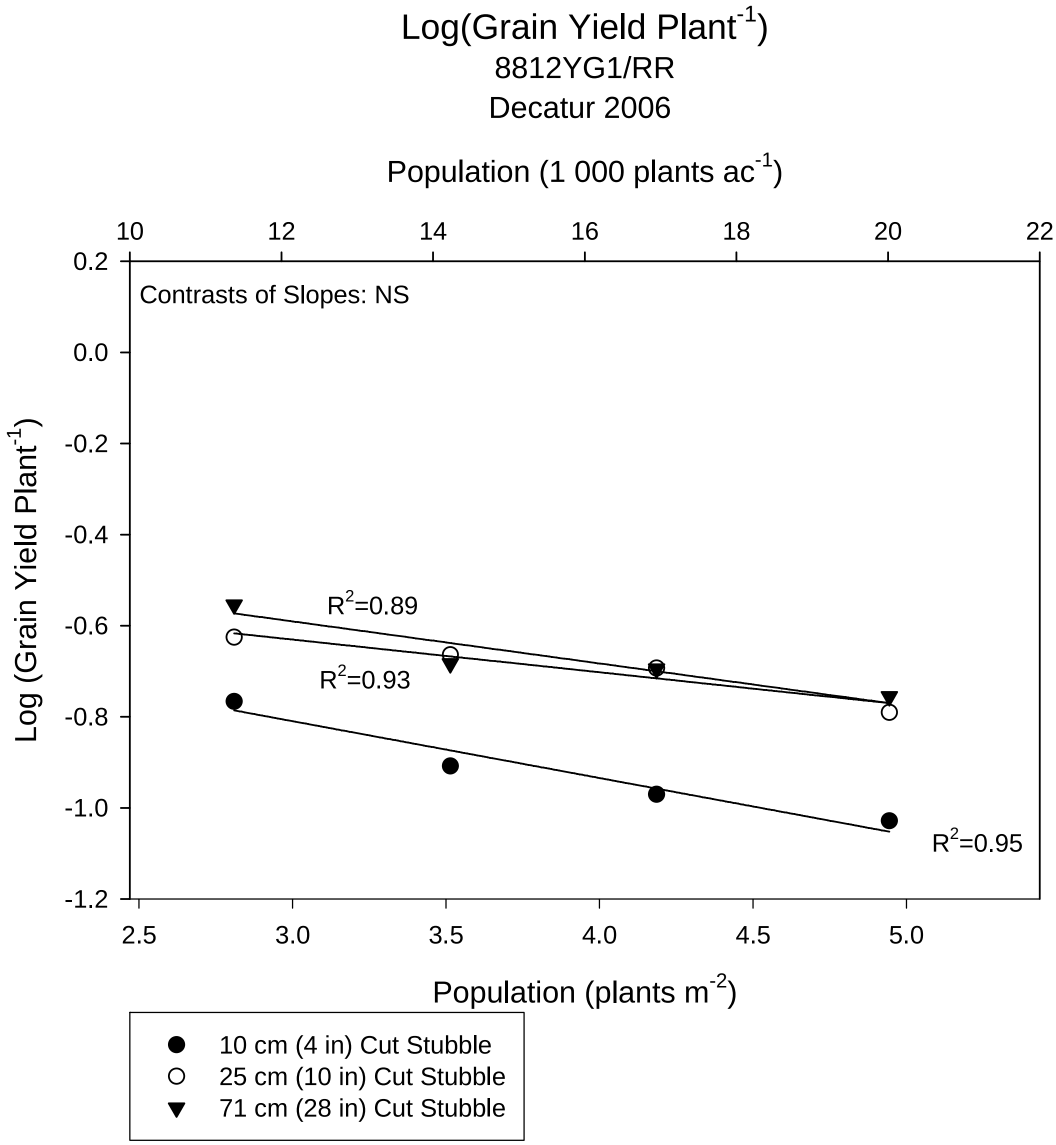

Figure 3.23 - Decatur 2006 Log(Grain Yield Plant^{-1}) - 8812YG1/RR - Stubble x Population

No differences in the response to increasing plant population were observed among stubble treatments for 8812YG1/RR when evaluated with the effect of crowding term (Figure 3.23).

At Red Willow 2007, a wet year with good growing conditions, the longer season hybrid produced higher yields than the short season hybrid at all populations and was more responsive to increases in plant population. Higher levels of all yield components were also observed for the longer season hybrid. The hybrid X population responses observed at Decatur 2006 and Red Willow 2007 agree with work presented by Larson and Clegg (1999). They found in southeast Nebraska that in years of water stress, long season hybrids were more susceptible to yield reductions at high plant populations. However, in a year with good growing conditions long season hybrids produced maximum yield at high plant populations. Two of the three short season hybrids evaluated in their study produced similar yields across populations and independent of late season water stress.

Yield plant^{-1} and kernels plant^{-1} exhibited negative linear relationships to increasing plant population at every location with respect to various stubble and hybrid interactions as well. In the dry year of the study, Decatur 2006, kernels plant^{-1} for the 10 cm (4 in) stubble treatment were always lower than the other two stubble height treatments. Although not statistically comparable, kernels plant^{-1} were typically lower numerically for the 33 cm (13 in) stubble than the 71 cm (28 in) stubble at the Rawlins 2007 location.

Grain yield, yield plant^{-1}, and kernels plant^{-1} for 8812YG1/RR at Decatur 2006, were different among the three stubble treatments at the lowest population. As population increased the responses were not different and trended together. This typically occurred by the response of the stripped treatment declining sharply and matching the response of the intermediate cut stubble for the balance of the population range. Similar results were shown at Rawlins 2007 where yield plant^{-1} and kernels plant^{-1} with hybrids pooled, and kernel weight for 8534YG1/RR, were different between stubble treatments at the lowest population. Again, as population increased the first step, the response of the stripped stubble treatment rapidly declined. It is possible that this clear difference among stubble treatments at the lowest population is tied to the ratio of plant transpiration to soil evaporation. Ritchie and Burnett (1971) showed that plant transpiration relative to potential evaporation was influenced by leaf area index. Persuad and Khosla (1999) showed that total water use for dryland corn in Virginia remained unchanged across plant populations of 3.7, 4.9, and 6.2 plants m^{-2} (15 200 and 25 000 plants ac^{-1}). The partitioning between plant transpiration and soil evaporation changed with plant population, with the fraction allocated to transpiration decreasing as plant population decreased. This would imply that strategies effective in reducing bare soil evaporation would become more important at lower plant populations. Todd et al. (1991) showed in western Nebraska that both straw mulch and crop canopy shading played in important role in reducing evaporative losses. Crop canopy was the driving factor in their study, reducing evaporation 0.3 to 0.5 mm d^{-1}, while the presence of a straw mulch reduced evaporation up to 0.1 mm d^{-1} when compared with bare soil evaporation under dryland conditions. Amount and architecture of the straw mulch were not documented. Stripped stubble has been shown to reduce bare soil evaporation by 26% in some cases (Baumhardt, 2002). This advantage would be more prevalent at lower plant populations and could possibly explain some of the responses seen in this study. The effects of residue level and architecture on ET partitioning would be worthy of future study.

Kernel weight produced a variety of responses to stubble, population, hybrid, and environment. In the dry environment, Decatur 2006, kernel weight was influenced by a stubble X hybrid interaction with a plateau of approximately 26.5 g 100^{-1} at the 71 cm

(28 in) and 25 cm (10 in) stubble heights. However the shortest stubble treatment, 10 cm (4 in) drastically reduced kernel weight especially in the longer season hybrid, 8534YG1/RR. Kernel weight for the short season hybrid 8812YG1/RR also declined but was more linear in nature. Kernel weight is typically impacted by stress during grain fill whereas stresses at silking typically impact kernel number plant^{-1}. The additional depletion of soil water by the longer season hybrid likely put the plant under additional stress as grain fill was occurring, which was compounded by the lower amount of profile water in the short cut stubble at planting. Rawlins 2007 again demonstrated hybrid differences in kernel weight response, as 8812YG1/RR was completely unresponsive across populations while 8534YG1/RR showed a decreasing linear trend. At Red Willow 2007 kernel weight responded to population in a quadratic form across plant populations and was higher for the longer season corn. It would be reasonable to believe for the environmental conditions at Red Willow 2007, the quadratic response is assimilate source limited in the region below the curve, as the plant population was much less than what the environment could support. Areas above the region then represent a typical observation of reductions in kernel weight with increasing plant population.

Lack of differences between stubble height treatments of 25 cm (10 in) or 33 cm (13 in) and 71 cm (28 in) are contrary to field observations and on-farm research conducted by producers. One variable evidenced in anecdotal reports is the change in residue architecture through the overwinter period. In some cases, stripped stubble has been found to go completely flat, forming a mat on the soil surface, or is tilted at an angle, reducing the height of the residue. The stripped stubble in these studies was often at an angle, reducing effective height at planting time but was seldom flat prior to the planting operation (Figure 3.24). It is likely that in some years no differences result because of climatic implications. For example, in 2007 stubble height did not play any role in grain yield, even the short cut height of 10 cm (4 in). The abundance of growing season water supply and good climatic conditions resulted in plant population being the yield-limiting factor. In dry years, the benefit observed is certainly in part to improved soil water storage. The research plots in this study were of design size and shape that failed to fully capture the impacts that stubble height would have on microclimatic effects such as the wind speed component to evaporation and snow catch. Plots that are 15.2 x 15.2 m (50 x 50 ft.) with randomized stubble height treatments are conducted without regard to the fetch necessary for capturing microclimatic effects. The use of plot planters narrow in width and repeated machine and foot traffic in the plots results in more alteration and destruction of residue than would occur in a production field. Figure 3.24 shows a stripped stubble treatment area after planting.

Figure 3.24 - Photo of Corn Planted into Stripped Stubble Treatment - Red Willow 2007

The area between the two center rows continues to have residue primarily upright in architecture, whereas the wheel traffic outside these two rows has completely flattened the residue in those areas. The use of larger plots and equipment working widths would have been preferred and possibly resulted in different outcomes, however the logistical and spatial variability issues with such plots bring about other challenges.

Conclusions

It is extremely difficult to draw conclusions from this work that are robust enough to make producer recommendations. The two years of this study are representative of the climatic extremes experienced in the High Plains region and the accompanying extremes in dryland corn production. However, several generalized observations can be made. In dry years, the longer season hybrid was more susceptible to late season water stress. Population response of the long season hybrid was impacted by stubble height in a dry year. Grain yield declined with increasing population in stubble 10 cm (4 in) in height and increased with increasing population in stubble 25 cm (10 in) and 71 cm (28 in) in height. Differences between stubble heights of 25 cm (10 in) or 33 cm (13 in) and 71 cm (28 in) occurred, but were not consistent among any of the measured soil water or corn production properties. Corn planted into taller wheat stubble produced higher yields in extremely dry years and produced yields no different than that planted into shorter stubble in extremely wet years. Thus, in our work we did not find any disadvantages to planting corn into taller stubble, such as would result from stripper header harvest.

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CHAPTER 4 - Site Specific Corn Yield Response to Population

Abstract

Increasing seed cost and availability of spatially dense datasets have presented new opportunities in developing site-specific recommendations for seeding. Two approaches, traditional small-plot and field scale, were implemented across 3 cooperator fields in northeast Kansas in 2005 and 2006. Sites for traditional small-plots were selected based on expected differences in population response as identified by soil electro-conductivity (EC) and topography. Responses to population were evident at several of the small-plot sites in various forms. The ability to select sites differing in response to population was demonstrated. A field scale approach was implemented by applying strips of varying populations across a known soil EC gradient induced by textural variability. Soil EC, as-applied planting data, and filtered yield monitor data were aggregated into a dataset for use in a spatial regression procedure. A function describing optimal seeding rate with respect to soil EC was developed. In the field under study, optimal seeding rates varied from 3.08 to 8.74 plants m^{-2} (12 500 to 35 375 plants ac^{-1}). Soil EC was used to develop a relationship to measured water holding capacity values. This quadratic relationship was significant ($p<0.0001$) and explained variability in water holding capacity with respect to EC quite well (R^2=0.6239). Field scale approaches appear to have potential in developing site-specific seeding rate recommendations. It is not clear if traditional small-plot data can be utilized to develop site-specific seeding rates or validate the results of a field scale approach. In this case, soil EC described 0 – 15 cm (0 – 6 in) water holding capacity exceptionally well, thus opening many opportunities for site-specific management with regard to spatially variable water holding capacity.

Introduction

Since the advent of precision agriculture technologies, variable rate application of various crop inputs has typically been viewed as the ultimate goal of collecting and analyzing site-specific datasets. Typically the focus has been on variable rate application of crop nutrients. This has been driven both by the economic and environmental implications of effective crop nutrient management. The development of site-specific crop response functions has proven to be a challenge not only for variable rate seeding, but for most other inputs. These response functions are necessary if site-specific management is to prove feasible.

The presence of soil variability is a prerequisite to obtaining value from any variable rate management method. Lowenberg-Deboer (1999) reported that the economics of variable rate seeding improved greatly as the percentage of low yielding area within a field increased. Returns were actually presented as negative in medium yielding fields. However this was done with an assumed seed cost of \$67 bag^{-1}. In their study, variable rate seeding was assumed to be applied to three yield zones rather than a continuous spatial prescription across the field. Bullock et al. (1998) analyzed data from a seed company study carried out from 1987 through 1996 on 170 different fields throughout the U.S. Corn Belt. They concluded that potential returns ranged from \$0.15 to \$12.8 ha^{-1} (\$0.06 to \$5.18 ac^{-1}) depending upon the level of information the producer had available for management decisions. Various levels of adoption were evaluated from the producer having knowledge of the seeding response for every area of the field, and the capability to apply the correct rate, down to the level where the producer is making a whole-field seeding rate decision utilizing a few years of collected yield monitor data.

Taylor et al. (2000) implemented variable rate seeding in northeast Kansas with relatively basic information. Soil electro-conductivity (EC) was broken into 5 ranges, representative of yield potential. Replicated strips of plant populations were planted across an EC gradient. Using yield monitor data the optimal plant population for each of the 5 EC ranges was determined. A significant quadratic response of yield to seeding rate and EC was reported. This study was conducted over several fields and the yield response to a population x EC interaction was not consistent. They concluded that possible returns were in the range of \$0.49 to \$1.24 ha^{-1} (\$0.20 to \$0.50 ac^{-1}) and that less expensive ways of generating response functions would be necessary.

Ehsani et al. (2005) also used soil EC to classify seeding rate responses. When grain yield was evaluated simply as a function of seeding rate no response was evident. However response functions were clearly evident when the soil EC range within the field was divided into the 25, 50, and 75 percentile values and used to classify the yield data. A variety of models were used on the data with the most precise estimates of yield (R^2 = 0.89) resulting from the use of a neural network technique.

Shanahan et al. (2004) used replicated treatment strips of two hybrids at four plant densities to develop population response curves for dryland corn in northeast Colorado. The yields for each treatment were block kriged over the entire study area. Soil attributes including elevation, slope, soil brightness, soil EC, pH, and soil organic matter were also block kriged over the entire area. Correlation analysis and stepwise regression techniques were used to identify characteristics that were related to yield. These soil attributes were able to explain 47%, 95%, and 76% of the spatial variability in grain yields over the three years. Optimal plant densities were determined for low, medium, and high yield regions in the field. The optimum plant population varied by 5 plants m^{-2} (2 000 plants ac^{-1}) between the high and low yield regions of the field, reducing seed cost by an estimated \$6.25 ha-1 (\$2.53 ac^{-1}).

A common trend among efforts in variable rate seeding has been the use of soil EC data. Soil electro-conductivity has been found to be highly correlated with texture (Domsch and Giebel, 2004, Brownson et al., 2005), soil water content (McCutcheon et al., 2006), bulk density (Johnson et al., 2001), and depth to hardpan (Sudduth et al., 1996, 2003). These relationships provide opportunities to use soil EC data to create spatially continuous and dense approximations of plant available water, and at a relatively low cost, thus making it attractive for use in developing variable rate seeding prescriptions.

While many have attempted to use soil EC to classify zones for management, full benefit of variable rate technologies will result from managing at the smallest scale possible. The ability to develop seeding prescriptions into a continuous surface, as opposed to a management zone philosophy will aid in maximizing the potential benefit from site-specific management. The objective of this research was to examine the relationships between soil EC, plant available water, and response to corn population.

Materials and Methods

Three cooperator fields in northeast Kansas hosted a combination of small plot and field-scale population studies. All fields were in no-till management. Nutrient management and weed control was managed exceptionally well by the cooperator. A summary of fields is presented in Table 4.1. Soil electro-conductivity (EC) data had been previously collected for all fields using a Veris 3100 sensing platform (Veris Technologies, Salina, KS).

Table 4.1 - Field Locations and Descriptions

Field	Years	Latitude	Longitude	Soil Series	Soil Classification
Ogden	2005, 06	96° 42' N	39° 7' W	Reading silt loam, rarely flooded	fine-silty, mixed superactive, mesic, Pachic Argiudolls
Airport	2005, 06	96° 40' N	39° 7' W	Reading silt loam, rarely flooded	fine-silty, mixed superactive, mesic, Pachic Argiudolls
				Ivan and Kennebec silt loams, ocassionaly flooded	fine-silty, mixed, superactive, mesic, Cumulic Hapludolls
				Eudora-Bismarckgrove silt loams, rarely flooded	coarse-silty, mixed, superactive, mesic, Fluventic Hapludolls
				Stonehouse-Belvue complex, occasionally flooded	sandy, mixed, mesic, Typic Udifluvents
				Bismarckgrove-Kimo complex, rarely flooded	fine-silty, mixed, superactive, mesic, Fluventic Hapludolls
Hog Ranch	2006	96° 44' N	39° 0' W	Reading silty clay loam, rarely flooded	fine-silty, mixed, superactive, mesic, Pachic Argiudolls

Small Plot Population Trials

Sites were selected in an effort to locate plots in areas that represented the relative extremes of plant available water within the field. A summary of small-plot research sites and physical soil properties is presented in Table 4.2.

Table 4.2 - Small-plot site details and physical soil properties

Field	Site ID	Study Years	Irrigation	0 - 15 cm (0 - 6 in) Soil Properties				
				Sand	Silt	Clay	Bulk Density	Water Holding Capacity
				-- percent by mass --			$g (cm^3)^{-1}$	$(cm^3)(cm^{-3})$
Ogden	1	2005, 2006	Dryland	13.5	62.3	24.2	1.56	-
	2	2005, 2006	Dryland	25.5	57.9	16.6	1.49	-
	3	2005, 2006	Dryland	36.7	51.7	11.6	1.51	-
Airport	1	2005	Dryland	-	-	-	-	0.154
	2	2005, 2006	Dryland	7.2	58.5	34.3	1.37	0.096
	3	2005, 2006	Dryland	41.2	49.3	9.6	1.45	0.110
	4	2005. 2006	Center Pivot	37.9	54.1	8	1.62	0.098
	5	2005	Center Pivot	-	-	-	-	0.100
	6	2005, 2006	Dryland	77.8	18.2	4	1.65	0.082
	7	2005	Center Pivot	-	-	-	-	0.079
	8	2006	Center Pivot	27.7	57.7	14.6	1.37	0.130
	9	2006	Center Pivot	60.6	33.4	6.1	1.59	0.163
Hog Ranch	1	2006	Center Pivot	7.6	66.8	25.6	1.31	-
	2	2006	Dryland	6.4	64.3	29.3	1.29	-

At the Ogden field, this was largely done with respect to topography and soil EC. All three sites at the Ogden location were located in one transect 12.2 m (40 ft) wide running the width of the field.

Three sites were placed along this transect, the first located at a relatively flat portion of the field, the second on the upward slope towards a ridge, and the third was centered across the peak of a ridge running perpendicular to the plots.

Sites at the Airport field were selected using shallow soil EC, 0-15 cm (0-6 in) measured PAW values, an EC – PAW mathematical relationship derived from sample data (described later), and location with respect to center-pivot irrigation coverage (Figure 4.1).

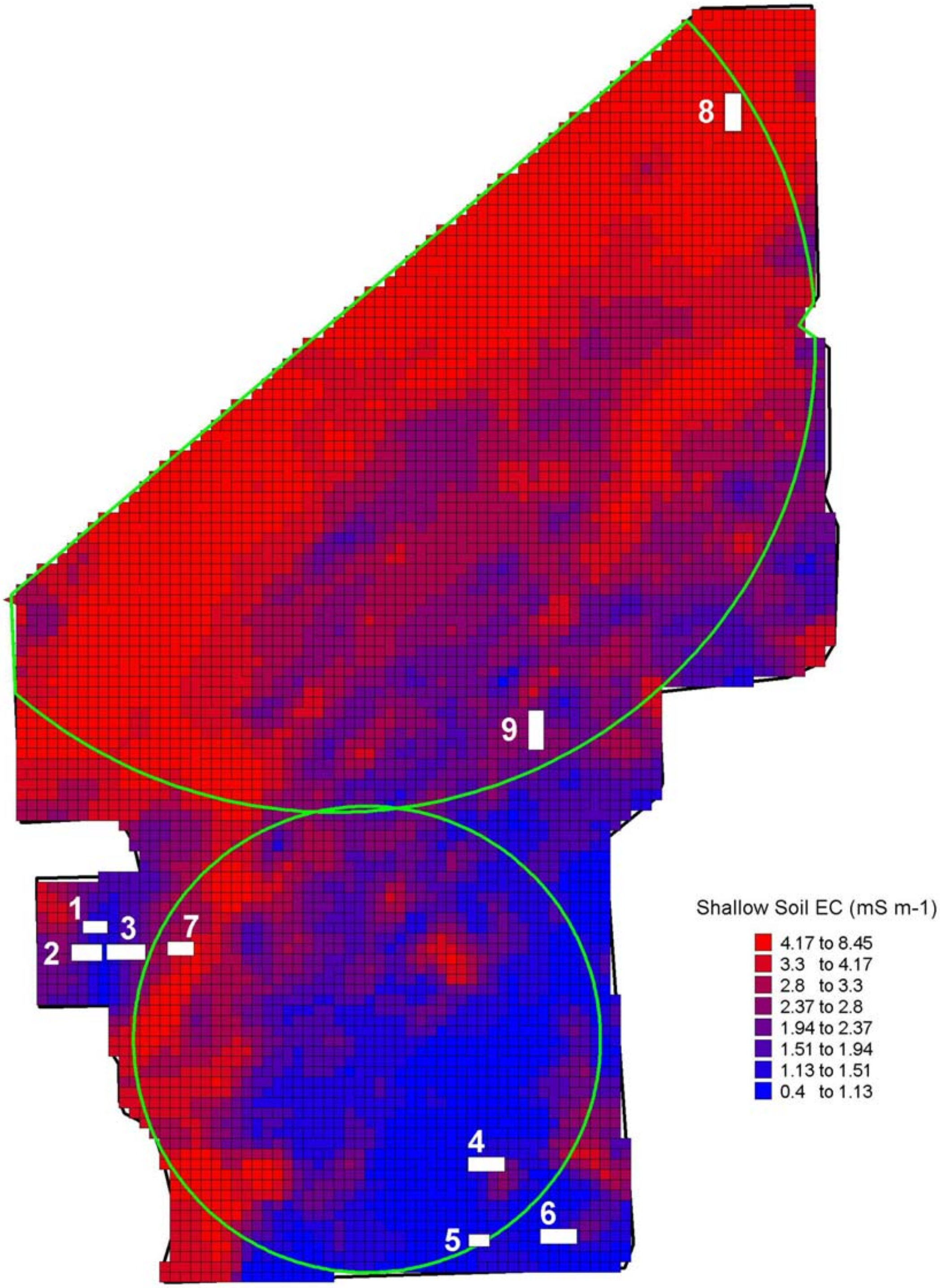

Figure 4.1 – Airport Field soil EC, center pivot coverage, and small plot study sites

Plot areas were planted by the cooperator with commercial seeding equipment. Seeding rates in these areas were increased to 9.4 plants m^{-2} (38 000 plants ac^{-1}). Plots were hand thinned to the treatment populations no later than the four leaf stage. Each plot consisted of four 76.2 cm (30 in) rows measuring 6.1 m (20 ft) in length. Treatments were arranged as a randomized complete block design with four replications. In 2005 four population treatments were used at the Airport location: 5.2, 5.9, 6.7, and 7.4 plants m^{-2} (21, 24, 27, and 30 000 plants ac^{-1}). Four population treatments were also used at the Ogden location: 4.5, 5.4, 6.2, and 6.9 plants m^{-2} (18, 22, 25, and 28 000 plants ac^{-1}). In 2006, a fifth population treatment was added so that treatments were: 5.2, 5.9, 6.7, 7.2, and 7.9 plants m^{-2} (21, 24, 27, 29, and 32 000 plants ac^{-1}) at all sites.

The center two rows of each plot were hand harvested at physiological maturity. Ear counts were made at the time of harvest. Ears where mechanically shelled, grain was sieved to USDA standards and analyzed for moisture content and test weight. Yields are reported at 15.5% grain moisture content. Kernel weight was obtained by randomly selecting 100 kernels from each plot, drying for 2 days at 105°C (221°F), and weighing. Kernels $plant^{-1}$, kernels ear^{-1}, and ears $plant^{-1}$ are calculated values.

The data were analyzed by site using Proc Stepwise in SAS version 9.1.3. Yield and yield components were modeled as independent variables with replication, population, and $population^2$ dependent variables available for selection.

Electro-Conductivity to Water Holding Capacity Relationship

Fifty-three randomly selected points within the Airport field were selected and sampled at a depth of 0 to 15.2 cm (0 to 6 in). These samples were analyzed for water content at field capacity and permanent wilting point using the pressure plate method (Klute, 1986). Soil electro-conductivity data was filtered by evaluating each individual data point in relation to its neighbors. Any point that was greater than 2 mS m^{-1} different from both adjoining points was deleted. A buffering algorithm developed in MapInfo 7.5 (MapInfo Corporation, Troy, NY) was used to query and average all soil EC points within a designed radius of the soil sample point and assign that value to a table. Radii of 15, 21, 30, 40, 46, 55, 61, and 70 m (50, 70, 100, 130, 150, 180, 200, and 230 ft.) were evaluated. Data were analyzed using Proc Stepwise with available water content of the sample as the independent variable and all linear and squared combinations of soil EC as dependent variable options. The search radii producing the best model was 30 m (100 ft) as determined by R^2 and Cp values.

Field Scale Population Trials

The Airport field was divided into cells measuring 12.2 m (40 ft) in width and 45.7 m (150 ft) in length for assignment to various population treatments (Figure 4.2). These cells were in line with the cooperators existing traffic patterns in the field. In the north half of the field, rows and cells ran north-south, while in the south half of the field, rows and cells ran east-west. Population treatments were assigned in two manners. First, solid strips of specified population were laid across the field for the length of the transect. These treatments, 6.2, 6.4, 6.9, 7.2, 7.4, and 8.6 seeds m^{-2} (25, 26, 28, 29, 30, and 35 000 seeds ac^{-1}) were designed to offer some baseline response curves across the soil EC trend. The rest of the cells in the field were randomly assigned seeding rates ranging from 5.4 to 8.6 seeds m^{-2} (22 to 35 000 seeds ac^{-1}).

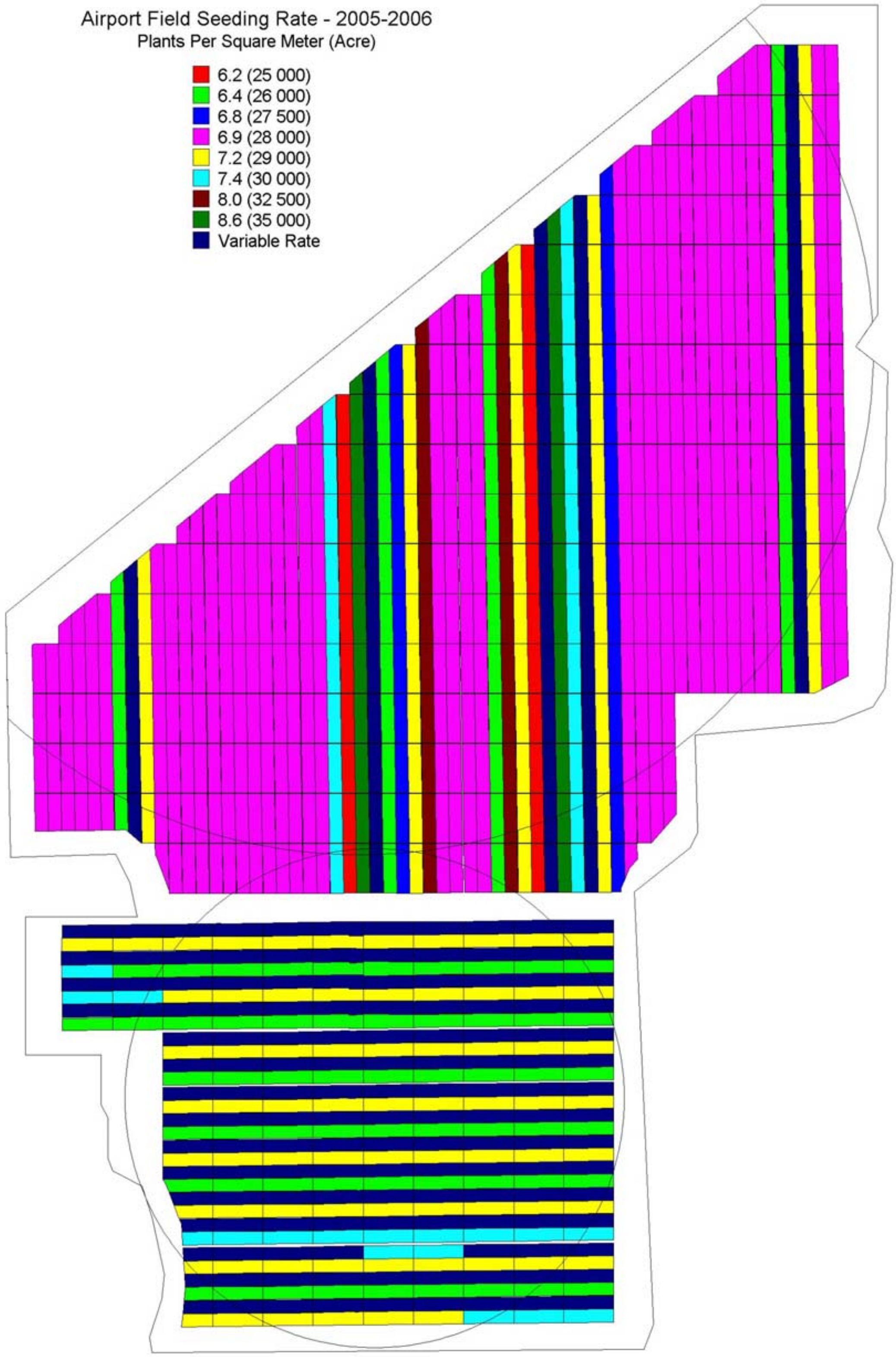

Figure 4.2 - Airport 2006 - VRT Seeding Blocks

After preparation, the prescription was applied by the cooperator at planting time through the use of a variable rate control system interfaced to a handheld computer. The field was machine harvested and yield was recorded with a properly calibrated yield monitor. Yield data were filtered with Yield Editor software (Sudduth and Drummond, 2007). Through this software, yield points collected at ground speeds outside the range of 3.2 to 10.5 kph (2 to 6.5 mph) were discarded. Any yield points that occurred in conjunction with a groundspeed change of greater than 10% were removed. A maximum yield limit of 20.4 Mg ha^{-1} (325 bu ac^{-1}) was used to eliminate any remaining outliers.

Yield and soil EC data were aggregated to the prescription blocks (Figure 4.2). Blocks were first selected and trimmed to represent the irrigated portion of the field. The dryland portions lacked the necessary size to amass a meaningful dataset for analysis. As-applied rate data logged at planting was assigned to each respective cell. In the process of converting soil EC data to a continuous surface, it became apparent that due to the pattern of data collection, second degree stationary could not be assumed and spatial variance structures were anisotropic in nature. Attempts to fit anisotropic semivariograms failed to result in an acceptable model over all axis, thus point or block kriging was not an option. The soil EC data were interpolated using GS+ version 7.0 (Gamma Design Software, Plainwell, MI). The inverse distance weighting method was used with a cell size of 40 m (131 ft), power of 1.5, and a smoothing factor of 2. Soil EC values were assigned to each population cell as a weighted average, based upon the proportion of each cell area that a given EC cell shared. Yield data points falling within a population block were averaged, and that value was assigned to the block. At the end of the aggregation process, each population block had a value for as applied seeding rate, soil EC, and grain yield.

The aggregated data were analyzed with a spatial regression technique that has been successful in various precision agriculture data analyses involving the use of yield monitor data (Lambert and Lewenberg-DeBoer, 2004, Anselin et al., 2004, Griffin et al., 2005). The data were analyzed with GeoDa version 0.9.5-i (Spatial Analysis Laboratory, Department of Agricultural and Consumer Economics, Univ. of Ill., Urbana, IL.). Spatial weights were created for the population blocks using the distance method, where spatial correlations are weighted with the distance between centroids of the population blocks. Spatial correlation was evaluated using Moran's I. An ordinary least-squares regression was ran on the dataset, where yield was the independent variable. All linear and squared combinations of population and soil EC were used as dependent variables. Four hybrids were planted in the field, one was assumed to represent the average condition and three dummy variables were created to represent the impact of the other hybrids and were entered as dependent variables. The residuals from the OLS regression were analyzed for spatial structure using the Lagrange multiplier for spatial error models. The residuals had significant spatial structure, $P<0.0001$. A spatial error regression model was ran, dependent variables were added and removed until the residual sum of squares was minimized. The regression results and associated transformations were plotted in SigmaPlot 8.0 (SPSS, Chicago, Ill.)

Results and Discussion

Small Plot Population Trials

Success in quantifying population responses using small plots was mixed in the two-year study. In 2005 only three of the small plot sites were responsive to changes in plant population. A quadratic response was observed at Ogden – Site 3 (Figure 4.3). This site is laid across the peak of a ridge that runs perpendicular to the plots, thus two reps were on each side of the peak. The optimum population was calculated as 5.18 plants m^{-2} (20 980 plants ac^{-1}).

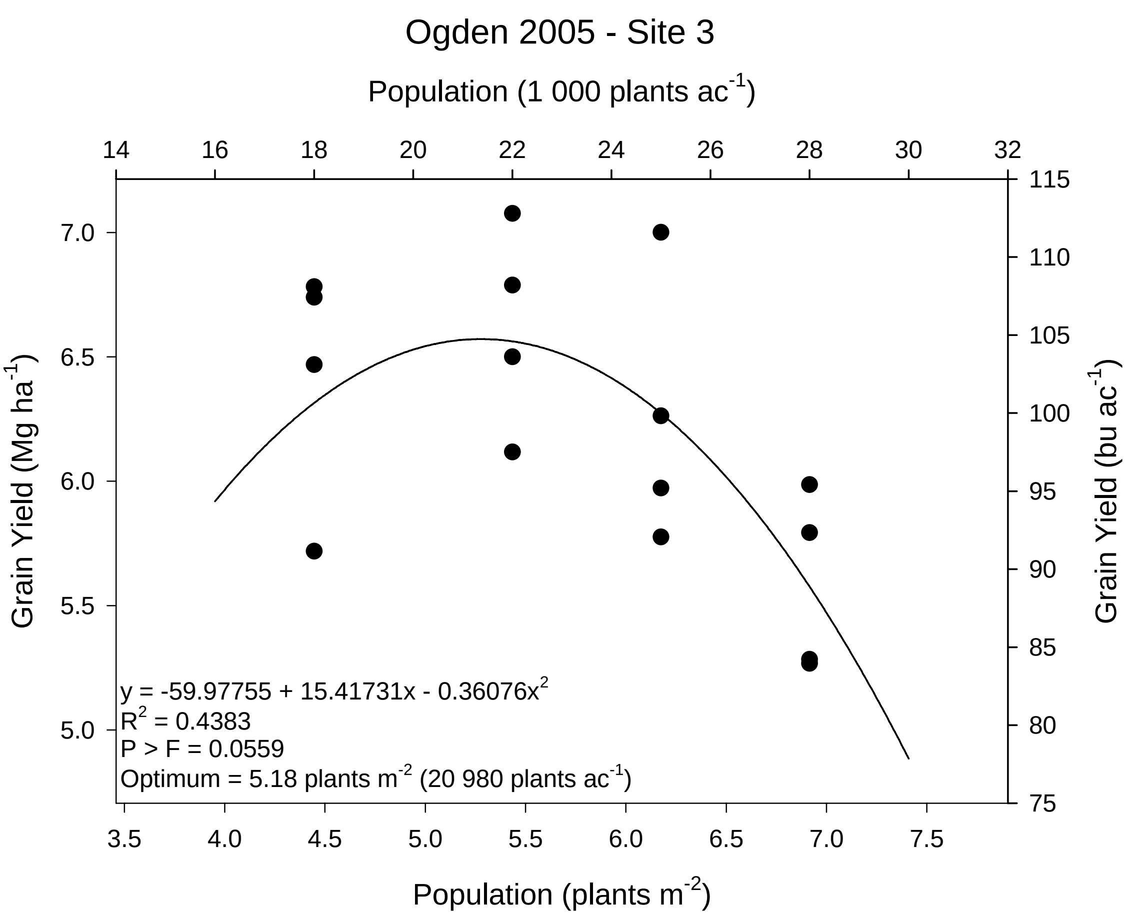

Figure 4.3 - Ogden 2005 – Site 3 Population Response

The absence of a response among the other sites at the Ogden field in 2005 makes it difficult to put this plot into perspective. One possible use of a single data point such as this in pursuit of a variable rate seeding procedure would be to correlate this population response with areas of the field that typically resemble this one with regard to yield data.

Airport sites 3 (Figure 4.4) and 7 (Figure 4.5) both produced quadratic responses to population in 2005. Site 7 is located approximately 36.6 m (120 ft) east of Site 3. Over this range shallow soil EC varies from 2.11 at Plot 3 to 3.66 at Plot 7.

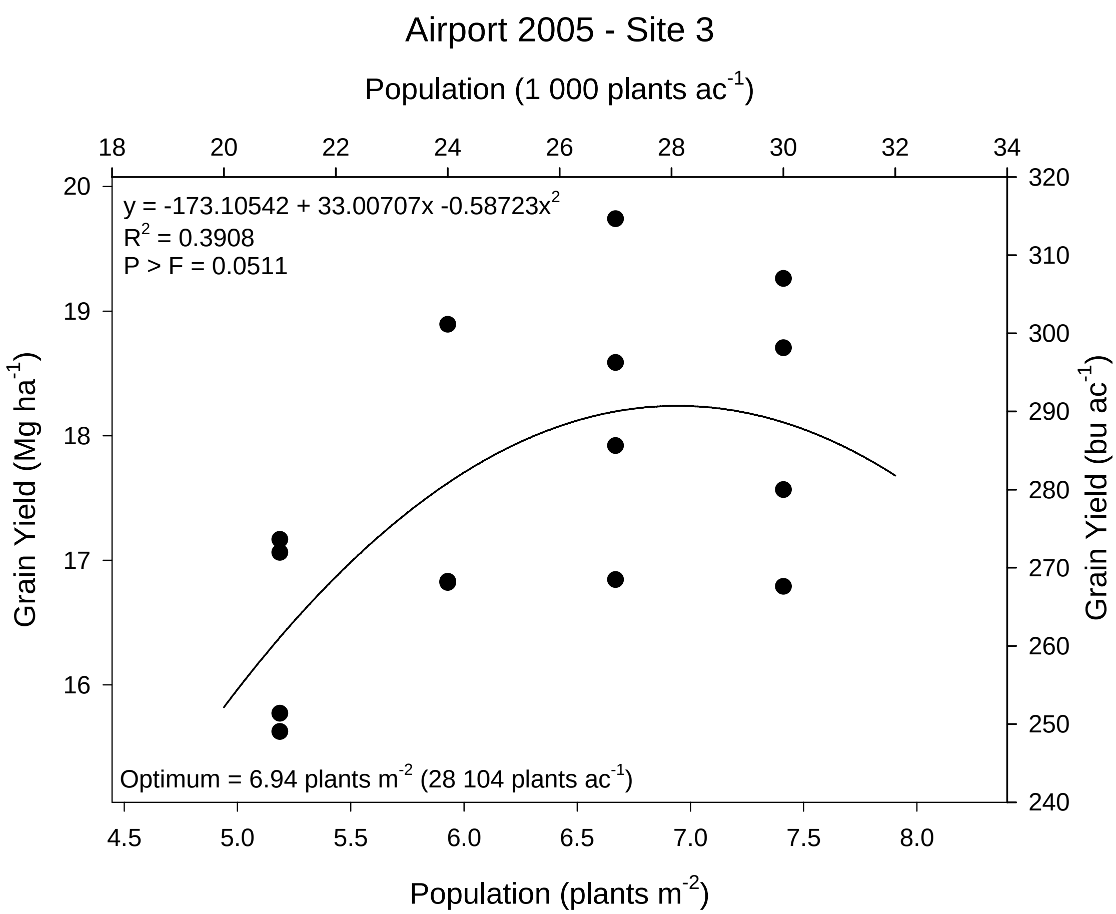

Figure 4.4 - Airport 2005 - Site 3 Population Response

The optimum population at site 7 is 0.3 plants m^{-2} (1 190 plants ac^{-1}) higher than that at site 3, which is relatively small. The difference however is intuitive as the grain yield at optimal population is 1.46 Mg ha^{-1} (23.3 bu ac^{-1}) less for site 7.

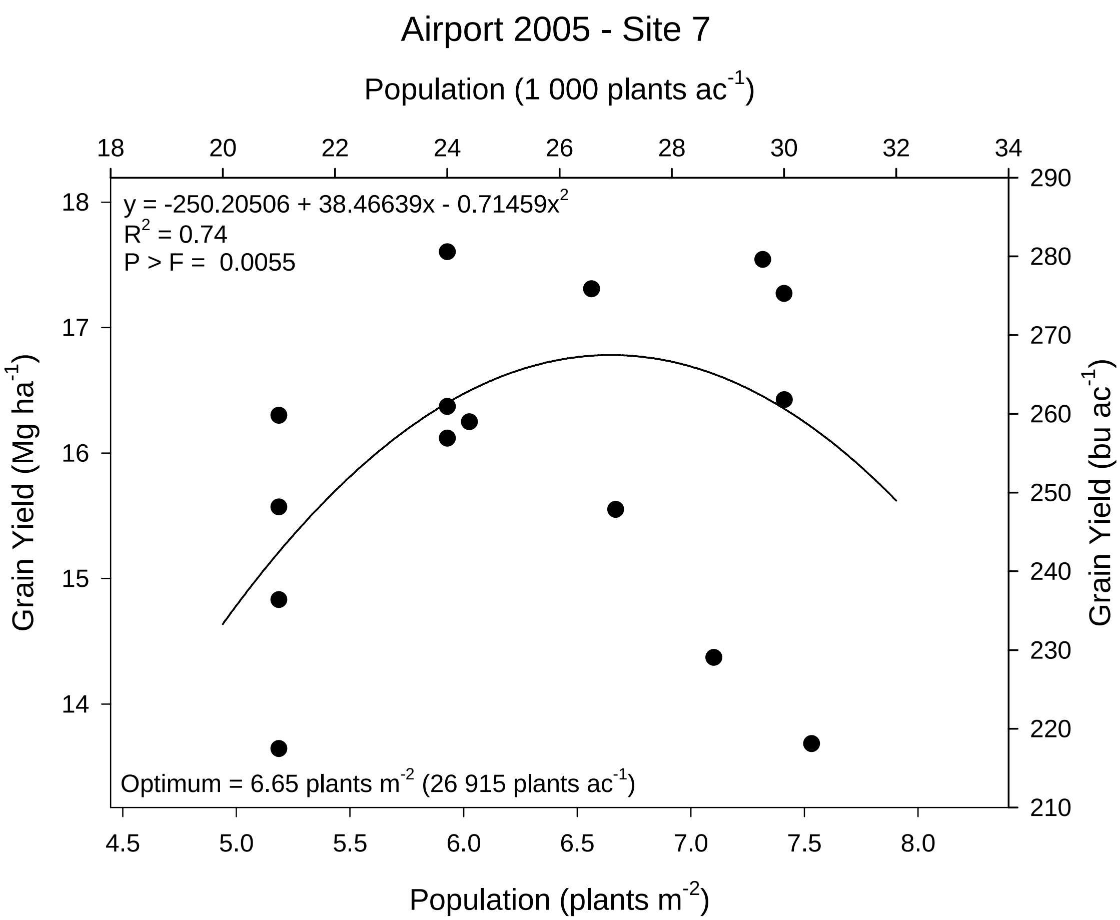

Figure 4.5 - Airport 2005 – Site 7 Population Response

The Airport field in 2006 provided three responsive plots across a range of yield potentials and optimum populations. Site 2 is a dryland location located on good soil (Table 4.2 contains physical properties for sites). However, being a dryland plot, yield declined in a negative curvilinear trend as population increased (Figure 4.6).

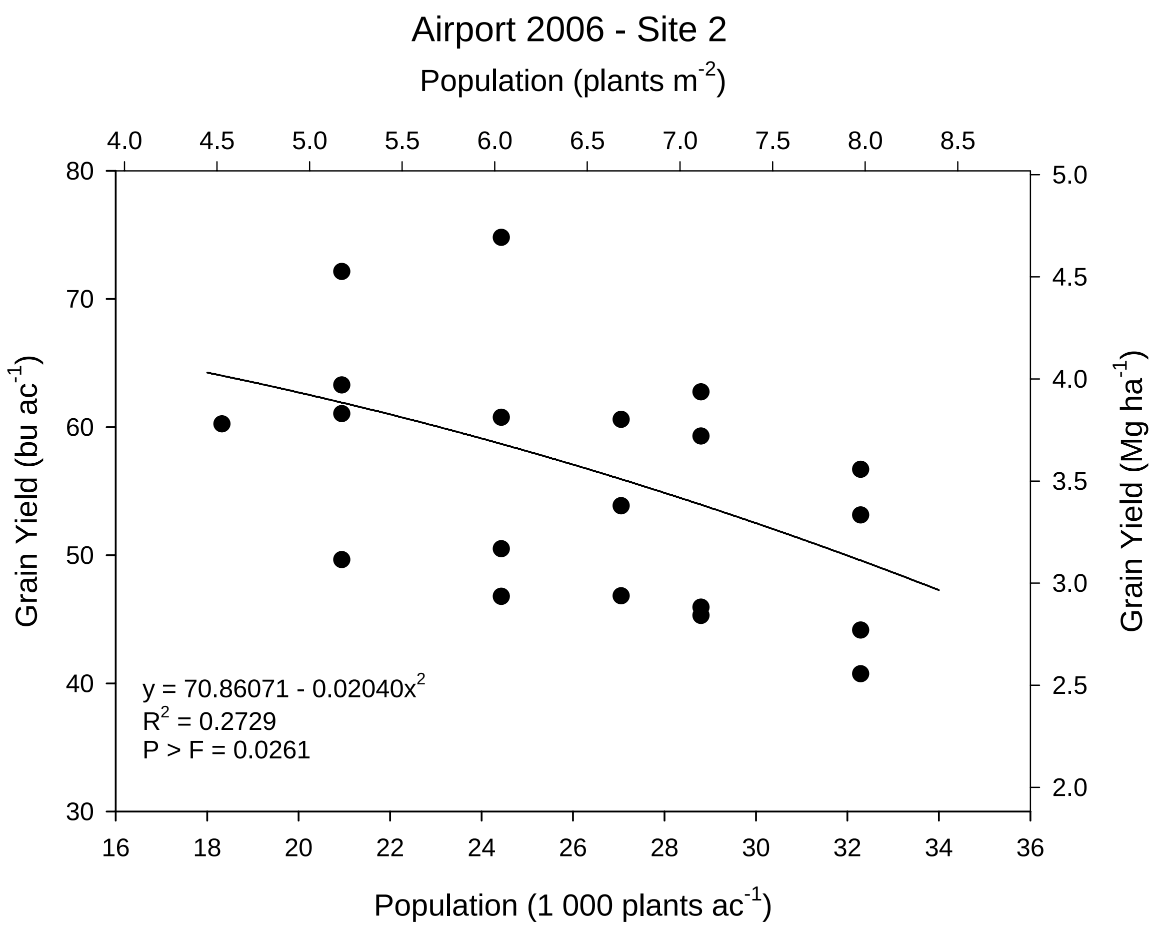

Figure 4.6 - Airport 2006 - Site 2 Population Response

The contrast between responses at sites 4 and 8 is quite interesting. Site 4, located in a generally sandier portion of the field yet its response to increasing plant population is a positive linear trend (Figure 4.7).

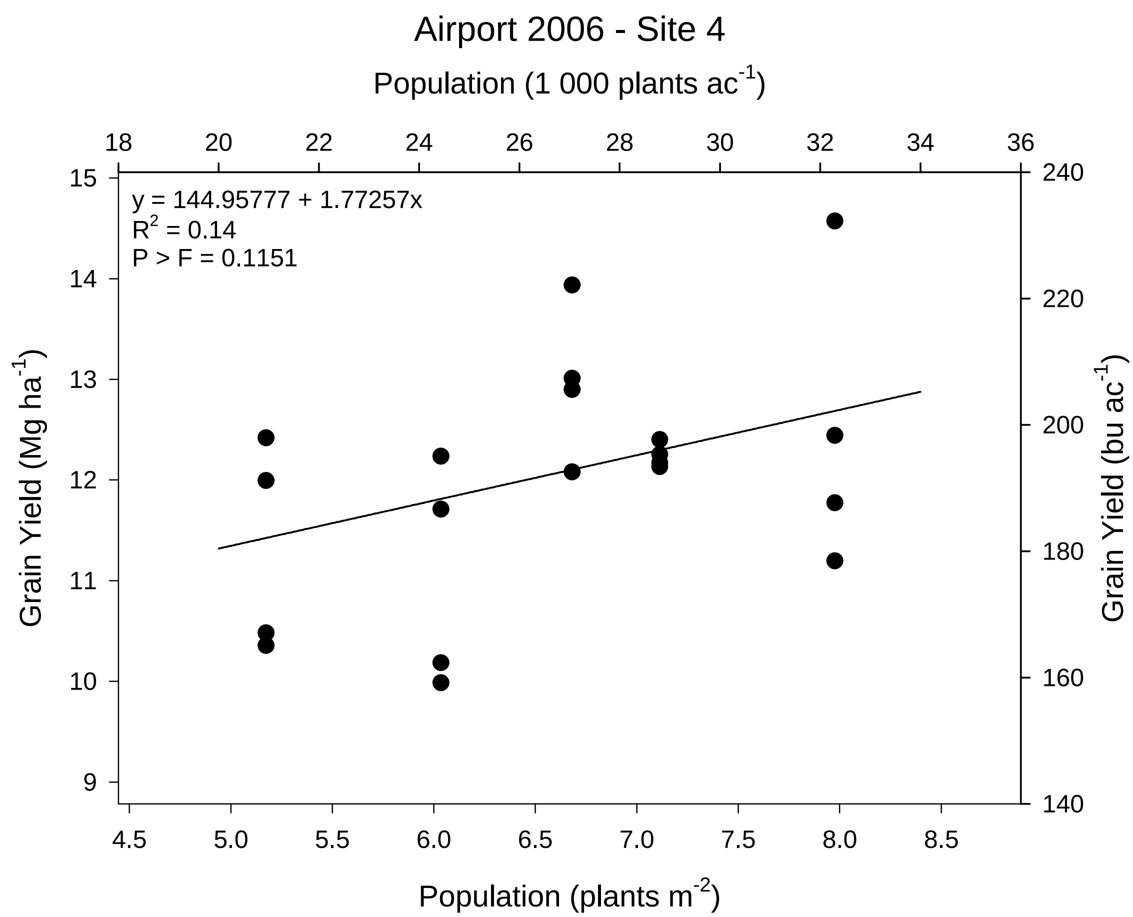

Figure 4.7 - Airport 2006 - Site 4 Population Response

Site 8, is situated in at a soil much higher in water holding capacity but exhibits a quadratic response to plant population (Figure 4.8).

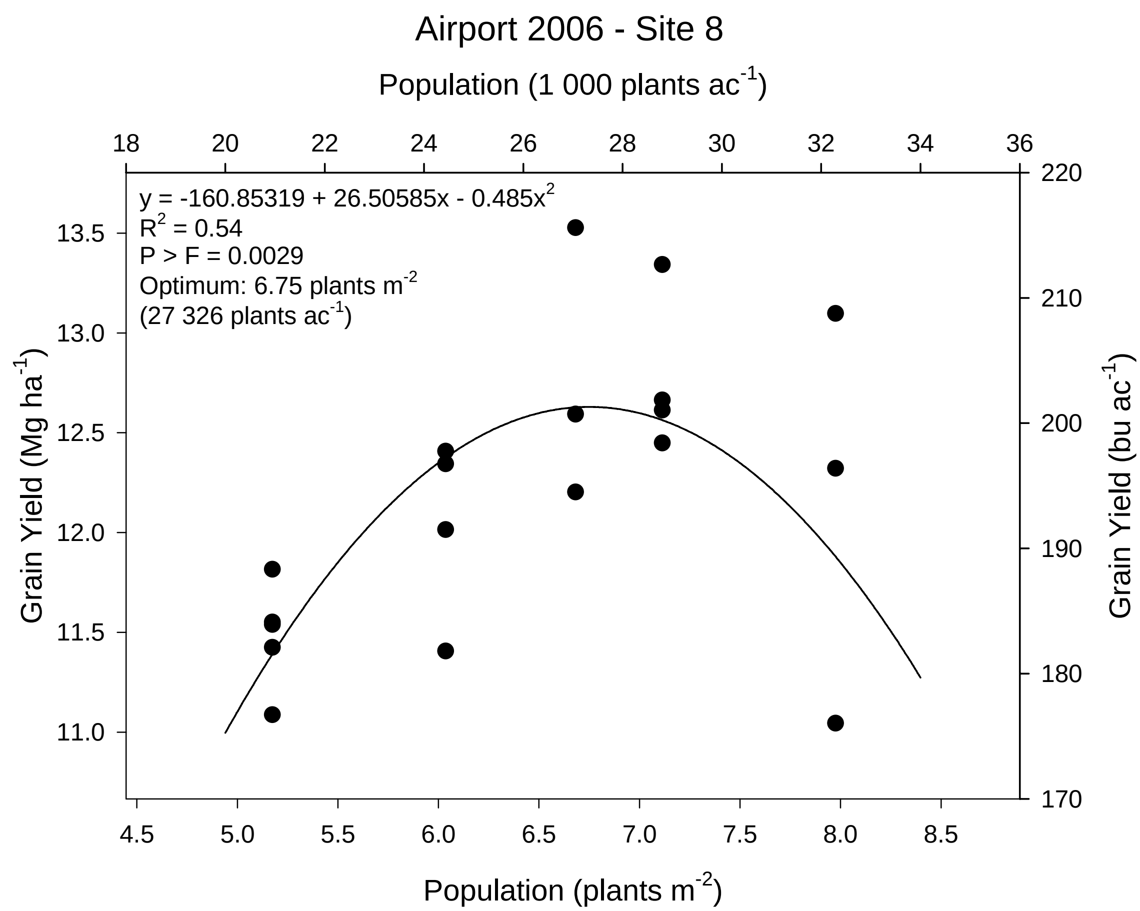

Figure 4.8 - Airport 2006 - Site 8 Population Response

Both plots produced the same approximate grain yield. Several explanations may be in order. Sites 4 and 8 are both irrigated but not under the same center-pivot system. Water consumption is recorded jointly for both pivots and application measurements were not collected as part of this research. It is possible that site 4 received a water application much closer to a critical timing event, or perhaps received more water total. Site 4 is also partially located on a better soil than its surroundings as indicated in Figure 4.1.

Two plot sites at the Hog Ranch field produced strikingly different responses, as would be expected from one plot located under center-pivot irrigation, and the other located on dryland. Site 1, under center pivot irrigation, produced a positive linear response to increasing plant populations (Figure 4.9). It would appear that for this site in 2006, the optimum population was at the upper range of the study, or possibly above. Conversely, site 2, located in a dryland portion of the field, produced a negative curvilinear response to increasing plant population (Figure 4.10). Again, one might believe that these two plots have no use without the responses of accompanying plots in the field under the same irrigation status. However, information from these sites could be applied to other areas of the field that are similarly characterized in regard to yield potential.

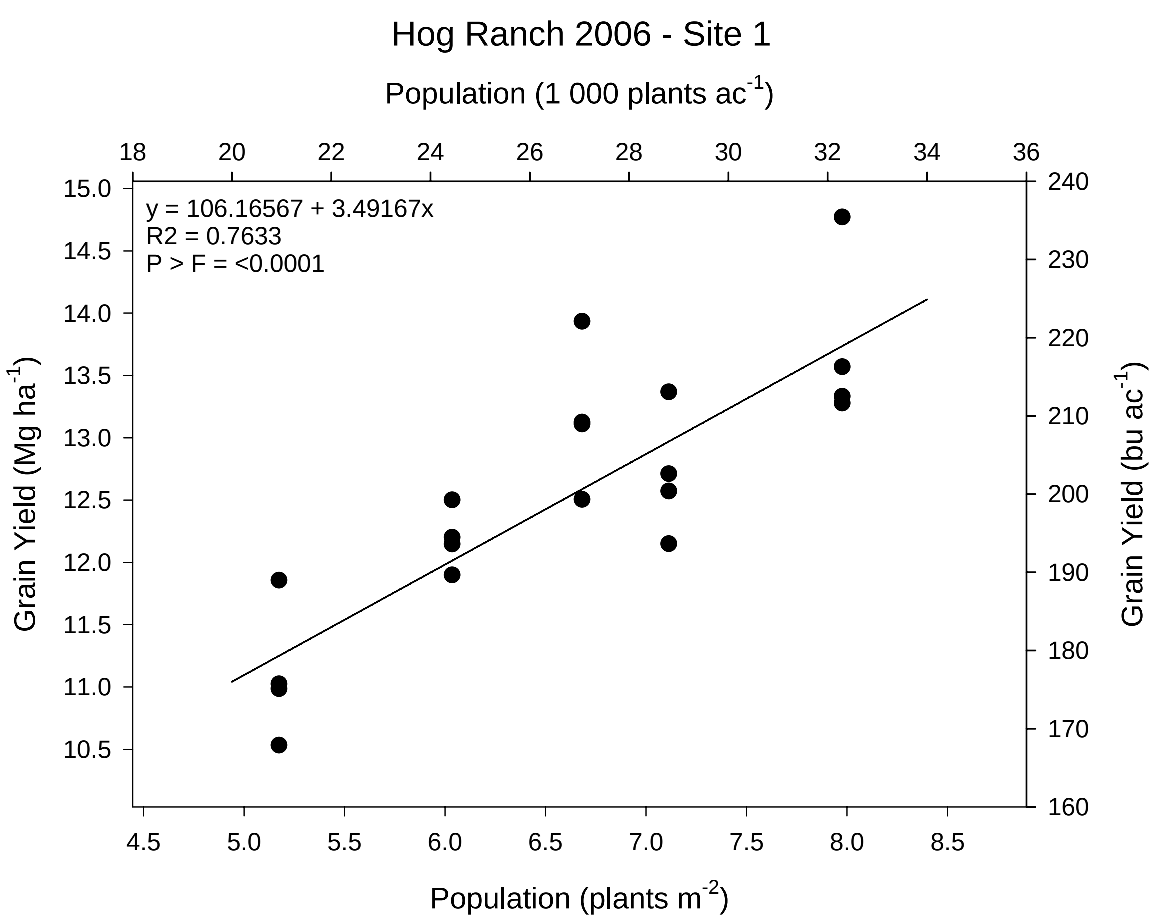

Figure 4.9 - Hog Ranch 2006 - Site 1 Population Response

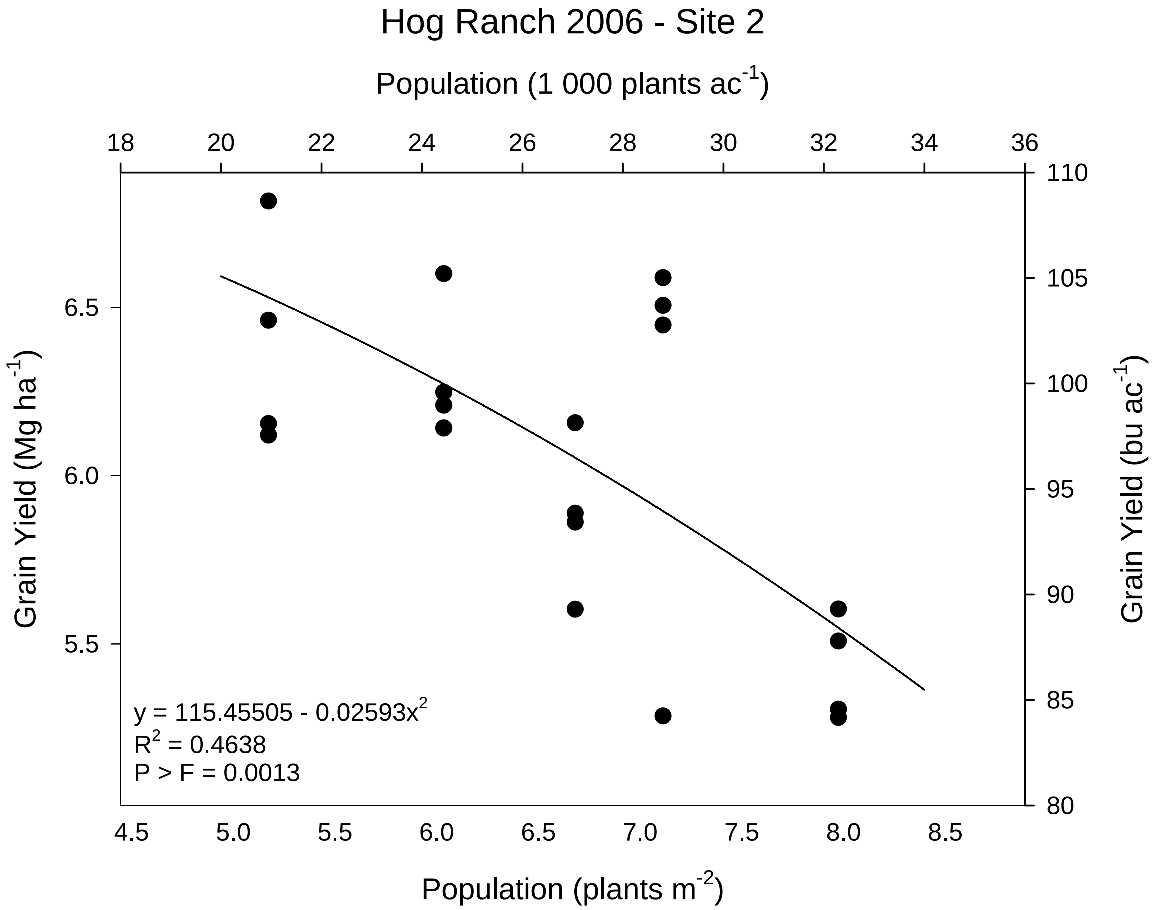

Figure 4.10 - Hog Ranch 2006 - Site 2 Population Response

Although the nature of data collected from the small-plot sites prevented creation of site-specific seeding recommendations as intended, it is important to acknowledge that the ability to identify locations where population responses are anticipated to vary is important. Additionally, identifying characteristics of sites not responsive to population would be of immense value in reducing seed inputs.

Electro-Conductivity vs. Spatial Plant Available Water

In environments where soil water is the limiting factor in relation to crop production, a quick and inexpensive way to quantify plant available water in the soil profile would be of importance to producers and researchers alike. Use of the stepwise procedure resulted in a model using both linear and squared terms soil EC, as shown in Figure 4.11.

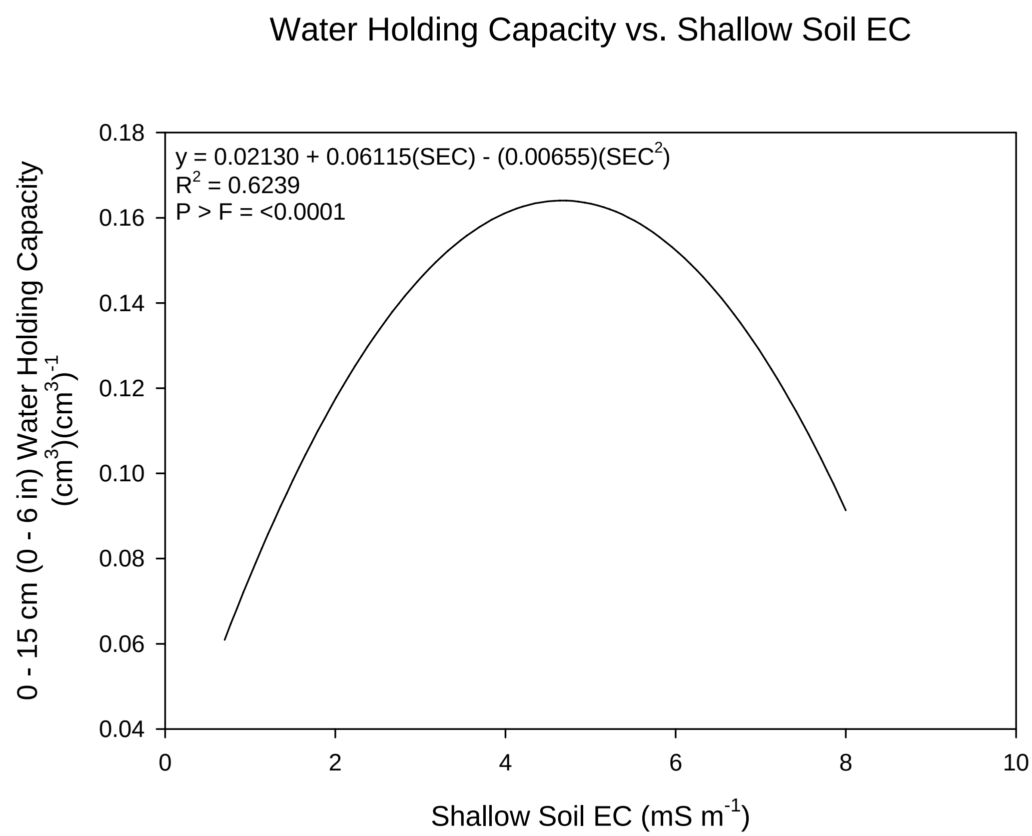

Figure 4.11 - Airport 2006 - Modeled Plant Available Water from Soil EC

Simpler models were also tested in the procedure and were statistically significant, however this model resulted in the lowest residuals and highest R^2 values.

Field Scale Population Trials

Moran's I analysis was conducted on the variables of yield and soil EC to determine their spatial structure and nature of the correlation. The Moran's I plot and value for yield (Figure 4.12) were statistically significant at p-value = 0.0010. This shows that positive spatial autocorrelation was present.

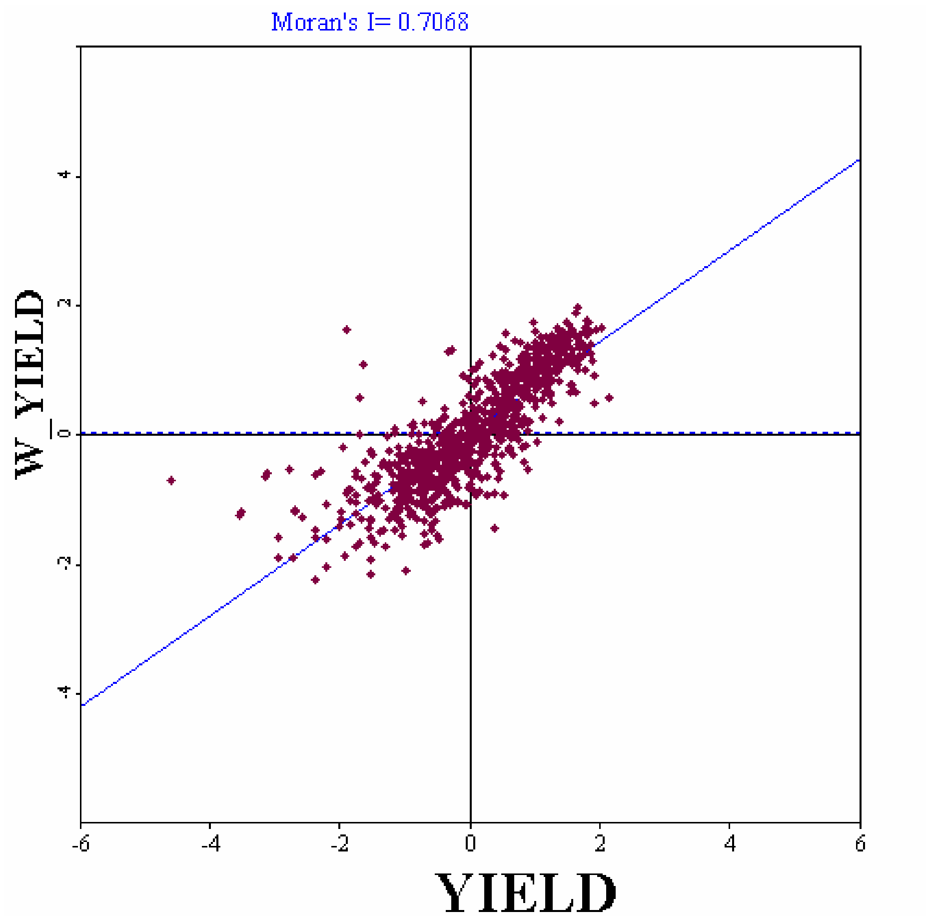

Figure 4.12 - Airport 2006 - Moran's I for Yield

The Moran's I plot and value for soil EC are shown in Figure 4.13. It also shows a strong positive autocorrelation with p-value = 0.0010.

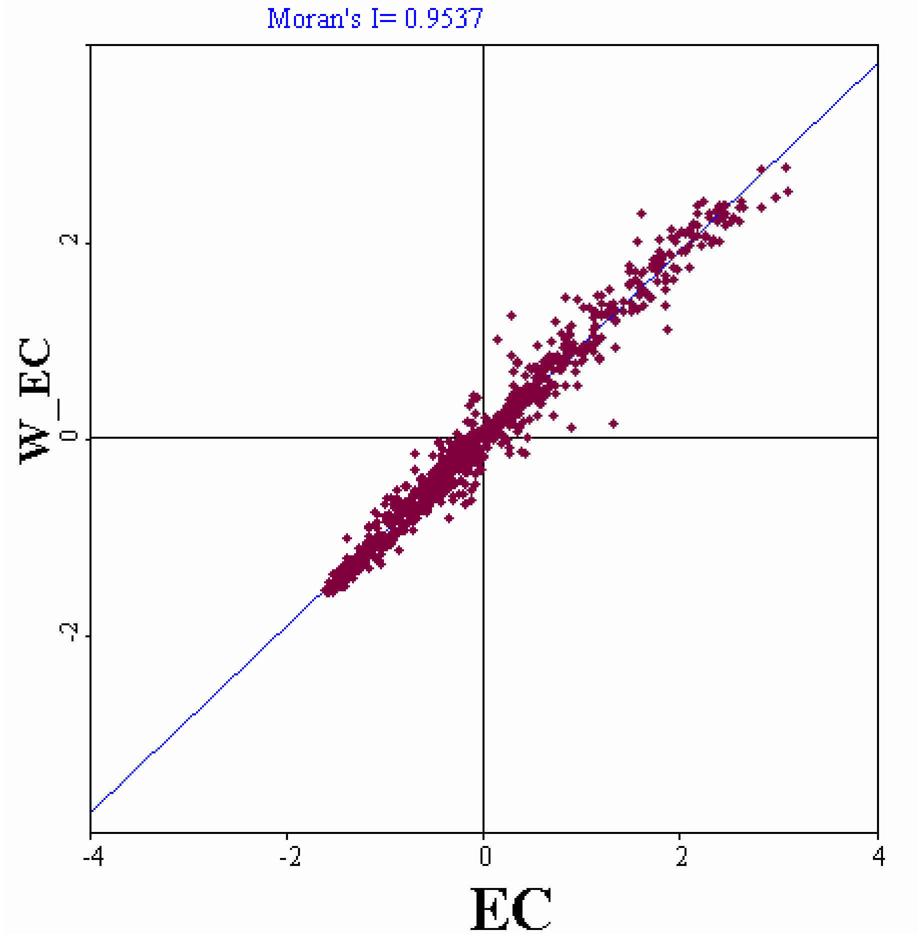

Figure 4.13 - Airport 2006 - Moran's I for soil EC

The results of the spatial regression are shown in Table 4.3. A spatial error regression was used which makes estimates based on the maximum likelihood method. R^2 values are not presented here because they are of little value in spatial regression models (Griffin, 2007).

Table 4.3 – Airport 2006 – Field Scale Spatial Regression Results

Variable	Coefficient	Std.Error	z-value	Probability
CONSTANT	153.954900	9.136653	16.850250	0.00000
Population	-0.984631	0.676751	-1.454939	0.14569
Population^2	0.022075	0.014675	1.504318	0.13250
soil EC	6.444395	2.399237	2.686018	0.00723
EC^2	-0.709495	0.292344	-2.426916	0.01523
Hybrid 7B15BT	-11.753720	3.550434	-3.310502	0.00093
Hybrid 8K389	-7.685813	4.806466	-1.599057	0.10981
Hybrid 9B258	-5.816455	1.708440	-3.404541	0.00066
LAMBDA	0.722922	0.021226	34.057570	0.00000

In spatial regression results, the coefficients, standard errors, z-value, and probability has similar interpretation as non-spatial models, with the z-value corresponding to the t-value. Although several of the factors, most notably those relating to population, are not statistically significant in the traditional sense, some freedom is given to the interpretation of these results due to the missing element of design, and the subjective weighting process that is integral to the spatial regression method. If the hybrid dummy variables are not included, that is we assume the average condition, which is the unlisted hybrid, then we can interpret the balance of the coefficients into meaningful relationships. Figure 4.14 shows the population X soil EC model developed by the spatial regression technique.

Airport 2006 - Population x Soil EC Model

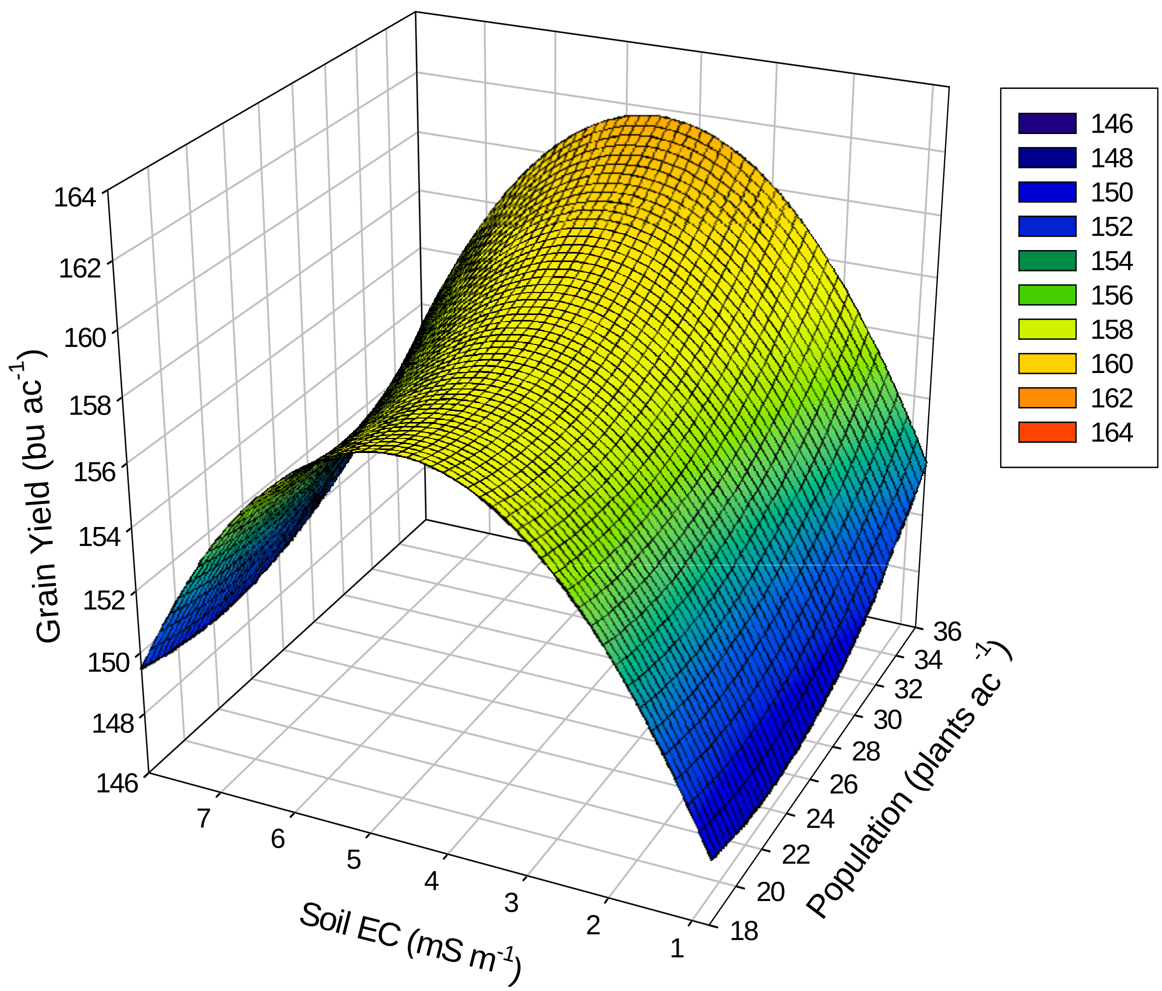

Figure 4.14 - Airport 2006 - Population x Soil EC Model

As evidenced in the figure, yield responded to soil EC in a quadratic manner at all levels. The placement of the optimum population changed with EC as well. In order to turn this information into something of value for the producer, a function must be derived that will allow for determining the optimal seeding rate for a known EC value. This can be accomplished by taking the first derivative of the above model with respect to seeding rate. The resulting equation returns a seeding rate value for a given EC value (Figure 4.15).

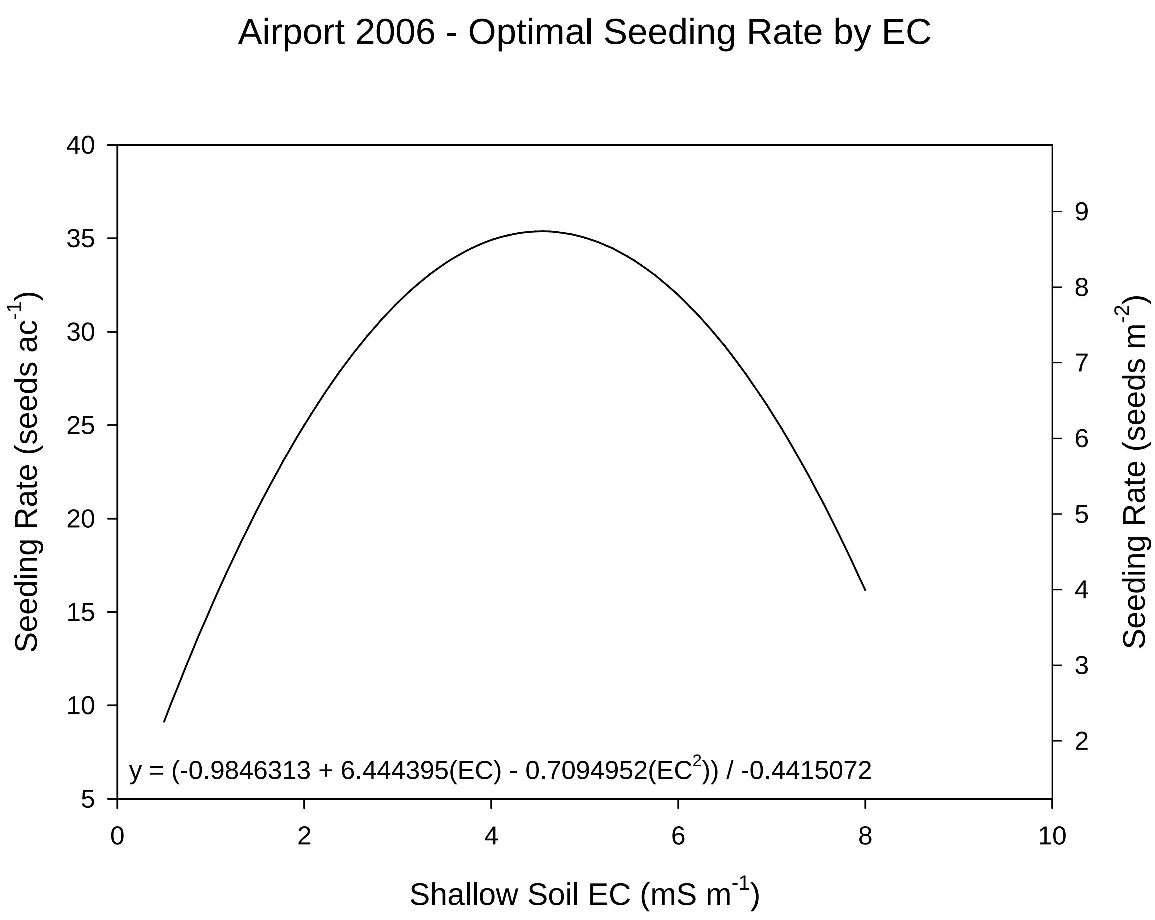

Figure 4.15 - Airport 2006 - Optimal Seeding Rate by EC

Had this relationship been available at prior to the 2006 season, seeding rates at the Airport field would have ranged from 3.09 to 8.74 seeds ac^{-1} (12 500 to 35 375 seeds ac^{-1}). This range should be approached with caution however as some recommendations lie close to the edge of the inference space provided in model. The resulting seeding rate prescription is shown in Figure 4.16.

If the farmer selected practice of seeding at a rate of 6.9 plants m^{-2} (28 000 plants ac^{-1}) is considered in the area of the field under study, approximately 67% of the area is seeded below the optimal rate, and 33% above the optimal seeding rate.

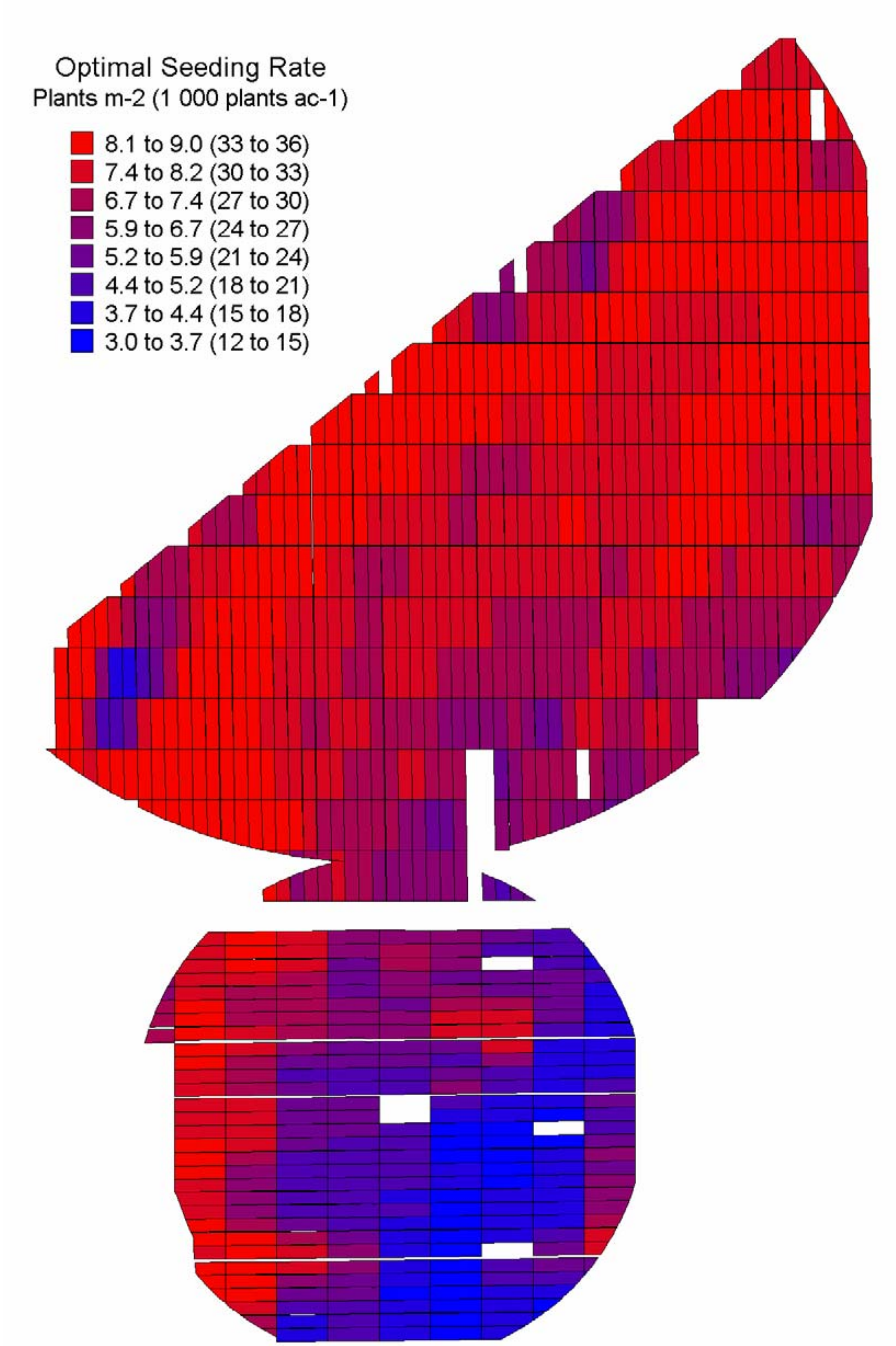

Figure 4.16 - Airport Recommended Seeding Based on 2006 Model

Conclusions

A wide variety of responses to plant population were observed in field trials. It is apparent that in some fields much opportunity exists for the use of soil EC in guiding variable rate seeding decisions. The close relationship between EC, soil textural properties, and plant available water have been relatively clear in this example, however it should be noted that this field was selected for its inherent extremes in soil texture. In fields with more homogeneous soils it is likely that the relationships will not be as evident. It is in these instances that additional covariates be considered to bring more information into the process.

For fields with high levels of variability that is unevenly distributed, the field-scale process here appears to provide one method of driving site-specific seeding rates based on spatially variable water supply as represented by differences in soil EC.

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