STRATEGIES FOR IMPROVING WHEAT AND SOYBEAN PRODUCTION SYSTEMS IN NORTH DAKOTA

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Peder E. Kenneth Schmitz

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

DOCTOR OF PHILOSOPHY

SUPERVISORY COMMITTEE:

Dr. Joel Ransom
Chair

Dr. Hans Kandel

Dr. Tom DeSutter

Dr. Andrew Friskop

Approved:

March 3, 2021
Date

Dr. Richard D. Horsley
Department Chair

ABSTRACT

Planting date (PD), seeding rate (SR), genotype, and row spacing (RS) influence hard red spring wheat (HRSW, *Triticum aestivum* L. emend. Thell.) and soybean [*Glycine max* (L.) Merr.] yield. Evaluating HRSW economic optimum seeding rates (EOSR) is needed as modern hybrids may improve performance and have different SR requirements than cultivars. Two cultivars and five hybrids were evaluated in five North Dakota environments at two PDs and five SRs ranging from 2.22-5.19 million live seeds ha^{-1} in 2019-2020. Planting date, SR, and genotypes have unique yield responses across environments. Hybrid yield was the most associated with kernels $spike^{-1}$ (r=0.17 to 0.43). The best hybrid yielded greater than cultivars in three environments. The EOSR ranged from 4.08-4.15 and 3.67-3.85 million seeds ha^{-1} for cultivars and hybrids, respectively. Hybrids are economical if seed prices are within \$0.18 kg^{-1} of cultivars. In soybean, individual and synergistic effects of PD, SR, genotype relative maturity (RM), and RS on seed yield and agronomic characteristics, and how well canopy measurements can predict seed yield in North Dakota were investigated. Early and late PD, early and late RM, and two SRs (457 000 and 408 000 seed ha^{-1}) were evaluated in 14 environments and two RS (30.5 and 61 cm) were included in four environments in 2019-2020. Individual factors resulted in 245 and 189 kg ha^{-1} more yield for early PD and late RM, respectively. The improved treatment of early PD, late RM, and high SR factors had 16% yield and \$140 ha^{-1} more partial profit greater than the control. When including RS, 30.5 cm RS had 7% more yield than 61 cm RS. Adding 30.5 cm RS to the improved treatment in four environments resulted in 26% yield and \$291 ha^{-1} more partial net profit compared to the control. A normalized difference vegetative index (NDVI) at R5 was the single best yield predictor, and stepwise regression using canopy measurements explained 69% of yield variation. North Dakota farmers are recommended to

combine early PDs, late RM cultivars, 457 000 seed ha^{-1} SR, and 30.5 cm RS to improve soybean yield and profit compared to current management trends.

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LIST OF ABBREVIATIONS

DOY .... Day of Year

EOSR .... Economic Optimum Seeding Rate

FGCC .... Fractional Green Canopy Cover

NDVI .... Normalized Difference Vegetative Index

OPD .... Optimum Plant Density

OSR .... Optimum Seeding Rate

PAR .... Photosynthetically Active Radiation

PD .... Planting Date

RM .... Relative Maturity

RS .... Row Spacing

SR .... Seeding Rate

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INTRODUCTION

Sound agronomic practices are vital to economically and sustainably improve crop production and farm income. Currently, global crop production must double by year 2050 to meet projected demands due to population growth (Ray et al., 2013). This means that current yield gains of wheat (*Triticum aestivum* L. emend. Thell.) of 0.9% yr^{-1} and soybean [Glycine max (L.) Merr] of 1.3% yr^{-1} must increase to 2.4% yr^{-1} (Ray et al., 2013). Although harvestable land area increased 3% between 1985 and 2005 (Foley et al., 2011), yields have stagnated on 37% of the wheat and 23% of the soybean production area globally (Ray et al., 2012). Moreover, adapting crop production to current climate change trends requires improved germplasm and crop management adjustments (Gregory and George, 2011; Howden et al., 2007; Lobell et al., 2011).

Gaps between potential and observed yields occur in all crops, including wheat and soybean. In Europe, a 30% yield gap, the difference between observed and maximum attainable genetic yield, has been reported for wheat (Senapati and Semenov, 2020). The soybean yield gap was found to be 22% in the north-central US between the average and maximum farm yields in similar environments (Rattalino Edreira et al., 2017). For small grains, a change from inbred to hybrid germplasm has the potential to offer a 10% yield increase (Cassman, 1999). Muhleisen et al. (2014) reported that potential hybrids of wheat, barley (*Hordeum vulgare* L.), and triticale (×*Triticosecale* Wittmack) have the potential for enhancing yield stability across broad environments. Similarly, modern soybean cultivars have increased yield stability and seed yield compared to older cultivars with both farm and genetic yield gains in the US of 29 kg ha^{-1} yr^{-1} (Rincker et al., 2014).

Attributing crop yield increases due to either genetic enhancement or agronomic improvement is often difficult. Mourtzinis et al. (2014) found synergistic interactions between soybean genetic and agronomic improvements with more recently released cultivars yielding greater at earlier planting dates. Nitrogen (N) management and fungicide use were found to be more critical yield contributing factors than genetics in winter wheat that was intensively managed for high yield (de Oliveira Silva et al., 2020). Further investigation of synergistic genetic and management interactions will be beneficial to understand yield optimization, decrease the gap between best and average yielding fields, and thereby produce the technology and practices that can help meet the global crop production requirements of 2050 and beyond.

North Dakota is the top spring wheat producing state in the USA with 24% of its arable land devoted to spring wheat in 2019 (USDA, 2020). North Dakota contributes 6% to soybean production in USA and 20% of North Dakota's cropland was planted to soybean in 2019 (USDA, 2020). Together, spring wheat and soybean account for nearly half of North Dakota's cropland demonstrating the importance of these crops to the state. Optimizing the planting date, seeding rate, crop relative maturity and selecting cultivars or hybrids with higher yield resulting in higher spring wheat and soybean production will unquestionably benefit North Dakota farmers and the state's economy altogether.

This document first evaluates how spring wheat cultivars and hybrids respond to planting date and seeding rate to determine if hybrids offer agronomic or economic advantages compared to cultivars. Secondly, the effect of planting date, seeding rate, relative maturity, and row spacing on soybean agronomic performance are investigated. In addition, soybean canopy measurements throughout the season are incorporated into a predictive model to determine if they can be used in yield predictions and to what degree. Finally, the management implications of planting date, seeding rate, and genotype are discussed as to how they improve North Dakota wheat and soybean production systems.

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CHAPTER 1. OPTIMUM SEEDING RATES OF SPRING WHEAT HYBRIDS IN DIVERSE ENVIRONMENTS

Abstract

Planting date, seeding rate, and genotype influence hard red spring wheat (HRSW, *Triticum aestivum* L. emend. Thell.) production. Evaluating economic optimum seeding rates (EOSR) is needed as modern HRSW hybrids may improve performance in different environments and have different seeding rate requirements than inbred cultivars. Two cultivars and five hybrids were evaluated in five diverse North Dakota environments at two planting dates and five seeding rates ranging from 2.22 to 5.19 million live seeds ha^{-1} in 2019-2020. Planting date, seeding rate, and genotypes have unique responses in different environments. Hybrid HRSW yield as seeding rate varied was the most associated with kernels $spike^{-1}$ (r=0.17 to 0.43). The best hybrid yielded greater than cultivars in three environments. The EOSR ranged from 4.08 to 4.15 and 3.67 to 3.85 million seeds ha^{-1} for cultivars and hybrids, respectively. Optimum plant densities ranged from 2.10 to 2.48 million plants ha^{-1}. Hybrids are economical if seed prices are within \$0.18 kg^{-1} of the price of conventional cultivars.

Introduction

Current global crop production needs to double by the year 2050 to meet the projected global demand with wheat yield gains needing to increase from 0.9 to 2.4% yield gain yr^{-1} (Ray et al., 2013). Maximizing crop production efficiency and profitability is challenged by market instability (Winders et al., 2016) and increasing production cost is often a critical barrier to achieving these goals. Yield is the primary factor affecting profitability when paired with efficient use of crop production inputs like fertility and seed cost (Sonka et al., 1989). HRSW grain yield is determined by the complex interaction between genotype, environment, and management (Martin et al., 2014). Environment cannot be fully controlled nor accurately predicted, However, producers can select and anticipate the effect of management practices such as crop rotation (Lafond et al., 1992), genotype (Faris and DePauw, 1981), seeding date (Wiersma, 2002), seeding rate (Chen et al., 2008; Lafond et al., 1992; Wiersma, 2002), row spacing (Chen et al., 2008), weather and soil management (Gooding and Davies, 1997), genetic disease control (Singh et al., 2016), and pest management (Wratten et al., 1995).

Planting date is considered one of the most important agronomic management factors for small grain production and late planting can account for 7-18% of annual global yield losses (Deryng et al., 2011). Briggs and Ayten-Fisu (1979) reported early seeding of wheat supported yield maximization in central Alberta. McKenzie et al. (2008) found that the yield of irrigated cereal crops declined by 0.6 to 1.7% d^{-1} when seeded after 30 April in southern Alberta, Canada. In addition to lower yields, Wiggans (1956) reported lower test weight for oats (*Avena sativa* L.) with later than optimal seeding between 1 and 20 April in Iowa. Seeding cereal crops early increases yield potential by allowing for a longer established crop canopy (Fischer and Maurer, 1976) and by enabling increased tillers $plant^{-1}$ (Juskiw and Helm, 2003). In addition, He et al. (2012) predicts that earlier future HRSW seeding dates will be needed to optimize yields in Saskatchewan, Canada due to climate changes raising spring temperatures.

Seeding rate is an integral component of management practices required for high wheat yields. The optimal seeding rate has been shown to vary between HRSW cultivars in eastern North Dakota and western Minnesota (Mehring, 2016). Guitard et al. (1961) found seeding rate to be a direct determinant of optimal spikes $plant^{-1}$ and yield. Chen et al. (2008) reported the optimum seeding rate of spring wheat to be 2.15 million live seeds ha^{-1} in central Montana. Whereas Wiersma (2002) found the maximum yield was achieved with seeding rates between

4.84-5.31 million live seeds ha^{-1} for seven HRSW cultivars in northwest Minnesota. When combined over eight HRSW cultivars, it was concluded that the highest seeding rate of 4.30 million seeds ha^{-1} resulted in the highest yield in Saskatchewan, Canada (Baker, 1982). Utilizing optimal plant densities limits potential yield loss by reducing light-use inefficiency (Puckridge and Donald, 1967) and maximizing nutrient use efficiency for the plant population (Nass and Reiser, 1975).

An important crop production goal is for the input use to be economically optimal. Agronomic and economic optimal seeding rates can differ depending on yield response of a cultivar and the cost of seed used. When the yield response to seeding rate followed a quadratic model, the agronomic optimum seeding rate was found to be 5.43 million seeds ha^{-1} and an economic optimum seeding rate to be between 4.24 and 4.83 million seeds ha^{-1} for winter wheat in Ohio (Lindsey et al., 2020). Seed costs for wheat grown in the northern plains typically represents about 13% of the yearly variable input costs (Vocke and Ali, 2013). McKenzie et al. (2008) reported EOSR, the seeding rate, which is the most economically profitable, ranged from 2.00 to 2.40 million live seeds ha^{-1} for irrigated soft white spring wheat in southern Alberta, Canada. Similarly, Khah et al., (1989) found 2.00 million seeds ha^{-1} to be the economic optimum for spring wheat. Seeding rates above the optimum can potentially result in decreased yield because of increased lodging (Laghari et al., 2011). Limited information on the response of hybrids of spring wheat to agronomic inputs is available; however, Lloveras et al. (2004) found a linear relationship between hybrid winter wheat yield and seeding rate up to 5.00 million seed ha^{-1}. As seeding rate is an important input in wheat production, it is a production practice that can be targeted to reduce production costs by minimizing seed related inputs while maximizing economic profit.

Since the advent of hybrid maize (*Zea mays* L.) (Shull, 1909), exploiting heterosis as a means of increasing yields in various crops like rice (*Oryza sativa* L.) and barley (*Hordeum vulgare* L.) has been explored (Virmani, 1996; Muhleisen et al., 2013; Shull, 1948). Interest in exploiting wheat's heterosis began after male-sterility advances were reported by Kihara (1951), Fukasawa (1953), and Kihara (1967). Livers and Heyne (1968) found hybridized wheat genotypes yielding 30% greater than the best performing cultivar at the time. More recent efforts have reported a 20% yield improvement in comparison to the best commercial cultivar and greater yield stability between environments in the hybrids (Gowda et al., 2012). Using hybrid wheat may be an effective way to increase wheat yield. However, hybrid wheat seed production has been inefficient and not cost effective. Currently, blend hybrids (Wilson, 1997), a mixture of male parent and hybrid seed, or PowerPollen (PowerPollen, Ankeny, IA) technology, a pollen preservation technology, may be more cost-effective approaches to exploit the benefits of hybrids.

Seed production costs are an important component in the determination of hybrid seed prices. The additional cost of hybrid technology must be paid for by an increase in revenue from improved yield, nutrient content, or grazing value. Retzlaff (1976) reported wheat hybrid seed costs of \$0.84 kg^{-1} to be 5 times greater than the average price of \$0.15 kg^{-1} for non-hybrid wheat seed. Wheat seed prices in USA in 2002 ranged from \$0.65 to 1.10 kg^{-1} and \$0.25 to 0.55 kg^{-1} (2.5 times greater) for hybrid and certified seed, respectively (Cisar and Cooper, 2002). Cisar and Cooper (2002) also reported hybrid seed use increased profits by \$25 ha^{-1}.

Objectives

The objective of this research was to determine the EOSR for new spring wheat hybrids and to determine the contribution of their various yield components to yield relative to conventional cultivars.

Materials and Methods

Location Description

Field experiments were established in three environments in 2019 and two environments in 2020. In 2019, experiments were located in Hettinger, Langdon, and Minot, North Dakota representing a large geographical area of HRSW production. In 2020, field experiments were conducted in Grand Forks and Prosper North Dakota. Table 1.1 summarizes physical characteristics of the experimental locations.

Table 1.1. Soil series, soil taxonomy, previous crop, and location of the 2019 and 2020 experiment locations.

Location	Soil Series†	Soil Taxonomy	Previous Crop‡	GPS Coordinates
2019				
Hettinger§	Shambo	Fine-loamy, mixed, superactive, frigid Typic Haplustolls	Soybean	46.040, -102.384
Langdon	Barnes	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls	Soybean	48.450, -98.205
	Svea	Fine-loamy, mixed, superactive, frigid Pachic Hapludolls		
Minot	Forman	Fine-loamy, mixed, superactive, frigid Calcic Argiudolls	Soybean	48.106, -101.184
2020				
Grand Forks	Bearden	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls	Dry Bean	47.789, -97.066
Prosper	Bearden	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls	Soybean	47.073, -97.619
	Lindaas	Fine, smectitic, frigid Typic Argiaquolls		

†Soil data obtained from NRCS-USDA, 2020.
‡Soybean, [*Glycine max* (L.) Merr.]; Dry Bean, *Phaseolus vulgaris* L.
§All locations had conventional tillage soil management except for Hettinger which was no-till.

Experimental Design and Treatments

Treatments consisted of a factorial combination of genotypes (consisting of two self-pollinated cultivars and five HRSW hybrids), seeding rates, and planting date in a randomized complete block design with a split-split plot arrangement with four replications. The whole plot was planting date, the sub-plot was seeding rate, and the sub-sub plot was genotype. The 2020 Prosper environment had no planting date factor resulting in a split-plot arrangement with the main plot as seeding rate and the sub-plot as genotype. The planting dates used were an optimal (early) date, which was as soon as practical in the spring as recommended by Wiersma and Ransom (2017) and a late date, which was two weeks thereafter. Seeding rates were 2.22, 2.96, 3.71, 4.45, and 5.19 million pure live seed ha^{-1}. The genotypes included the HRSW cultivars ‘SY Ingmar’ and ‘SY Valda’, which will be referred to as Ingmar and Valda, and five experimental hybrids which will be identified as H_A, H_B, H_C, H_D, and H_E. All genotypes were developed by AgriPro. The cultivars, Ingmar and Valda, occupied a total of 33% of the total HRSW hectares cultivated in North Dakota in 2019 (Ransom et al., 2019), and both cultivars have similar disease resistance relative to other common North Dakota grown cultivars (Table 1.2). The hybrids included had not yet been commercially released and their pedigrees were not disclosed resulting in limited knowledge of their genetic backgrounds and other plant characteristics.

Table 1.2. Agronomic characteristics of the two cultivars included in the experiment.

Cultivar	Company	Height	Straw Strength	Days to Heading‡	Stem Rust	Leaf Rust	Stripe Rust	Tan Spot	BLS	Head Scab
		cm	1-9†	d		1-9§				
Ingmar	AgriPro	71	3	60	1	3	6	6	5	5
Valda	AgriPro	69	4	60	1	2	7	6	6	5

†Straw Strength = 1 to 9 scale, with 1 the strongest and 9 the weakest.
‡Days to Head = the number of days from planting to head emergence from the boot, averaged based on data from several North Dakota locations in 2019 (Ransom et al., 2019).
§Disease reaction scores from 1 to 9, with 1 = resistant and 9 = very susceptible.

General Procedures

The amount of seed that was planted for each genotype and seeding rate was on a live seed basis. Live seed numbers were determined from a germination test that consisted of placing 100 seeds on a moist paper towel that was then covered by another paper towel and folded over, placed in a sealed plastic bag and kept at room temperature for 5 d and replicated three times. Plot size, seeding date, and harvest date information are summarized for each location in Table 1.3. Management of the trials varied slightly at each location based on the preferred practices as determined by cooperating researchers at Hettinger, Langdon, and Minot locations. Soils were tested for plant essential nutrients before seeding to ensure fertility was not a limiting factor (Table 1.4) and N rates were adjusted to ensure they were not limiting.

Table 1.3. Important dates and seeding information for HRSW environments in 2019 and 2020.

Year	Location	Plot Size	Row Spacing	Early Seeding	Late Seeding	Early Harvest	Late Harvest
		m	cm	DOY†			
2019	Hettinger	1.62 x 6.69	17	116	148	244	260
	Langdon	1.06 x 6.69	17	127	148	244	260
	Minot	1.24 x 3.65	19	113	140	232	241
2020	Grand Forks	1.24 x 3.65	19	125	149	237	248
	Prosper	1.24 x 3.65	19	125	-	233	-

†DOY = day of year; Day 113 = 23 April; Day 260 = 17 September.

Table 1.4. Soil test results for all wheat environments in 2019 and 2020.

Year	Location	Depth	NO_3-N	P (ppm)	K	pH	OM†
		cm	kg ha^{-1}	mg kg^{-1}			%
2019	Hettinger	0 - 15	32	23	336	5.4	3.1
		15 - 61	30	-	-	7.6	-
	Langdon	0 - 15	24	7	279	6.9	3.7
	Minot	0 - 15	8	32	263	6.7	3.5
		15 - 61	24	-	105	7.7	-
2020	Grand Forks	0 - 15	13	6	314	8.1	4.3
		15 - 61	15	5	202	8.4	4.0
	Prosper	0 - 15	11	12	273	7.5	4.4
		15 - 61	27	13	128	7.9	2.9

†OM = organic matter.

The fungicide combination of pydiflumetoen and propiconazole (1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3- dioxolan-2-yl]methyl]-1H-1,2,4-triazole, 1H-Pyrazole-4-carboxamide and 3-(difluoromethyl)-N-methoxy-1-methyl-N-[1- methyl-2-(2,4,6-trichlorophenyl)ethyl]) commercially marketed as Miravis Ace (Syngenta Crop Protection, LLC, Greeensboro, NC) was applied to all locations at Feekes 10.51 (Large, 1954) to reduce Fusarium head blight incidence (*Fusarium graminearum*) and fungal leaf spots. The experiments were grown according to North Dakota State University extension recommendations regarding cultivation, fertilization, and herbicide and pesticide applications (Wiersma and Ransom, 2017).

Data Collected

Plant density and spike density were obtained by counting plants and spikes in two of the innermost rows of each plot from a 0.91 m length at a stake randomly placed after sowing. Plant density was determined at approximately Feekes 1 which was prior to tiller production. Productive spike density was determined by counting spikes at approximately Feekes 11 within the same 0.91 m of rows used for plant density measurements. Small spikes that were deemed not to contribute to yield were not counted.

Agronomic traits such as plant height, plant lodging, and disease ratings were evaluated by cooperating researchers. Plant height was determined on five randomly selected plants in each experimental unit by measuring from the soil surface to the tip of the spike excluding the awns. Lodging was recorded on a 1 to 9 scale with 9 being erect and 1 being flat on the ground at Feekes 11. Bacterial Leaf Streak (BLS), caused by *Xanthomonas campestris* pv. t*ranslucens*, disease severity was observed and scored in the 2020 growing season using a double-digit scale from (00 to 99) assessing foliar disease severity (Saari and Prescott, 1975). The first digit (D_1) represents disease progress in canopy height and the second digit (D_2) indicates leaf area severity with both digits using a 0 to 9 scale with 0 being negligible disease height and leaf severity. Percent disease severity was derived from individual disease score where % disease severity = $[(D_1/9) \times (D_2/9) \times 100]$ (Kandel et al., 2012).

Spikes plant^{-1} and kernels spike^{-1} were derived from plant density, spike count, and kernel weight measurements. Yield was collected for each plot using a small plot combine and was adjusted to 13.5% moisture. Moisture and test weight were determined using a GAC 2100 moisture tester (Dickey-John Corp., Minneapolis, MN). Percent grain protein content was measured using a DA 7250 NIR analyzer (Perten Instruments, Stockholm, Sweden) and is reported on a 12% moisture basis.

The wheat quality analysis was performed on grain of each genotype from the 2.96 million live seed ha^{-1} seeding rate plots from each location with grain samples separated into two replicates for each genotype and environment. Grain samples were analyzed by the North Dakota State University Wheat Quality Laboratory to further quantify test weight, kernel size distribution, kernel weight, protein, falling number, milling extraction, mixograph score, peak max time, maximum torque, total energy, and loaf volumes according to standard protocols (AACC, 1995).

Statistical Analysis

Bartlett's test for homogeneity of variance was significant for yield and agronomic traits when comparing all environment combinations preventing a combined analysis. Therefore, individual ANOVAs were performed for each environment and dependent variable (Table 1.5). The ANOVA was performed using the GLIMMIX procedure on SAS 9.4 (SAS Institute, Cary, NC) using the Lines statement for pairwise t-test mean ($\alpha = 0.05$) comparisons when F tests were significant at an $\alpha = 0.05$. Fixed effects were planting date, seeding rate, and genotype while rep was considered a random effect (Table 1.5). All interactions of fixed effects were considered fixed. Orthogonal linear and polynomial contrasts for cultivar and hybrid comparisons for the genotype factor were performed using GLIMMIX with SAS 9.4 at an $\alpha = 0.05$. Regression analysis of yield and plant density averaged over each seeding rate was performed using the Reg procedure in SAS.

Table 1.5. Sources of variation and error terms for ANOVA of single environments in 2019 and 2020.

Source of Variation	df	F test Denominator
Rep	r-1	-
A [Planting Date]	a-1	Error(a) MS
Error(a)	(r-1)(a-1)	-
B [Seeding Rate]	b-1	Error(b) MS
A x B	(a-1)(b-1)	Error(b) MS
Error(b)	a(r-1)(b-1)	-
C [Genotype]	c-1	Error(c) MS
A x C	(a-1)(c-1)	Error(c) MS
B x C	(b-1)(c-1)	Error(c) MS
A x B x C	(a-1)(b-1)(c-1)	Error(c) MS
Error(c)	ab(r-1)(c-1)	-

Since planting dates within environments can have differing yield responses, data were partitioned into high (>5000 kg ha^{-1}) and low (<5000 kg ha^{-1}) yielding environment data sets by considering individual planting dates as a single environment for a total of 10 environments. Yield environments were evaluated by standardizing the distribution of each using z-scores. Data were transformed using the Standard procedure in SAS to calculate a z-score for yield using the formula $\text{z-score} = (x - \bar{x})/\sigma_1$ where x is yield, $\bar{x}$ is the yield mean of the high or low yielding environment, and σ_1 is the standard deviation of the high or low yield environment (Clark-Carter, 2014). The z-score adjusts the data distribution to have a mean of 0 and standard deviation of 1. Next, the z-score data was used to adjust yield values to be relative to the yield of the individual environment using the formula $\hat{Y} = (\text{z-score} \times \sigma_2) + \mu$ where, $\hat{Y}$ is estimated yield, z-score is z-score of yield, σ_2 is standard deviation of the individual environment, and μ is the mean of the high or low yield environment.

Relationships between yield components and yield for high and low yielding environments were analyzed using yields adjusted by the z-score approach previously discussed. Multiple linear regression was used to determine the relative importance of each yield component on yield using the Reg procedure which also derived partial correlation coefficients (r^2) and adjusted R^2. The EOSRs were calculated by determining the first derivative of each quadratic regression equation of selected wheat seed cost (0.35 – 1.76 $ kg^{-1}) to grain market price (0.17 – 0.29 $ kg^{-1}) ratios and solving for the EOSR variable (Cerrato and Blackmer, 1990). The wheat seed cost range minimum price based on local seed prices, and the grain market price range was based on 2015-2020 Minneapolis Grain Exchange, Inc prices. To produce EOSR recommendations for North Dakota, data were combined over years and locations as well as for high and low yielding environments and quadratic regression analysis was performed using LSMEANS. Quadratic regression equations were derived from the REG procedure in SAS. Wheat end quality characteristics were analyzed using the GLM procedure in SAS with single degree of freedom linear contrasts for cultivar and hybrid comparison evaluated at $\alpha = 0.05$.

Results and Discussion

Discussion of results will follow a pattern of explaining planting date, seeding rate, and genotype main effects or their interactions as they relate to grain yield, grain protein content, yield components, and agronomic characteristics. Next, an analysis of EOSR for cultivars and hybrids will be explored and is followed by examination of grain quality characteristics as affected by genotype and the environment.

Seeding dates were dependent on appropriate seeding conditions which were primarily affected by rainfall each year (Figures 1.1 and 1.2). Yield variation between environments can be largely attributed to weather and soil effects since management factors were similar in 2019. Hettinger had relatively normal temperatures and rainfall during the growing season and yields were slightly above the mean for the region. In 2019, rainfall was less than normal in Minot and Langdon with Minot generally having warmer temperatures than Langdon. In Minot, minimal rainfall and above normal temperatures between 140 to 170 DOY during tiller formation (Feekes 1 and 2) greatly reduced yield potential. The 2020 growing season began with above normal rainfall and cooler than normal temperatures in Grand Forks and Prosper (Figure 1.2). Low early season temperatures and normal rainfall allowed for favorable tiller formation and grain development in Prosper resulting in high grain yield.

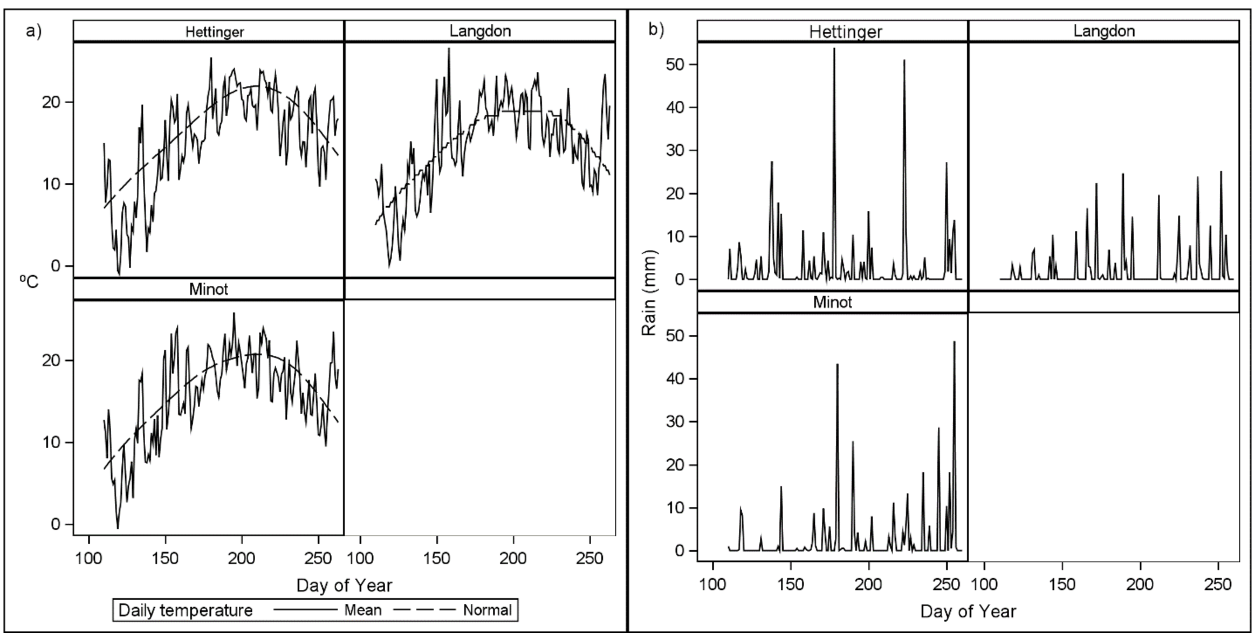

Figure 1.1. Wheat growing season a) daily mean and normal temperatures and b) daily rainfall in 2019 where Day of Year 100 is 10 April.

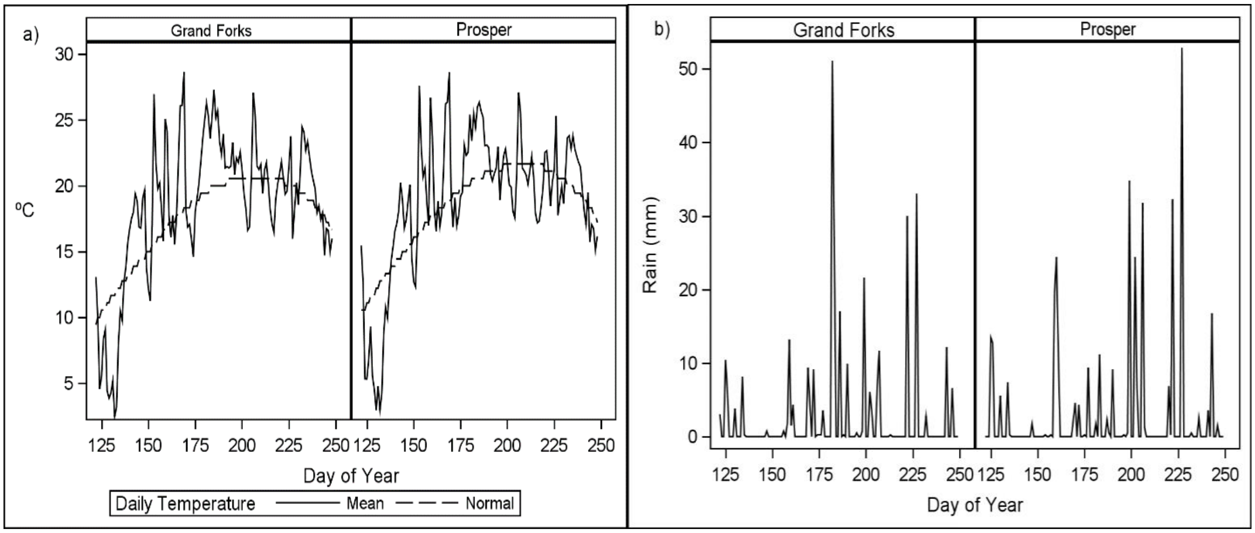

Figure 1.2. Wheat growing season a) daily mean and normal temperatures and b) daily rainfall in 2020 where Day of Year 125 is 4 May.

Yield

Yield data were analyzed separately for each environment. Planting date, planting date by seeding rate, and genotype were commonly significant for yield within an environment (Table 1.6). The significant planting date by seeding rate interaction in Minot was due to a change in magnitude caused by the early planted 2.22 million seed ha^{-1} seeding rate being 414 kg ha^{-1} greater than when late planted (Table 1.6 and 1.8). Also, the significant planting date by genotype interactions in Langdon were due to a change in magnitude where genotypes that were planted late yielded more than when planted early (Table 1.6 and 1.9).

Table 1.6. Results for ANOVA of agronomic characteristics in each environment.

SOV†	Environment	PS	SD	T	KWT	KS	Protein	Yield	Ht‡	L	DTH	BLS
	Grand Forks											
A [Planting Date]		ns	ns	ns	*	ns	**	ns	**	ns	***	*
B [Seeding Rate]		***	**	***	ns	*	ns	*	ns	ns	ns	ns
A x B		**	***	ns	ns	***	**	ns	ns	ns	ns	***
C [Genotype]		***	***	***	***	**	***	**	***	ns	***	**
A x C		ns	ns	*	***	**	***	ns	ns	ns	**	ns
B x C		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
A x B x C		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Hettinger										ns	ns
A [Planting Date]		ns	ns	*	ns	ns	ns	*	*	ns	***	ns
B [Seeding Rate]		***	**	*	ns	ns	ns	ns	ns	ns	***	ns
A x B		**	ns	***	ns	ns	ns	ns	ns	ns	ns	ns
C [Genotype]		ns	ns	ns	ns	ns	*	ns	*	ns	ns	ns
A x C		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B x C		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
A x B x C		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Langdon											
A [Planting Date]		ns	ns	ns	*	*	ns	*	**	-	***	ns
B [Seeding Rate]		***	ns	***	ns	ns	ns	ns	ns	-	***	ns
A x B		*	***	**	ns	***	ns	ns	ns	-	ns	ns
C [Genotype]		***	***	***	***	***	***	***	***	-	***	ns
A x C		ns	ns	ns	**	*	**	**	**	-	ns	ns
B x C		ns	ns	ns	ns	ns	ns	ns	ns	-	ns	ns
A x B x C		ns	ns	ns	ns	ns	ns	ns	ns	-	ns	ns
	Minot											
A [Planting Date]		**	*	**	***	**	*	ns	-	-	***	ns
B [Seeding Rate]		***	***	***	ns	***	ns	ns	ns	-	***	ns
A x B		*	*	***	ns	*	**	**	-	-	ns	ns
C [Genotype]		ns	ns	ns	ns	ns	ns	ns	ns	-	**	ns
A x C		ns	ns	ns	ns	ns	ns	ns	-	-	ns	ns
B x C		ns	ns	*	ns	ns	ns	ns	-	-	ns	ns
A x B x C		ns	ns	ns	ns	ns	ns	ns	-	-	ns	ns
	Prosper											
B [Seeding Rate]		***	ns	**	ns	ns	*	ns	ns	ns	ns	ns
C [Genotype]		ns	ns	*	***	ns	***	***	***	ns	***	ns
B x C		ns	ns	ns	ns	ns	ns	*	ns	ns	ns	ns

*, **, ***, and ns indicate significance at $P\leq0.05$, $P\leq0.01$, $P\leq0.001$, and not significant, respectively.

†SOV, source of variation; PS, plant stand density; SD, spike density; T, tillers plant^{-1}; KWT, 1000 kernel weight; KS, Kernels spike^{-1}; Ht, plant height; L, Lodging; DTH, days to heading; BLS, Bacterial leaf streak index.

‡Heights were not recorded for the early planting date in Minot and lodging was not observed in Langdon and Minot.

Planting Date

Grain yield across the five environments ranged from 3833 to 5795 kg ha^{-1} for the early planting date and 3847 to 5923 kg ha^{-1} for the later planting date (Table 1.7). Early planting resulted in higher yields in Hettinger, but at Langdon, late planting out yielded early planting. In other research, planting wheat early favored greater yields similar to that observed in Hettinger (Briggs and Ayten-Fisu, 1979; Subedi, et al., 2007). In contrast, Hunt et al. (1996) reported early May planting dates yielded less than late May planting dates in Minnesota. Atypical North Dakota weather in 2019 compared to normal likely caused the unexpected yield differences for planting date in Langdon. High temperatures in Langdon between 4 to 5 leaf stage and post-anthesis for the early planting date possibly reduced spikelet numbers. Fischer (1985) found temperatures between 14 to 22 ℃ 30 d prior to anthesis accelerated spike development and reduced kernels m^{-2} which are more likely to occur for delayed planting dates in North Dakota.

Seeding Rate

Yield response to seeding rate was similar between the 2.96 and 5.19 million seeds ha^{-1} rates suggesting increasing seeding rates does not necessarily increase yields in some environments. Based on this data, 2.96 million seeds ha^{-1} would seem to be an appropriate seeding rate recommendation in Grand Forks. However, the 2.96 million seeds ha^{-1} recommendation is limited to the genotypes and seeding rates tested in these experiments as Faris and DePauw (1981) recommend evaluating seeding rate for individual genotypes.

Table 1.7. Wheat yield influenced by planting date, seeding rate, and genotype for individual environments in 2019 and 2020.

Treatment	Grand Forks	Hettinger	Langdon	Minot	Prosper†
			kg ha^{-1}		
Mean Yield	4584	4901	5859	3842	5335
Planting Date					
Early	4535	5202a‡	5795b	3864	5335
Late	4633	4599b	5923a	3846	-
P	0.183	0.039	0.048	0.937	-
Seeding Rate					
Million seeds ha^{-1}					
2.22	4305b	4780	5845	3828	5329
2.96	4610a	4948	3803	3812	5272
3.71	4677a	4938	5810	3944	5375
4.45	4722a	4893	3684	3691	5376
5.19	4606a	4938	3942	3932	5324
P	0.043	0.399	0.224	0.090	0.948
Genotype					
Ingmar	4367c	4747	5507d	3801	5081b
Valda	4645ab	4854	5804c	3739	5465a
H_A	4630ab	4940	5969b	3812	5377a
H_B	4522bc	4841	5829bc	3903	5326a
H_C	4644ab	4875	5841bc	3909	5108b
H_D	4725a	5021	6141a	3846	5467a
H_E	4556ab	5020	5955b	3872	5369a
P	0.005	0.149	<.001	0.671	<0.001

†The Prosper environment did not have a late planting date level
‡Means with the same letter, within the same main effect, are not significantly different. Comparisons were made using pairwise comparisons between all treatments at an α = 0.05.

Table 1.8. Significant planting date by seeding rate interactions for yield and protein at Grand Forks and Minot, 2019 and 2020.

Environment	Planting Date	Seeding Rate (million live seeds ha^{-1})				
		2.22	2.96	3.71	4.45	5.19
				Yield (kg ha^{-1})		
Minot	Early	4034a	3741bcd	3981ab	3580d	3851abc
	Late	3620cd	3882ab	3906ab	3805abcd	4016ab
				Protein (g kg^{-1})		
Grand Forks	Early	144cdef	143def	143def	140f	141ef
	Late	150a	148abc	149ab	146cde	147bcd
Minot	Early	145c	150ab	146bc	151ab	153ab
	Late	146c	145c	144c	144c	143c

†Means with the same letter, within the same environment, are not significantly different. Comparisons were made using pairwise comparisons between all treatments at an α = 0.05.

Seeding rate effect on yield was further analyzed using regression analysis and orthogonal polynomial contrasts. At Grand Forks, the highest yield, 4800 kg ha^{-1}, was achieved with a seeding rate of 4.50 million seed ha^{-1}. There are individual significant differences between the quadratic response of Ingmar to the mean quadratic response of the five hybrids and the linear Valda response to the linear hybrid mean averaged across seeding rate (Figure 1.3a). H_D and the combined mean of Ingmar and Valda (IV) had inverse parabolic responses to seeding rate whereas H_D had greater yields at low and high seeding rates compared to IV (Figure 1.3c and 1.3d). In general, wheat yields are stable across seeding rates and more stable than barley but less than oats relative to the optimum seeding rate (Guitard et al., 1961).

Table 1.9. Significant planting date and genotype interactions for wheat yield and protein in Grand Forks and Langdon.

		Genotype						
Environment	Planting Date	Ingmar	Valda	H_A	H_B	H_C	H_D	H_E
		Yield (kg ha^{-1})						
Langdon	Early	5444g†	5890cde	5966c	5677efg	5871cde	6018bc	5713def
	Late	5570fg	5718def	5989c	5942cd	5828cde	6329a	6251ab
		Protein (g kg^{-1})						
GF	Early	159a	154c	157a	157a	158a	158a	157ab
	Late	155bc	154c	149d	150d	149d	149d	150d
Langdon	Early	144ab	134de	133ef	133ef	132ef	133ef	138cd
	Late	148ab	139bc	133de	134de	136cde	129f	136cde

†Means with the same letter, within the same environment, are not significantly different. Comparisons were made using pairwise comparisons between all treatments at an $\alpha = 0.05$.

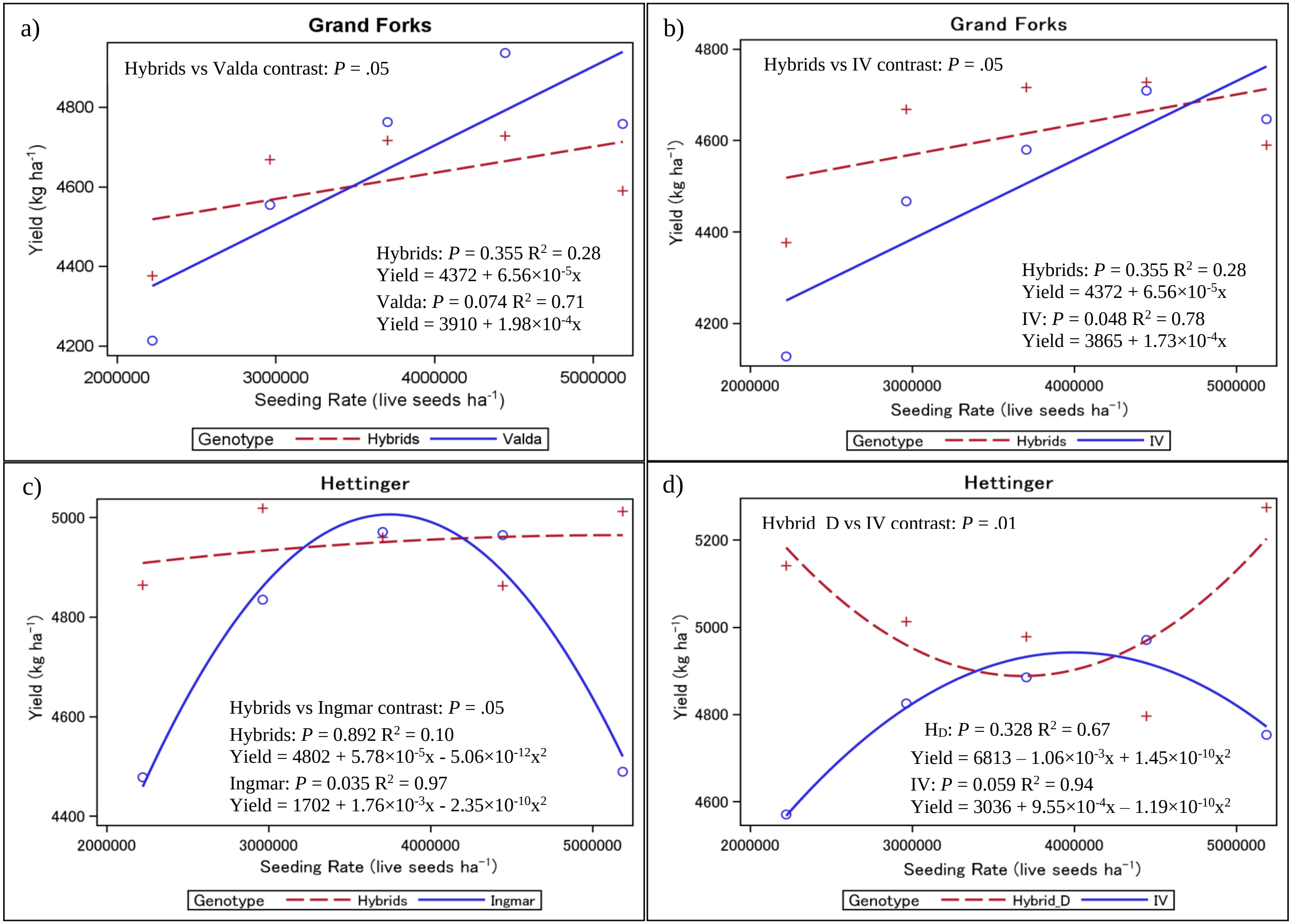

Figure 1.3. Polynomial contrasts of seeding rate by genotype [Ingmar, Valda, Ingmar and Vada (IV), Hybrids, and H_D] interactions for yield.

Segregating environment and planting date combinations creates a natural division between 4 high (>5000 kg ha^{-1}) and 5 low (<5000 kg ha^{-1}) yielding environments. High and low yielding environments had mean yields of 5716 and 4267 kg ha^{-1}, respectively, and yields were standardized relative to high or low yield environments using z-scores. In addition, Valda and H_D have common high yielding characteristics in this experiment. Averaging seeding across high yielding environments, H_D required more seeds to reach the OSR than in low yield environments (Figure 1.4). Seeding rate yield explanation for H_D ($R^2 = 0.84$) was high relative to Valda. In contrast, OSR trends for Valda were opposite to H_D and required lower seeding rates in high yield environments and higher rates in low yield environments compared to H_D. H_D had a greater maximum yield than Valda in high yield environments suggesting that wheat hybrids potentially capitalize on environments favoring higher grain yields. In low yield environments, hybrids require less seed to reach maximum yield which could be economically beneficial depending on seed cost. However, higher seeding rate requirements for maximum yield in high yield environments could have negative economic impacts to wheat growers depending on hybrid wheat price.

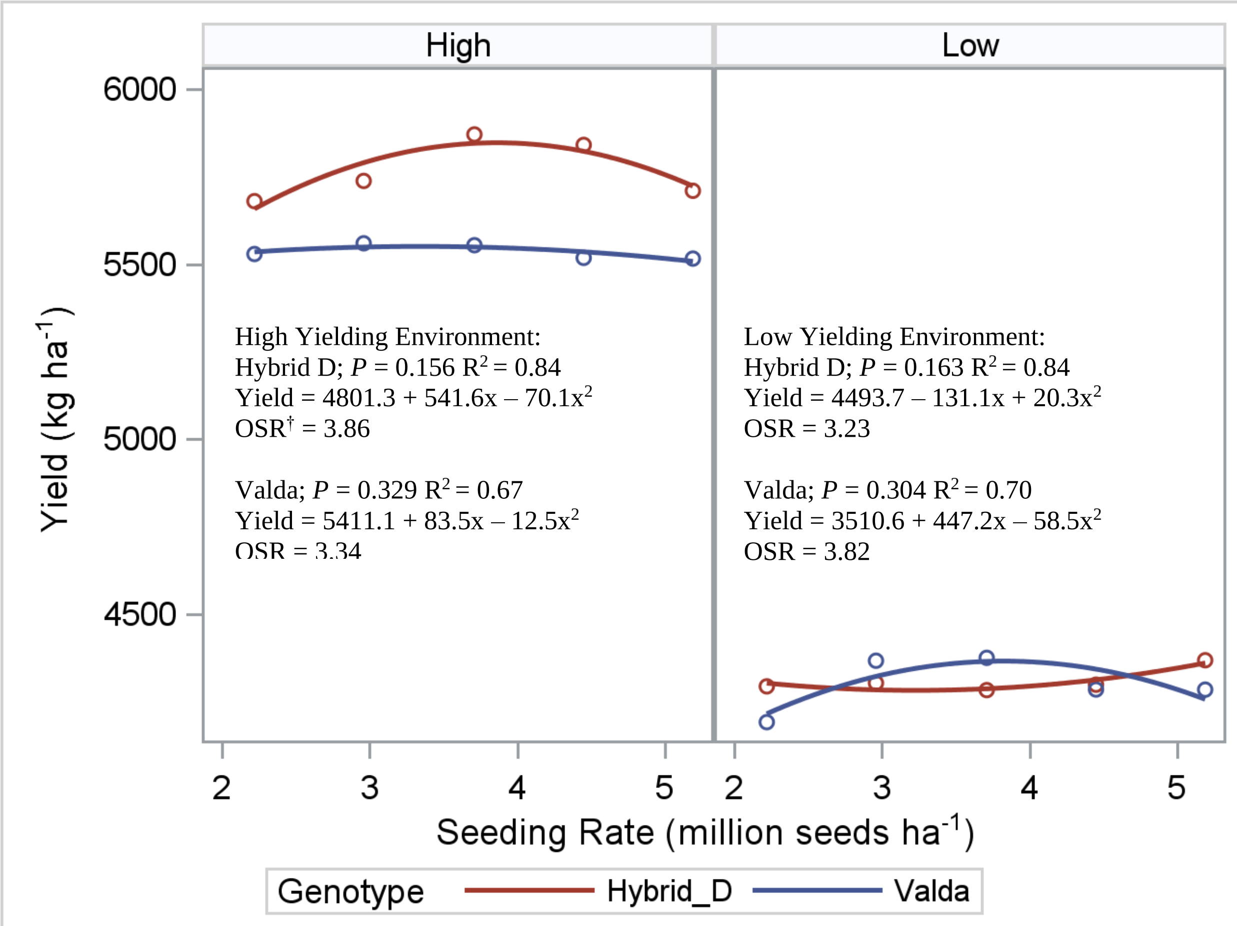

Figure 1.4. H_D and Valda standardized quadratic yield response to seeding rate for four high (>5000 kg ha^{-1}) and five low (<5000 kg ha^{-1}) yield environments (YE) and averaged across seeding rate in 2019 and 2020.
†OSR, Optimum Seeding Rate (million seeds ha^{-1}).

Plant Density Effect on Grain Yield

Established plant density better determines wheat grain yield than seeding rate when mortality rates vary between environments. Seedling mortality from planting to Feekes 1 between environments ranged from 19 to 43% loss (data not shown). Plant density was averaged across each seeding rate using LSMEANS in a regression analysis for yield and protein (Table 1.10). Many of the regression equations had small or no relationship to plant density and yield or protein (Table 1.10). The optimal plant density (OPD) ranged from 2.10 to 2.38 million plants ha^{-1} with a significant OPD of 2.38 million plants ha^{-1} for a maximum yield of 4700 kg ha^{-1} in

Grand Forks. An established plant density of 3.00 to 3.20 million plants ha^{-1} is considered optimum for HRSW production in the Great Plains region (Wiersma and Ransom, 2012). Based on these data, HRSW producers would need to understand how their environment management and seeding rate result in the OPD for maximum yield.

Table 1.10. Linear and quadratic regression analysis for HRSW yield and protein content response to established plant density averaged across seeding rate for each environment.

Environment	*P*	R^2	OPD†	Yield	Order	Regression Equation
			Million plants ha^{-1}	kg ha^{-1}		
Grand Forks	0.143	0.56	-	-	L	$\hat{y}$= 4156.7 + 196.0x
	0.020	0.98	2.38	4712	Q	$\hat{y}$= 2568.1 + 1800.0x - 377.8x^2
Hettinger	0.228	0.43	-	-	L	$\hat{y}$= 4629.9 + 111.0x
	0.121	0.88	2.48	4947	Q	$\hat{y}$= 2652.6 + 1850.0x - 372.9x^2
Langdon	0.999	0.00	-	-	L	$\hat{y}$= 5871.9 - 0.05x
	0.981	0.02	2.48	4947	Q	$\hat{y}$= 2652.6 + 1850.0x - 372.9x^2
Minot	0.861	0.01	-	-	L	$\hat{y}$= 3807.6 + 11.6x
	0.861	0.01	2.41	3830	Q	$\hat{y}$= 3898.0 - 56.7x + 11.8x^2
Prosper	0.910	0.01	-	-	L	$\hat{y}$= 5309.5 + 4.0x
	0.718	0.28	2.10	5348	Q	$\hat{y}$= 4956.8 + 372.5x - 88.6x^2
	P	R^2	OPD	Protein		Regression Equation
			Million plants ha^{-1}	g kg^{-1}		
Grand Forks	0.376	0.26	-	-	L	$\hat{y}$= 153 + 0.07x
	0.700	0.30	1.42	154	Q	$\hat{y}$= 155 - 0.17 x + 0.06x^2
Hettinger	0.050	0.77	-	-	L	$\hat{y}$= 153 - 0.33x
	0.149	0.85	1.88	147	Q	$\hat{y}$= 134 + 1.35x - 0.36x^2
Langdon	0.520	0.15	-	-	L	$\hat{y}$= 145 + 0.06x
	0.840	0.16	3.67	146	Q	$\hat{y}$= 142 + 0.22x - 0.03x^2
Minot	0.222	0.44	-	-	L	$\hat{y}$= 137 - 0.05x
	0.241	0.76	2.67	137	Q	$\hat{y}$= 133 + 0.32x - 0.06x^2
Prosper	0.032	0.83	-	-	L	$\hat{y}$= 159 - 0.43x
	0.140	0.86	2.98	148	Q	$\hat{y}$= 169- 1.43x + 0.24x^2

*, **, ***, and ns indicate significance at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$, and not significant, respectively.

†OPD, optimum plant density for maximum yield based on regression from PROC REG; L, Linear; Q, Quadratic; ŷ, Predicted Yield; x, plant density (million plants ha^{-1}).

The environment is a major factor contributing to crop yield potential. Separating the planting date by environment combinations into high and low yield environments allows for farmers to target an OPD for maximum yield taking into account the yield potential of an environment. Plant density for H_D best described yield in high yield environments and had greater OPD than low yield environments (Table 1.12). To maximize yield, Valda had a higher

OPD than H_D when yield potential was constrained (Figure 1.5). Using plant density to calculate maximum yield typically requires historical seed mortality knowledge, which can change depending on seedborne and seedling diseases, soil moisture, temperature, seedbed conditions, and other management factors. In higher yielding environments, hybrids should provide opportunities to increase yield with modest seeding rate adjustments if seeding loss is held constant.

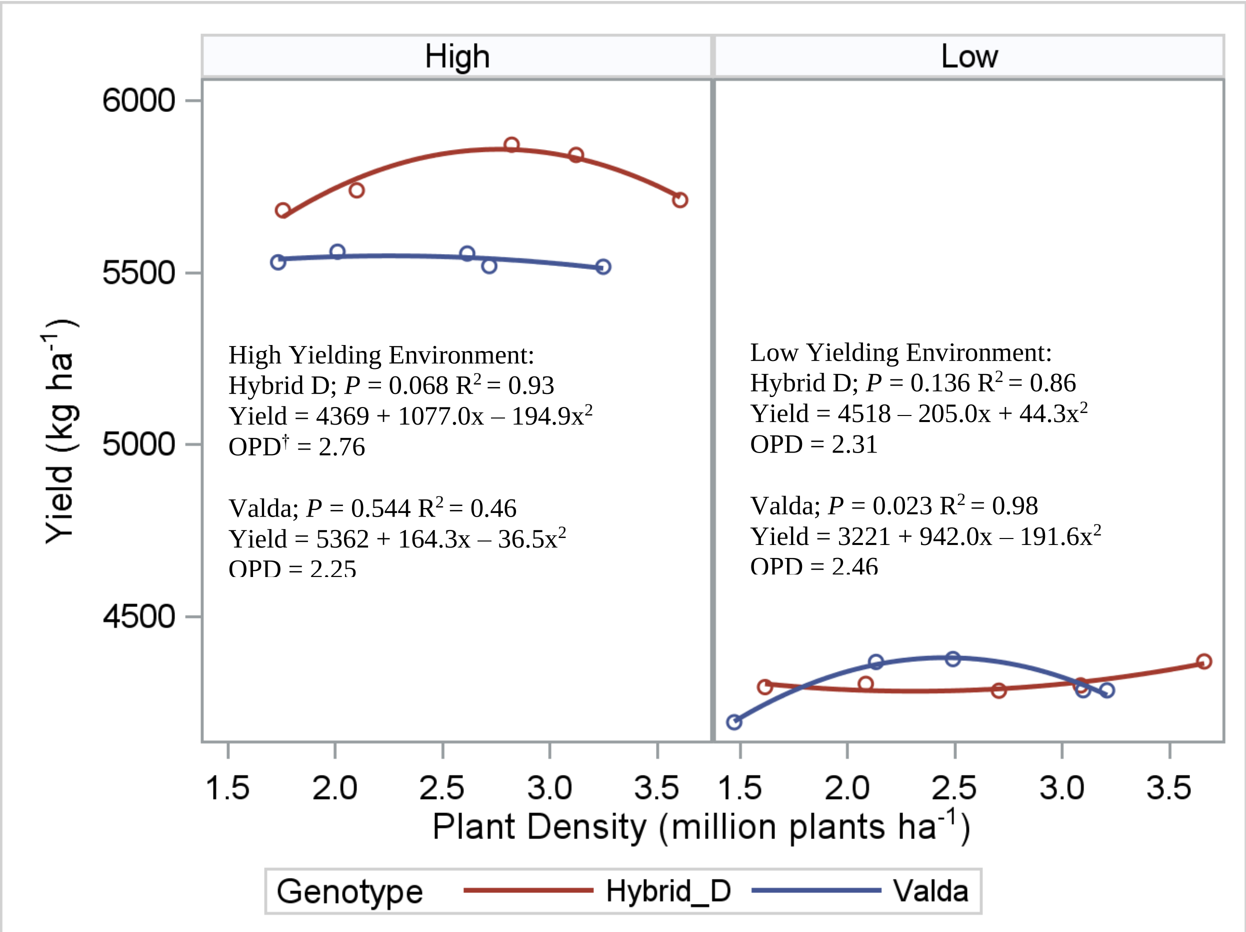

Figure 1.5. H_D and Valda standardized quadratic yield response to established plant density averaged across seeding rate for four high (>5000 kg ha^{-1}) and five low (<5000 kg ha^{-1}) yield environments (YE) and averaged across seeding rate in 2019 and 2020.
†OPD, Optimum plant density (million plants ha^{-1}).

Genotype

Genotype was a significant factor in the ANOVA for yield when the data from each environment were analyzed individually. Additionally, single degree of freedom contrasts comparing HRSW cultivars to hybrids were also statistically significant for both yield and protein differences. Wheat hybrids as a group yielded significantly greater than Ingmar in three environments and greater than Valda at one environment (Table 1.11). Similar trends were observed when comparing Ingmar and Valda to the highest yielding hybrid. These contrasts suggest that hybrids have the potential to out-yield well adapted inbred cultivars, but at least within the group of hybrids tested, heterosis does not guarantee better performance than a well-adapted cultivar. As the hybrids used were experimental and are not expected to be released commercially, performance variability between environments was expected. Furthermore, one can expect variability in hybrid performance, as noted in this study, so only adapted hybrids can be expected to outperform cultivars.

Table 1.11. Results (*P*-values) of contrasts comparing cultivar to hybrid genotypes for yield and protein in each environment.

Contrast	Grand Forks	Hettinger	Langdon	Minot
		P		
		Yield		
Ingmar [I] vs Hybrids	<0.01	0.03	<0.01	0.48
Valda [V] vs Hybrids	0.68	0.32	0.02	0.10
IV vs Hybrids	0.04	0.04	<0.01	0.13
Ingmar vs Best Hybrid†	<0.01	0.01	<0.01	0.35
Valda vs Best Hybrid	0.38	0.11	<0.01	0.10
IV vs Best Hybrid	<0.01	0.02	<0.01	0.14
		Protein		
Ingmar [I] vs Hybrids	<0.01	<0.01	<0.01	0.23
Valda [V] vs Hybrids	0.99	0.78	<0.01	0.19
IV vs Hybrids	<0.01	0.04	<0.01	0.10
Ingmar vs Best Hybrid†	<0.01	<0.01	<0.01	0.53
Valda vs Best Hybrid	<0.01	<0.01	<0.01	0.46
IV vs Best Hybrid	0.70	0.11	<0.01	0.51

†The best hybrid was Hybrid D in GF, Hettinger, and Langdon and Hybrid C in Minot.

Seeding Rate by Genotype

Seeding rates of genotypes had significantly different yield at Prosper. The interaction was due to a change in rank at the 5.19 million seeds ha^{-1} seeding rate where H_D yielded significantly more than Valda contrasting their yield similarity at the other rates (data not shown). In all environments, a greater seeding rate by genotype response was expected based on previous research in Northwestern Canada (Faris and De Pauw, 1981) and North Dakota (Otteson et al., 2007). As previously discussed, high performance variability may have limited the potential genetic response to seeding rate.

Grain Protein Content

Grain protein content was analyzed separately for each environment and planting date and genotypes commonly differed significantly in protein content within an environment (Table 1.6). Significant planting date by seeding rate interactions were due to a change in magnitude where the late planting date and early planting date had greater protein content in Grand Forks and Minot, respectively (Table 1.8). Also, the significant planting date by genotype interaction in Grand Forks were due to a change in magnitude where the late planting date yielded greater than the early date (Table 1.9).

Planting Date

Grain protein content ranged from 135 to 157 g kg^{-1} for the early planting date and 137 to 151 g kg^{-1} for the late planting date and early planting increased protein content in Grand Forks (6 g kg^{-1} greater) and Minot (5 g kg^{-1} greater) (Table 1.12). The increase in protein content was likely a function of decreased yield for early planting in the two environments (Table 1.7). Simmonds (1995) confirmed that the negative yield and protein relationship exists among grass cereals due to the dilution of protein by starch in the seed.

Table 1.12. Wheat grain protein content influenced by planting date, seeding rate, and genotype for individual environments.

Treatment	Grand Forks	Hettinger	Langdon	Minot	Prosper[†]
			g kg^{-1}		
Mean Protein	154	145	136	147	151
Planting Date					
Early	157a[‡]	142	135	149a	151
Late	151b	148	137	144b	-
P	0.008	0.062	0.543	0.018	-
Seeding Rate					
Million seeds ha^{-1}					
2.22	154	147	145	136	155a
2.96	153	146	148	137	152b
3.71	155	146	145	136	149cd
4.45	154	143	147	136	150bc
5.19	155	144	147	135	147d
P	0.308	0.057	0.641	0.334	0.012
Genotype					
Ingmar	157a	148a	146a	148	156a
Valda	154b	145bc	136bc	148	151b
H_A	153b	146ab	133de	146	149bc
H_B	154b	147ab	133d	146	148c
H_C	154b	144bc	134cd	146	149bc
H_D	153b	143c	131e	146	150bc
H_E	154b	145bc	137b	145	151bc
P	<.001	0.013	<.001	0.777	<.001

[†]Means with the same letter, within the same main effect, are not significantly different. Comparisons were made using pairwise comparisons between all treatments at an $\alpha = 0.05$.
[‡]The Prosper environment did not have a late planting date level.

Seeding Rate

Seeding rate significantly affected protein content in Prosper with decreasing protein content as seeding rate increases, which was similar to what was found by Chen et al. (2008). These findings reinforce the inverse yield-protein relationship discussed previously which is often described linearly but can also have quadratic response in some situations.

In Minot, early planting increased protein content whereas late planting decreased protein content as seeding rate increased 0.2 and 0.1 g kg^{-1} for every million live seeds ha^{-1}, respectively (Figure 1.6a). Quadratic seeding rate responses for protein were significant for contrasts between both Valda and IV compared to the hybrids. Ingmar and IV means are both positive parabolic shapes compared to the negative parabola of the hybrid mean (Figure 1.6b and 1.6c). For hybrids, maximum protein content was achieved at 3.3 million live seed ha^{-1}. Faris and De Pauw (1981) describe grain protein content as negatively correlated with yield in most environments; however, various studies have previously affirmed seeding rate often does not significantly affect grain protein (Cambell et al., 1991; Carr et al., 2003; Larter et al., 1971).

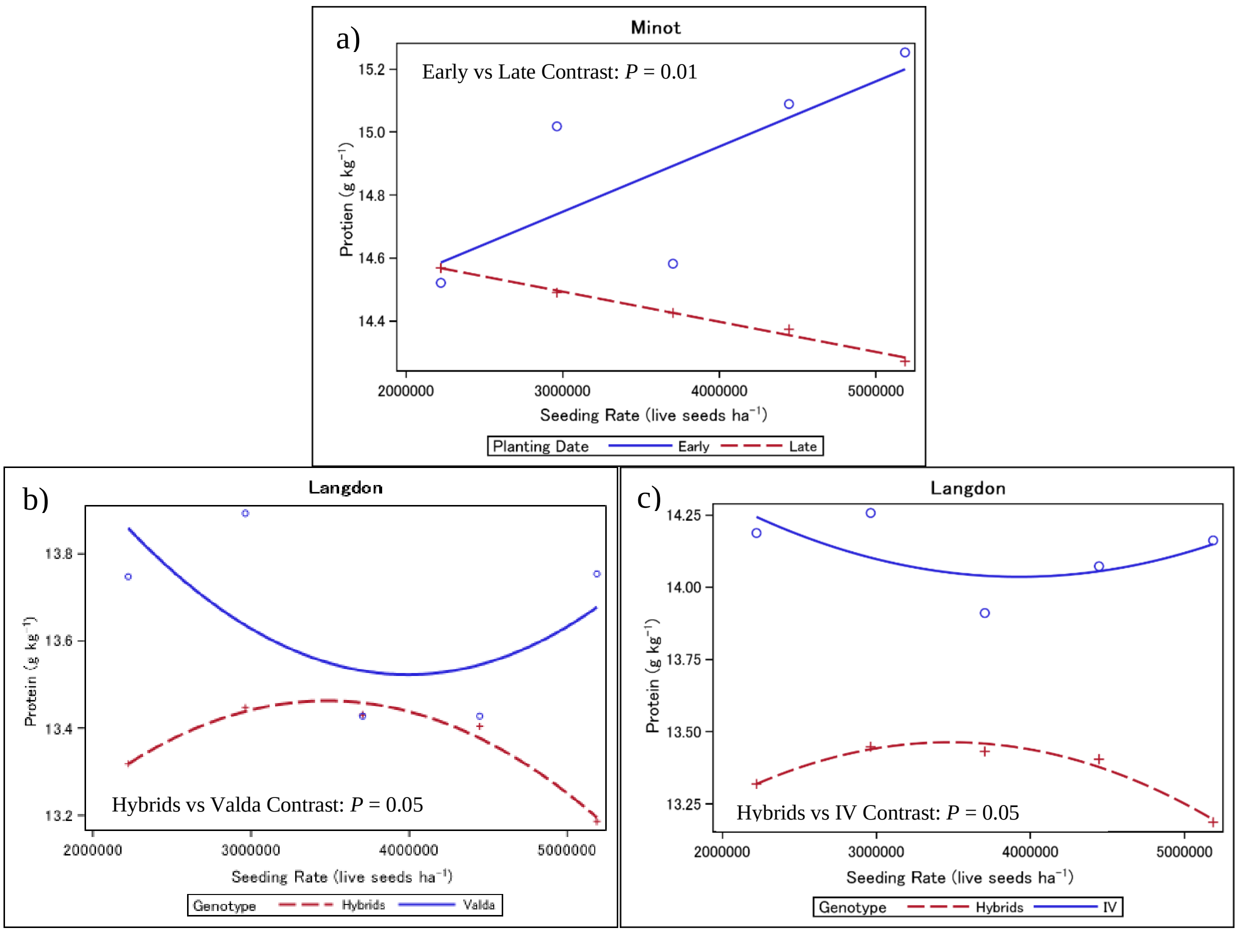

Figure 1.6. Polynomial contrasts of a) planting date by seeding rate, b) seeding rate by Hybrids and Valda, c) seeding rate by Hybrids and Ingmar and Valda (IV) interactions for protein content.

Model parameters for a) Early Planting Date: P = 0.132 R^2 = 0.58 Protein = 142 + 0.24x, Late Planting Date: P = 0.001 R^2 = 0.98 Protein = 148 + 0.47x b) Hybrids: P = 0.005 R^2 = 0.99 Protein = 124 + 1.47×10^{-6} – 5.24×10^{-13}, Valda: P = 0.685 R^2 = 0.32 Protein = 153 - 2.22×10^{-6} + 7.14×10^{-13} and c) Hybrids: P = 0.005 R^2 = 0.99 Protein = 124 + 1.47×10^{-6} – 5.24×10^{-13}, IV: P = 0.653 R^2 = 0.35 Protein = 151 - 1.46×10^{-6} + 4.76×10^{-13}.

Plant Density Effect on Protein Content

At two environments, protein content decreased -3.3 and -4.3 g kg^{-1} per million plants ha^{-1} (data not shown). Grain protein decreased 3.0 g kg^{-1} per million plants ha^{-1} in Hettinger and was optimized at 2.02 million plants ha^{-1} in Minot when planted two weeks later than recommended (data not shown).

Genotype

Genotypes differed significantly in protein content in two of the five environments with Ingmar having the greatest protein content (Table 1.12). Grain protein contents across genotypes were similar to published variety trial results in each area. Protein content levels were relatively consistent across the hybrids given the assumed high genotypic variance between hybrids.

As a group, hybrids had lower protein contents than Ingmar and Valda in Grand Forks, Hettinger, and Langdon (Table 1.12 and 1.11). Ingmar had significantly greater protein, than the hybrid with the highest protein content in Grand Forks and Langdon. However, non-significant contrasts in Hettinger and Minot suggest that the hybrids tested did not have lower grain protein content compared to Ingmar and Valda. Contrary to these findings, Martin et al. (1995) reported hybrid HRSW genotypes with 1 g kg^{-1} greater protein content than conventional cultivars. The data suggest hybrid wheat protein contents can be similar to high protein, cultivars like Ingmar in certain environments.

Planting Date by Genotype

Significant planting date by genotype interactions in Langdon for protein were due to a change in rank of the Valda genotype where the late planting date had greater protein content than the early date whereas the protein content was greater across the other genotypes (data not shown).

Yield Components

Plant Density

Hard red spring wheat plant density was influenced by seeding rate, genotype, and the planting date by seeding rate interaction at some environments (Table 1.6). Plant density increased as seeding rate increased (Table 1.13). Planting date by seeding rate interactions were usually due to greater plant densities for late planting dates, and the planting date by seeding rate interaction in Langdon and Hettinger had inconsistent changes in rank (Table 1.14). In southern Canada, spring barley plant density was not affected by planting date (Duczek and Piening, 1982; Juskiw and Helm, 2002). Early planting dates can expose seeds to low soil temperatures and reduce time to emergence. Temperatures below normal in Grand Forks and Minot after the early planting date may explain reduced plant densities as low air temperatures can slow emergence, prolonging exposure to seedling diseases like common root rot (*Bipolaris sorokiniana*) and Fusarium crown and root rot (*Fusarium spp*). Also, other factors independent of planting date like soil crusting and moisture can reduce plant establishment.

Genotype significantly affected plant density where Ingmar and H_A, H_B, H_C, H_D, and H_E had contrasting plant density differences in two environments. In Grand Forks, hybrids had greater plant densities than Ingmar but Ingmar had significantly greater densities than all but H_E in Langdon (Table 1.13). Genotype differences for plant density are not unusual as reported in previously conducted seeding rate studies (Gelata et al., 2002; Otteson et al., 2007). Allard and Bradshaw (1964) describe phenotypic agronomic traits besides yield often as less environmental stability as they are not the primary focus of breeding efforts.

Table 1.13. Wheat yield components influenced by planting date, seeding rate, and genotype for individual environments.

Treatment		GF†	H	L	M	P	GF	H	L	M	P	GF	H	L	M	P
		Million Plants ha^{-1}					Million Spikes ha^{-1}					Tillers plant^{-1}				
PD	Early	1.96	2.53	2.91	2.69	2.08	5.55	4.72	5.43	4.12	5.95	2.9	1.0	1.0	0.8	2.2
	Late	2.40	2.48	2.99	3.14	-	5.46	5.12	5.32	3.73	-	2.4	1.3	0.9	0.2	-
SR	2.22	1.34	1.81	1.72	1.90	1.32e	4.70	4.54c‡	3.36	5.22	5.61	3.4a	1.7	1.1	1.8	3.3a
	2.96	1.82	2.36	2.29	2.50	1.54d	5.37	4.78bc	3.60	5.26	5.43	3.1ab	1.2	0.6	1.2	2.8b
	3.71	2.19	2.61	2.98	2.99	2.18c	5.88	5.00ab	3.99	5.37	5.44	2.8b	1.1	0.4	0.8	1.7c
	4.45	2.66	2.80	3.62	3.57	2.58b	5.86	5.03ab	4.03	5.59	6.45	2.3c	0.9	0.1	0.6	1.6c
	5.19	2.89	2.95	4.14	3.89	2.85a	5.73	5.27a	4.64	5.47	6.35	1.8d	0.8	0.1	0.4	1.3d
G	Ingmar	1.93c	2.55	3.44a	3.01	1.97	5.64b	4.91b	5.89b	4.06	5.97	3.1	1.1	0.9	0.5	2.5a
	Valda	2.05bc	2.43	2.67bc	2.85	1.94	6.04a	4.85a	6.24a	3.76	6.39	3.0	1.2	1.5	0.5	2.6a
	H_A	2.26a	2.47	2.83b	3.05	2.29	5.32bc	5.08c	5.04b	4.02	5.86	2.5	1.2	0.9	0.4	1.7d
	H_B	2.28a	2.46	2.84c	2.81	2.16	5.29c	4.83c	5.03b	3.83	5.80	2.4	1.1	0.9	0.6	1.9cd
	H_C	2.29a	2.51	2.97b	2.93	2.10	5.52bc	5.08c	5.08b	4.00	5.61	2.7	1.2	0.9	0.5	2.1bc
	H_D	2.24a	2.62	2.93b	2.97	1.99	5.38bc	4.88c	5.18b	3.83	5.79	2.4	1.1	1.0	0.4	2.1bc
	H_E	2.22ab	2.50	2.94ab	2.89	2.15	5.38bc	4.84c	5.02b	3.93	5.87	2.7	1.1	0.9	0.5	2.2b

Treatment		GF	H	L	M	P	GF	H	L	M	P
		1000 kernel weight (g)					kernels spike^{-1}				
PD	Early	31.1	33.9	35.4	36.3a	31.3	26.9	33.9	31.1	26.2	28.9
	Late	29.4	33.0	33.7	31.6b	-	29.6	28.0	34.1	34.1	-
SR	2.22	30.6	33.5	33.9	35.0	31.4	30.8	32.7	35.1	33.1	30.9
	2.96	30.3	33.4	33.8	34.9	31.9	29.0	32.0	32.6	33.2	30.9
	3.71	30.3	33.4	34.0	34.7	31.2	26.9	30.8	30.0	32.3	28.9
	4.45	30.2	33.4	33.5	34.1	31.1	26.9	30.3	28.2	31.8	26.8
	5.19	29.9	33.3	33.9	34.4	31.1	27.7	28.9	25.5	32.1	26.9
G	Ingmar	28.0	33.1	32.1	33.1	30.1d	27.9	30.3	29.8	29.4	29.0
	Valda	31.4	33.4	35.8	33.8	32.1b	25.0	31.3	26.6	31.3	27.0
	H_A	30.8	33.5	35.6	33.7	31.6c	29.1	30.0	34.2	29.7	29.3
	H_B	30.7	33.3	34.6	34.0	31.5c	28.7	31.1	34.2	31.3	29.7
	H_C	30.4	33.7	34.1	34.4	31.6c	28.1	29.8	34.4	29.2	26.7
	H_D	31.1	33.4	36.0	34.1	32.6a	29.0	32.1	33.8	30.8	29.4
	H_E	29.4	33.4	34.4	33.7	30.1d	29.8	32.0	35.3	30.8	30.7

†GF, Grand Forks; H, Hettinger; L, Langdon; M, Minot; P, Prosper; PD, Planting Date; SR, Seeding Rate (million live seed ha^{-1}); G, Genotype. The Prosper environment did not have a late planting date level.

‡Means with the same letter, within the same main effect, are not significantly different. Mean separations were made using pairwise t-test comparisons between all treatments at an $\alpha = 0.05$.

Table 1.14. Significant planting date by seeding rate interactions for yield components.

Environment	Planting Date	Seeding Rate (million live seed ha^{-1}) 2.22	2.96	3.71	4.45	5.19
				Million plants ha^{-1}		
Grand Forks	Early	1.22f †	1.57ef	2.08d	2.42cd	2.53bc
	Late	1.46ef	2.08d	2.30cd	2.90b	3.25a
Hettinger	Early	1.98de	2.24cd	2.79ab	2.66abc	2.97a
	Late	1.63e	2.45bcd	2.42bcd	2.95a	2.94a
Langdon	Early	1.88f	2.46e	2.90cd	3.37b	3.93a
	Late	1.90f	2.50de	3.05bc	3.85a	3.86a
Minot	Early	1.41f	2.10e	2.66d	3.60b	3.87b
	Late	2.02e	2.46d	3.28c	3.65b	4.30a
				Million spikes ha^{-1}		
Grand Forks	Early	4.46f	5.31cde	5.85abcd	6.02ab	6.20a
	Late	4.96ef	5.47bcde	5.93abc	5.71abcd	5.29de
Langdon	Early	5.11d	5.37abcd	4.93d	5.80ab	5.85ab
	Late	5.30bcd	5.05d	5.75abcd	5.27cd	4.94d
Minot	Early	3.70de	3.97cd	4.27bc	4.16c	4.64a
	Late	3.00f	3.34e	3.75d	3.94cd	4.63ab
				Tillers plant^{-1}		
Hettinger	Early	1.27bc	1.28bc	0.78d	0.93cd	0.69d
	Late	2.07a	1.10bcd	1.40b	0.84cd	0.98bcd
Langdon	Early	1.82a	1.25b	0.76de	0.77de	0.56ef
	Late	1.82a	1.06bc	0.91cd	0.42fg	0.30g
Minot	Early	1.79a	0.93b	0.72b	0.18e	0.22de
	Late	0.51c	0.40cd	0.16e	0.09e	0.08e
				Kernels spike^{-1}		
GF	Early	31.0ab	28.2cde	25.5ef	26.2ef	23.8f
	Late	30.5abc	29.7abcd	28.2bcde	27.7de	31.6a
Langdon	Early	32.2bcd	30.8cd	33.9abc	29.5d	29.4d
	Late	34.1abc	36.6a	31.1cd	35.1ab	35.8a
Minot	Early	30.8cb	26.3de	25.9de	24.3e	23.1e
	Late	39.4a	38.0a	33.7b	31.8b	27.7cd

†Means with the same letter, within the planting date main effect for that location, are not significantly different. Mean separations were made using pairwise t-test comparisons between the planting date and seeding rate interactions for all means within an environment at an $\alpha = 0.05$.

Tillering

Tiller numbers differed significantly for the main effects of seeding rate in Grand Forks and Prosper and genotypes in Prosper, and the planting date by seeding rate interaction in Hettinger, Langdon, and Minot, and the planting date by genotype interaction in Grand Forks

(Table 1.6). Tillering in Minot was likely reduced due to water stress during tiller formation as there was minimal rainfall from planting through the 180 DOY (Figure 1.1). In general, tillers plant^{-1} decreased as seeding rates increased (Table 1.13). On average, Valda produced 0.5 more tillers than other genotypes in Langdon whereas Ingmar and Valda produced significantly greater tillers than the hybrids in Prosper (Table 1.13). Planting date by seeding rate interactions for tillers per plant were not consistent between environments (Table 1.14). The significant planting date by genotype interaction in Grand Forks was due to Ingmar, H_C, and H_D producing 0.7, 1.2, and 0.7 more tillers plant^{-1}, respectively, when planting early compared to late while planting date did not affect tiller numbers in the other genotypes (Table 1.15).

Spike Density

Spike density was influenced by seeding rate in Hettinger, genotype in Grand Forks, Hettinger, and Langdon, and by the planting date by seeding rate interactions in Grand Forks, Langdon, and Minot (Table 1.6). The lowest seeding rate (2.22 million seeds ha^{-1}) had 10 to 16% less spikes ha^{-1} than seeding rates above 3.71 million seeds ha^{-1} in Hettinger, the interaction of planting date with seeding rate were typically derived from greater spike densities for the planting date which yielded greater in that environment (Table 1.14). Similarly, Chen et al. (2008) found increasing spike density as seeding rate increased. Higher seeding rates (4.45 and 5.19 million seed ha^{-1}) had greater spike density in Langdon and lower seeding rates (2.22 and 3.71 million live seed ha^{-1}) had less spikes ha^{-1} in Minot when planted early. As for genotypes, Valda had the greatest spike density compared to the other genotypes and had 7% more spikes ha^{-1} than Ingmar in Grand Forks (Table 1.15). Because spike density is a function of plant density and tillering rate, tillering can be reduced due to greater intra-row competition caused by greater plant densities (Elhani et al., 2007). In addition, Stanley et al. (2020) found genotypes have differing propensity to tiller which would influence the spike density and tillering differences between cultivars and hybrids.

Table 1.15. The effect of planting date and genotype on yield components at locations with significant interactions.

Environment	Planting Date	Genotype						
		Ingmar	Valda	H_A	H_B	H_C	H_D	H_E
		Tillers plant^{-1}						
Grand Forks	Early	3.5a	3.1abc	2.6cdefg	2.5defg	3.3ab	2.8bcdef	2.8bcde
	Late	2.7bcdef	3.0abcd	2.3efg	2.2efg	2.1fg	2.1g	2.6bcdef
		1000 kernel weight (g)						
Grand Forks	Early	33.1ed	35.9ab	37.2ab	35.2bc	35.5bc	36.7ab	34.6bcd
	Late	31.1f	35.8ab	33.9cd	34.0cd	32.3ef	34.8bcd	34.2cd
Langdon	Early	33.1ed	35.9ab	37.2ab	35.2bc	35.5bc	36.7ab	34.6bcd
	Late	31.1f	35.8ab	33.9cd	34.0cd	32.3ef	34.8bcd	34.2cd
		Kernels head^{-1}						
Grand Forks	Early	27.1bc	26.3cd	26.5cd	26.5cd	26.0cd	27.3bc	28.7abc
	Late	28.8abc	23.7d	31.7a	30.8a	30.2ab	30.8a	30.9a
Langdon	Early	28.6ef	27.3f	33.2cd	31.7d	32.1d	31.3de	34.0bcd
	Late	31.0de	25.9f	35.7abc	37.0ab	37.5a	37.7a	37.1ab

†Means with the same letter, within the same environment, are not significantly different. Mean separations were made using pairwise t-test comparisons between all treatments at an $\alpha = 0.05$.

Kernel Weight

Planting date, genotype, and the planting date by genotype interaction significantly impacted kernel weight (Table 1.6). Early planting significantly increased kernel weight by 15% in Minot and H_D had significantly greater kernel weight than Valda and Ingmar in Prosper (Table 1.13). Planting date by genotype interaction in Langdon was due to a change in magnitude whereas the Grand Forks interaction was caused by Valda producing kernels 0.87 mg kernel^{-1} heavier when planted late compared to the early planting date (Table 1.14). Delayed planting can reduce kernel weight due to the likelihood of high post-heading temperatures. Genotypes that are earlier to head and mature can avoid this late season stress in most season (Ortiz-Monasterio et al., 1994).

Kernels per Spike

The planting date by seeding rate and planting date by genotype interactions were significant for kernels spike^{-1} (Table 1.6). The planting date by seeding rate interactions were typically due to a change in magnitude, but in Langdon, the late planted 5.19 million seeds ha^{-1} seeding rate had 8 more kernels spike^{-1} than early planting whereas there were no differences for the other rates and dates (Table 1.14). The planting date by seeding rate interaction was significant in Grand Forks and Minot due to a change in the magnitude of the difference between the planting date and seeding rate effects. Late planted wheat hybrids generally produced more kernels spike^{-1} than Ingmar and Valda when compared to early planted hybrids (Table 1.15).

Component Contribution to Yield

Wheat yield components are considered plastic and compensate for one another which can cause different expression in high or low yielding environments for Valda and H_D. Plant density was not significantly related to Valda or H_D in either yield environment Table 1.16. In high yielding environments, the relationship between spike density, kernels spike^{-1}, and kernel weight for yield was stronger for H_D compared to Valda. Although H_D r^2 values are higher than Valda, the multiple linear regression coefficients for Valda and H_D in high yield environments show that the relative importance of the yield components are similar. Yield components in high yield environments better explain yield for H_D (R^2=0.79) than Valda (R^2=0.56). Furthermore, yield component contribution to yield for Valda and H_D have no discernable differences in low yield environments.

Spike density, kernel weight, and kernels spike^{-1} consistently explained yield for both Valda and H_D in both high and low yield environments. Slafer et al. (2014) describes kernels spike^{-1} as a coarse yield regulator accounting for large changes in yield caused by genotypic differences and can be targeted with management practices to improve overall yield. Improving wheat yield potential through maximizing spike density, kernels spike^{-1}, and kernel weight may benefit hybrid wheat more than inbred cultivars if used for selection during the breeding process.

Table 1.16. Cultivar Valda and Hybrid D (H_D) in high (>5000 kg ha^{-1}) and low (<5000 kg ha^{-1}) yield environment partial correlation coefficients (r) and significance for relationships between the yield and yield components and corresponding standardized multiple linear regression equations.

	High		Low	
	Valda	H_D	Valda	H_D
PD†	0.01^{ns}	0.01^{ns}	0.03^{ns}	0.01^{ns}
SD	0.55^{***}	0.74^{***}	0.77^{***}	0.79^{***}
Kernels	0.55^{***}	0.78^{***}	0.60^{***}	0.64^{***}
KWT	0.35^{***}	0.63^{***}	0.33^{***}	0.39^{***}

	R^2	Equation
High		
Valda	0.56	$\hat{y} = 0.03PD + 1.53SD + 1.58Kernels + 0.55KWT - 1.69\times10^{-15}$
H_D	0.79	$\hat{y} = -0.01PD + 1.41SD + 1.60Kernels + 0.65KWT - 1.49\times10^{-15}$
Low		
Valda	0.79	$\hat{y} = -0.09PD + 1.55SD + 1.07Kernels + 0.36KWT + 4.90\times10^{-15}$
H_D	0.81	$\hat{y} = -0.03PD + 1.46SD + 1.03Kernels + 0.45KWT - 1.05\times10^{-15}$

†PD, Plant Density; SD, Spike Density; Kern, Kernels per spike; KWT, 1000 kernel weight; R^2, adjusted R^2.

Agronomic Characteristics

Significant differences were found for plant height, days to heading, and bacterial leaf streak indices. There were no significant differences in any of the factors for plant lodging in any of the environments. Plant height was influenced by planting date and genotype (Table 1.6). Early planting resulted in plants 3 to 4 cm taller than when planted late in Hettinger and Langdon (Table 1.17). Hybrids tended to be taller in two environments while H_B tended to be similar in plant height to Valda (Table 1.17). There was a significant planting date by genotype interaction for plant height; however, there was no change in rank between genotypes for plant height for each planting date (data not shown).

Table 1.17. Wheat plant height and days to heading influenced by planting date, seeding rate, and genotype for individual environments.

Treatment	GF[†]	H	L	M	P	GF	H	L	M	P
	Plant Height					Days to Heading				
Planting Date	- - - - - - - - - - - - cm - - - - - - - - - - - -					- - - - - - - - - - - - - - - days - - - - - - - - - - - -				
Early	72.7b‡	85.3a	82.2b	64.7	71.7	52.2	67.1a	55.7a	60.5a	55.3
Late	78.0a	82.2b	88.6a	-	-	45.2	48.1b	46.8b	46.2b	-
Seeding Rate										
Million live seed ha^{-1}										
2.22	73.7	84.0	66.8	85.5	72.2	49.2	49.2a	51.8a	53.9a	55.7
2.96	75.1	83.2	63.7	86.0	71.2	48.6	48.6a	51.8a	53.1b	55.5
3.71	75.5	83.8	65.3	85.1	71.1	48.5	48.5b	51.2bc	53.0bc	55.3
4.45	75.6	83.8	62.8	84.8	71.3	48.5	48.5bc	51.3c	52.7c	55.3
5.19	76.7	84.1	64.5	84.5	72.8	48.6	48.6c	51.3c	52.3c	54.7
Genotype										
Ingmar	68.5d	80.8c	86.6	65.1	72.9d	49.7	57.6	51.3b	52.5bc	56.7a
Valda	70.4c	83.1bc	90.3	66.2	73.8c	49.3	57.6	51.9a	53.8a	56.2b
H_A	78.9a	84.4ab	88.9	64.1	74.2b	48.5	57.5	51.3bc	52.3bc	54.4d
H_B	78ab	83.8ab	90.2	64.8	74.7a	48.3	57.6	51.2bc	52.7c	54.4d
H_C	77.3ab	83.9ab	85.6	65.9	72.1e	48.4	57.7	51.4bc	53.3bc	54.9c
H_D	76.5b	84.5ab	74.6	64.4	67.7f	48.7	57.3	52.0a	53.5ab	55.0c
H_E	77.8ab	85.9a	78.3	62.0	67.0g	48.2	57.7	51.4bc	52.8bc	54.9c

[†]GF, Grand Forks; H. Hettinger; L. Langdon; M. Minot; P, Prosper. Minot did not have heights recorded for the late planting date and the Prosper environment did not have a late planting date level

[‡]Means with the same letter, within the same main effect and column, are not significantly different. Comparisons were made using pairwise comparisons between all treatments at an $\alpha = 0.05$.

Days to heading was affected by planting date, seeding rate, genotype, and by a planting date by genotype interaction (Table 1.6). Earlier planted wheat required more days to reach the heading stage than the late planting date (Table 1.17). Days to heading typically increased as seeding rate increased (Table 1.17). The significant planting date by genotype interactions for heading date in Langdon was due to differences in magnitude (data not shown). Ingmar often had the most days to heading, but the hybrids reached heading sooner than Ingmar and Valda in Prosper (Table 1.17). The earlier heading demonstrated by the hybrids can be an advantage in certain environments as earliness is critical in kernel weight determination by avoiding high temperature post-heading stress therefore increasing yield (Ortiz-Monasterio et al. 1994).

Bacterial leaf streak index scores recorded in Grand Forks and Prosper were only significantly different in Grand Forks for genotype and the planting date by seeding rate interaction (Table 1.18). Higher seeding rates likely resulted in higher BLS indices due to more physical or rain splash transfer of BLS exudates from higher plant densities. The planting date by seeding rate interaction was due to differences in magnitude with greater disease presence in the late planting date (Table 1.18). The early planting date had a significantly lower BLS index of 11 compared to the late planting date of 31. Plant tissue usually requires wounding for bacterial infection and BLS symptoms are more likely to be observed following rainstorms with high winds at Feekes 9. Weather for the early planting date following Feekes 9 was relatively mild with normal windspeeds. The late planting date experienced high wind. Rainstorms at Feekes 9 (visible flag leaf ligule) and two weeks after (Feekes 10.54) likely contributed to the higher BLS. H_B, H_C, H_D, and H_E had BLS indices significantly greater than Ingmar and Valda (Table 1.18). Ingmar and Valda have moderate BLS ratings of 5 and 6 (Table 1.18), and results suggest that the tested hybrids have less BLS tolerance than Ingmar and Valda.

Table 1.18. Mean wheat bacterial leaf streak index scores influenced by planting date and genotype for Grand Forks.

Treatment				
Planting Date	Seeding Rate	Index	Genotype	Index
	Million live seeds ha^{-1}			
Early	2.22	10ed†	Ingmar	10d
	2.96	11ed	Valda	15cd
	3.71	11ed	H_A	20bc
	4.45	6e	H_B	26ab
	5.19	16cd	H_C	24ab
Late	2.22	25b	H_D	23ab
	2.96	25b	H_E	27a
	3.71	32b		
	4.45	29b		
	5.19	43a		

†Means with the same letter, within the same column, are not significantly different. Mean separation was made using pairwise t-test comparisons between all treatments at an $\alpha = 0.05$.

Economic Analysis

Hybrid wheat seed costs in the past have ranged from 2.5 to 5 times greater than certified inbred seed (Cisar and Cooper, 2002; Retzlaff, 1976). A partial budget sensitivity analysis considering a range of wheat seed costs and grain market prices using quadratic regression equations can be used to EOSR. Comparisons between the EOSR of Ingmar and Valda, hybrids, and the top performing hybrids for each environment were made to better understand potential hybrid wheat use.

Quadratic regression using seeding rate as the independent variable was significant in Grand Forks for the Ingmar and Valda and Hybrid groupings and for the H_D (Table 1.19). The EOSR differences between cultivars and hybrids differ in magnitude in Grand Forks. (Table 1.20). The EOSR varies from 2.48 to 3.82 and 2.87 to 4.36 million live seeds ha^{-1} and grain yields of 4489 to 4750 and 4402 to 4688 kg ha^{-1} for wheat hybrids and Ingmar and Valda, respectively (Table 1.20). The EOSR for Ingmar and Valda occur at greater seeding rates. The hybrids required lower seeding rates than the cultivars to achieve the EOSR.

Although hybrids had lower EOSR, hybrid seed cost values could dramatically change a farmer's seed cost ha^{-1}. When planted at the EOSR, \$1.10 kg^{-1} of hybrid seed would cost a farmer 2.2 times more than \$0.37 kg^{-1} of Ingmar or Valda seed at a grain price of \$0.20 kg^{-1} ha^{-1} planted. When planted at the same seeding rate and seed cost, hybrids are expected to provide about 3.5% more profit ha^{-1}. However, hybrids no longer provide an economic advantage when their seed cost is \$0.35 kg^{-1} greater than Ingmar and Valda.

It is unlikely for a seed company to release multiple genotypes with similar characteristics allowing a reasonable comparison of the best hybrid in an environment. In Grand Forks, H_D has a greater EOSR with higher grain prices compared to the grouped hybrids EOSR

(Table 1.21). As seed cost increases, the EOSR for H_D was less than the IV and Hybrids groupings (Table 1.20 and 1.24). High performing hybrids allow for a greater EOSR range depending on seed costs and grain pricing. An associated degree of risk accompanies reduced seeding rates.

Table 1.19. Yield response of genotype groupings to seeding rate for EOSR regression analysis.

Environment	Grouping†	*P*	R^2	Regression Equation‡
Grand Forks	IV	0.027	0.64	$\hat{y}= 2572 + 932x - 1.0\times10^{-10}x^2$
	Hybrids	<0.001	0.49	$\hat{y}= 2902 + 928x - 1.2\times10^{-10}x^2$
	H_D	0.036	0.96	$\hat{y}= 3233 + 736x - 8.3\times10^{-11}x^2$
Hettinger	IV	0.097	0.49	$\hat{y}= 3036 + 955x - 1.2\times10^{-10}x^2$
	Hybrids	0.851	0.01	$\hat{y}= 4802 + 58x - 5.1\times10^{-12}x^2$
	H_D	0.328	0.67	$\hat{y}= 6813 - 1060x - 1.5\times10^{-10}x^2$
Langdon	IV	0.735	0.08	$\hat{y}= 5192 + 224x - 2.5\times10^{-11}x^2$
	Hybrids	0.488	0.06	$\hat{y}= 5715 + 173x - 2.8\times10^{-11}x^2$
	H_D	0.246	0.75	$\hat{y}= 6303 - 41x - 6.7\times10^{-13}x^2$
Minot	IV	0.684	0.10	$\hat{y}= 4454 - 413x - 5.7\times10^{-11}x^2$
	Hybrids	0.914	0.01	$\hat{y}= 3884 - 25x - 5.6\times10^{-12}x^2$
	H_C	0.638	0.36	$\hat{y}= 3631 + 267x - 4.8\times10^{-11}x^2$
Prosper	IV	0.732	0.09	$\hat{y}= 4991 + 240x - 4.1\times10^{-11}x^2$
	Hybrids	0.890	0.01	$\hat{y}= 5291 - 1x - 2.7\times10^{-12}x^2$
	H_D	0.203	0.80	$\hat{y}= 6469 - 682x - 1.0\times10^{-10}x^2$
Combined§	IV	0.086	0.91	$\hat{y}= 3849 + 629x - 7.6\times10^{-11}x^2$
	Hybrids	0.297	0.70	$\hat{y}= 4760 + 251x - 3.2\times10^{-11}x^2$
	H_D	0.501	0.50	$\hat{y}= 5746 - 452x + 5.9\times10^{-11}x^2$

†IV, Ingmar and Valda; Hybrids, Combined hybrids; H_C, Hybrid C; H_D, Hybrid D.
‡Quadratic regression equation from PROC REG.
§The Minot environment was excluded from the combined regression analysis.

Table 1.20. Seeding rate providing the maximum economic return based on seed cost and grain price for the combined Ingmar and Valda and Hybrid genotypes in Grand Forks.

	Market Price ($ kg^{-1})															
	Average response of Ingmar and Valda								Average response of Hybrids							
Seed Cost	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29
($ kg^{-1})	Million Seeds ha^{-1}								Million Seeds ha^{-1}							
0.35	4.21	4.25	4.27	4.30	4.32	4.33	4.35	4.36	3.69	3.72	3.74	3.76	3.78	3.79	3.81	3.82
0.44	4.13	4.17	4.21	4.23	4.26	4.28	4.30	4.31	3.61	3.65	3.68	3.70	3.73	3.75	3.76	3.78
0.53	4.05	4.10	4.14	4.17	4.20	4.23	4.25	4.27	3.54	3.58	3.62	3.65	3.67	3.70	3.72	3.73
0.62	3.96	4.02	4.07	4.11	4.14	4.17	4.20	4.22	3.46	3.51	3.56	3.59	3.62	3.65	3.67	3.69
0.70	3.88	3.94	4.00	4.05	4.08	4.12	4.15	4.17	3.39	3.45	3.49	3.54	3.57	3.60	3.63	3.65
0.79	3.79	3.87	3.93	3.98	4.03	4.06	4.10	4.12	3.31	3.38	3.43	3.48	3.52	3.55	3.58	3.61
0.88	3.71	3.79	3.86	3.92	3.97	4.01	4.05	4.08	3.23	3.31	3.37	3.42	3.47	3.50	3.54	3.56
0.97	3.62	3.72	3.79	3.86	3.91	3.96	3.99	4.03	3.16	3.24	3.31	3.37	3.41	3.45	3.49	3.52
1.06	3.54	3.64	3.72	3.79	3.85	3.90	3.94	3.98	3.08	3.17	3.25	3.31	3.36	3.41	3.45	3.48
1.15	3.46	3.57	3.66	3.73	3.79	3.85	3.89	3.93	3.01	3.11	3.19	3.25	3.31	3.36	3.40	3.44
1.23	3.37	3.49	3.59	3.67	3.73	3.79	3.84	3.89	2.93	3.04	3.13	3.20	3.26	3.31	3.35	3.39
1.32	3.29	3.41	3.52	3.60	3.68	3.74	3.79	3.84	2.86	2.97	3.06	3.14	3.21	3.26	3.31	3.35
1.41	3.20	3.34	3.45	3.54	3.62	3.68	3.74	3.79	2.78	2.90	3.00	3.08	3.15	3.21	3.26	3.31
1.50	3.12	3.26	3.38	3.48	3.56	3.63	3.69	3.75	2.71	2.84	2.94	3.03	3.10	3.16	3.22	3.27
1.59	3.04	3.19	3.31	3.41	3.50	3.58	3.64	3.70	2.63	2.77	2.88	2.97	3.05	3.12	3.17	3.23
1.67	2.95	3.11	3.24	3.35	3.44	3.52	3.59	3.65	2.56	2.70	2.82	2.91	3.00	3.07	3.13	3.18
1.76	2.87	3.04	3.17	3.29	3.39	3.47	3.54	3.60	2.48	2.63	2.76	2.86	2.95	3.02	3.08	3.14

Table 1.21. Seeding rate providing the maximum economic return based on seed cost and grain price for Hybrid D (H_D) in Grand Forks.

	H_D							
Seed Cost	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29
($ kg^{-1})	- - - - - - - - - - - - - - - - - - Million Seeds ha^{-1} - - - - - - - - - - - - - - - - - -							
0.35	5.19	5.19	5.19	5.19	5.19	5.19	5.19	5.19
0.44	5.03	5.13	5.19	5.19	5.19	5.19	5.19	5.19
0.53	4.82	4.94	5.04	5.13	5.19	5.19	5.19	5.19
0.62	4.62	4.76	4.88	4.98	5.06	5.13	5.19	5.19
0.70	4.41	4.58	4.71	4.82	4.92	5.00	5.07	5.13
0.79	4.21	4.39	4.54	4.67	4.78	4.87	4.94	5.01
0.88	4.01	4.21	4.38	4.52	4.63	4.73	4.82	4.90
0.97	3.80	4.03	4.21	4.36	4.49	4.60	4.70	4.78
1.06	3.60	3.84	4.04	4.21	4.35	4.47	4.58	4.67
1.15	3.39	3.66	3.88	4.06	4.21	4.34	4.46	4.55
1.23	3.19	3.48	3.71	3.90	4.07	4.21	4.33	4.44
1.32	2.99	3.29	3.54	3.75	3.93	4.08	4.21	4.33
1.41	2.78	3.11	3.38	3.60	3.79	3.95	4.09	4.21
1.50	2.58	2.93	3.21	3.45	3.65	3.82	3.97	4.10
1.59	2.38	2.74	3.04	3.29	3.50	3.69	3.84	3.98
1.67	2.22	2.56	2.88	3.14	3.36	3.56	3.72	3.87
1.76	2.22	2.38	2.71	2.99	3.22	3.42	3.60	3.75

Combining data across environments increases the recommendation domain for tentative hybrid HRSW use in North Dakota and nearby areas. The Minot environment experienced extra-ordinary dry and above normal temperatures for first half of the growing season greatly limiting tiller and spike formation and was excluded from the combined analysis. When environments were combined, seeding rate explains 91% of variation in yield for Ingmar and Valda and 70% for the hybrids (Table 1.18). Economic optimum seeding rates ranged from 4.08 to 4.15 million seeds ha^{-1} for Ingmar and Valda and 3.67 to 3.85 million seed ha^{-1} for the hybrids. Seeding rates greater than the EOSR result in diminishing returns for added seed. When seeded at the same rate with the same seed cost ($0.44 kg^{-1}), hybrids provide a 2% yield and $21 ha^{-1} advantage over Ingmar and Valda for combined environments. But, hybrids tested no longer have an economic advantage if hybrid seed costs $0.18 kg^{-1} more than the seed cost of Ingmar or Valda.

Table 1.22. Economic optimal seeding rate based on seed cost and grain price for Ingmar and Valda and Hybrids across combined environments.

	Market Price ($ kg^{-1})															
	Average response of Ingmar and Valda								Average response of Hybrids							
Seed Cost	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29
$ kg^{-1}	- - - - - - - - - - - - - - - Million Seeds ha^{-1} - - - - - - - - - - - - - - -								- - - - - - - - - - - - - - - Million Seeds ha^{-1} - - - - - - - - - - - - - - -							
0.35	4.14	4.15	4.15	4.15	4.15	4.15	4.15	4.15	3.83	3.83	3.84	3.84	3.84	3.84	3.84	3.85
0.44	4.14	4.14	4.14	4.15	4.15	4.15	4.15	4.15	3.82	3.82	3.83	3.83	3.83	3.84	3.84	3.84
0.53	4.14	4.14	4.14	4.14	4.14	4.15	4.15	4.15	3.81	3.81	3.82	3.82	3.83	3.83	3.83	3.83
0.62	4.13	4.14	4.14	4.14	4.14	4.14	4.14	4.14	3.80	3.81	3.81	3.82	3.82	3.82	3.83	3.83
0.70	4.13	4.13	4.13	4.14	4.14	4.14	4.14	4.14	3.79	3.80	3.80	3.81	3.81	3.82	3.82	3.82
0.79	4.12	4.13	4.13	4.13	4.14	4.14	4.14	4.14	3.78	3.79	3.79	3.80	3.81	3.81	3.81	3.82
0.88	4.12	4.12	4.13	4.13	4.13	4.13	4.14	4.14	3.77	3.78	3.79	3.79	3.80	3.80	3.81	3.81
0.97	4.12	4.12	4.12	4.13	4.13	4.13	4.13	4.14	3.76	3.77	3.78	3.79	3.79	3.80	3.80	3.81
1.06	4.11	4.12	4.12	4.12	4.13	4.13	4.13	4.13	3.75	3.76	3.77	3.78	3.79	3.79	3.80	3.80
1.15	4.11	4.11	4.12	4.12	4.12	4.13	4.13	4.13	3.74	3.75	3.76	3.77	3.78	3.79	3.79	3.80
1.23	4.09	4.10	4.10	4.11	4.11	4.12	4.12	4.12	3.73	3.74	3.75	3.76	3.77	3.78	3.78	3.79
1.32	4.10	4.10	4.11	4.11	4.12	4.12	4.12	4.13	3.72	3.73	3.75	3.76	3.76	3.77	3.78	3.78
1.41	4.09	4.10	4.11	4.11	4.12	4.12	4.12	4.12	3.71	3.73	3.74	3.75	3.76	3.77	3.77	3.78
1.50	4.09	4.10	4.10	4.11	4.11	4.12	4.12	4.12	3.70	3.72	3.73	3.74	3.75	3.76	3.77	3.77
1.59	4.09	4.09	4.10	4.10	4.11	4.11	4.12	4.12	3.69	3.71	3.72	3.73	3.74	3.75	3.76	3.77
1.67	4.08	4.09	4.10	4.10	4.11	4.11	4.11	4.12	3.68	3.70	3.71	3.73	3.74	3.75	3.75	3.76
1.76	4.08	4.09	4.09	4.10	4.10	4.11	4.11	4.11	3.67	3.69	3.71	3.72	3.73	3.74	3.75	3.76

Optimizing economic returns are likely different depending on the environmental yield potential, and previous findings in this study show high and low yield environments can require different optimum seeding rates, especially between Valda and H_D (Figure 1.5). In general, Valda requires lower seeding rates than H_D to reach maximum profits in high yielding environments (Table 1.23). Using the EOSR and regression equations in Figure 1.4, high yielding environments provide net partial profits ranging from \$750 to 1590 ha^{-1} and \$740 to 1670 ha^{-1} for Valda and H_D, respectively. Assuming a market price of 0.22 and initial seed cost of \$0.44 kg^{-1} while using the EOSR in high yielding environments, H_D seed costs must remain within \$0.44 kg^{-1} of Valda to uphold an economic advantage.

The EOSR were higher for Valda compared to H_D in low yield environments (Table 1.24). H_D had a positive parabolic shape changing the EOSR pattern which increased as seed price increased and market cost decreased. In low yield environments, H_D required seeds costs to be \$0.08 kg^{-1} less expensive than the Valda seed cost to have an economic advantage. In this case, the high yielding H_D genotype was not economically favorable to Valda unless seed costs were reduced. Laing and Fischer (1977) found that wheat lines selected under optimal conditions during the breeding process also perform well in stressed environments. Future improved wheat hybrids may further separate from highly adapted inbred cultivars in performance and be economically favored given seed costs are about double the cost or less.

Table 1.23. Economic optimal seeding rate based on seed cost and grain price for Valda and Hybrid D (H_D) averaged across high yielding environments.

	Market Price (\$ kg^{-1})															
	Valda								H_D							
Seed Cost	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29
\$ kg^{-1}	Million Seeds ha^{-1}								Million Seeds ha^{-1}							
0.35	3.24	3.25	3.25	3.26	3.27	3.27	3.28	3.28	3.84	3.84	3.85	3.85	3.85	3.85	3.85	3.85
0.44	3.21	3.22	3.23	3.24	3.25	3.26	3.26	3.27	3.84	3.84	3.84	3.84	3.84	3.85	3.85	3.85
0.53	3.18	3.20	3.21	3.22	3.23	3.24	3.25	3.25	3.83	3.84	3.84	3.84	3.84	3.84	3.84	3.84
0.62	3.16	3.18	3.19	3.20	3.21	3.22	3.23	3.24	3.83	3.83	3.83	3.84	3.84	3.84	3.84	3.84
0.70	3.13	3.15	3.17	3.18	3.20	3.21	3.21	3.22	3.82	3.83	3.83	3.83	3.83	3.84	3.84	3.84
0.79	3.11	3.13	3.15	3.16	3.18	3.19	3.20	3.21	3.82	3.82	3.83	3.83	3.83	3.83	3.84	3.84
0.88	3.08	3.11	3.13	3.14	3.16	3.17	3.18	3.19	3.81	3.82	3.82	3.83	3.83	3.83	3.83	3.83
0.97	3.05	3.08	3.11	3.12	3.14	3.16	3.17	3.18	3.81	3.81	3.82	3.82	3.83	3.83	3.83	3.83
1.06	3.03	3.06	3.08	3.11	3.12	3.14	3.15	3.16	3.80	3.81	3.81	3.82	3.82	3.82	3.83	3.83
1.15	3.00	3.03	3.06	3.09	3.11	3.12	3.14	3.15	3.80	3.81	3.81	3.82	3.82	3.82	3.82	3.83
1.23	2.97	3.01	3.04	3.07	3.09	3.11	3.12	3.13	3.80	3.80	3.81	3.81	3.82	3.82	3.82	3.82
1.32	2.95	2.99	3.02	3.05	3.07	3.09	3.11	3.12	3.79	3.80	3.80	3.81	3.81	3.82	3.82	3.82
1.41	2.92	2.96	3.00	3.03	3.05	3.07	3.09	3.11	3.79	3.79	3.80	3.80	3.81	3.81	3.82	3.82
1.50	2.90	2.94	2.98	3.01	3.03	3.05	3.07	3.09	3.78	3.79	3.80	3.80	3.81	3.81	3.81	3.82
1.59	2.87	2.92	2.96	2.99	3.01	3.04	3.06	3.08	3.78	3.79	3.79	3.80	3.80	3.81	3.81	3.81
1.67	2.84	2.89	2.93	2.97	3.00	3.02	3.04	3.06	3.77	3.78	3.79	3.79	3.80	3.80	3.81	3.81
1.76	2.82	2.87	2.91	2.95	2.98	3.00	3.03	3.05	3.77	3.78	3.78	3.79	3.80	3.80	3.80	3.81

Table 1.24. Economic optimal seeding rate based on seed cost and grain price for Valda and Hybrid D (H_D) averaged across low yielding environments.

	Market Price ($ kg^{-1})															
	Valda								H_D							
Seed Cost	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29
$ kg^{-1}	- - - - - - - - - - - - - - - Million Seeds ha^{-1} - - - - - - - - - - - - - - -								- - - - - - - - - - - - - - - Million Seeds ha^{-1} - - - - - - - - - - - - - - -							
0.35	3.80	3.80	3.81	3.81	3.81	3.81	3.81	3.81	3.29	3.29	3.28	3.28	3.27	3.27	3.27	3.26
0.44	3.80	3.80	3.80	3.80	3.80	3.81	3.81	3.81	3.31	3.30	3.29	3.29	3.28	3.28	3.28	3.27
0.53	3.79	3.79	3.80	3.80	3.80	3.80	3.80	3.81	3.33	3.32	3.31	3.30	3.30	3.29	3.29	3.28
0.62	3.78	3.79	3.79	3.79	3.80	3.80	3.80	3.80	3.34	3.33	3.32	3.31	3.31	3.30	3.30	3.29
0.70	3.78	3.78	3.79	3.79	3.79	3.80	3.80	3.80	3.36	3.34	3.33	3.33	3.32	3.31	3.31	3.30
0.79	3.77	3.78	3.78	3.79	3.79	3.79	3.79	3.80	3.37	3.36	3.35	3.34	3.33	3.32	3.32	3.31
0.88	3.77	3.77	3.78	3.78	3.79	3.79	3.79	3.79	3.39	3.37	3.36	3.35	3.34	3.33	3.33	3.32
0.97	3.76	3.77	3.77	3.78	3.78	3.78	3.79	3.79	3.41	3.39	3.37	3.36	3.35	3.34	3.34	3.33
1.06	3.76	3.76	3.77	3.77	3.78	3.78	3.78	3.79	3.42	3.40	3.39	3.37	3.36	3.35	3.34	3.34
1.15	3.75	3.76	3.76	3.77	3.77	3.78	3.78	3.78	3.44	3.42	3.40	3.39	3.37	3.36	3.35	3.35
1.23	3.75	3.75	3.76	3.77	3.77	3.77	3.78	3.78	3.45	3.43	3.41	3.40	3.38	3.37	3.36	3.36
1.32	3.74	3.75	3.76	3.76	3.77	3.77	3.77	3.78	3.47	3.45	3.43	3.41	3.40	3.38	3.37	3.36
1.41	3.73	3.74	3.75	3.76	3.76	3.77	3.77	3.77	3.49	3.46	3.44	3.42	3.41	3.39	3.38	3.37
1.50	3.73	3.74	3.75	3.75	3.76	3.76	3.77	3.77	3.50	3.48	3.45	3.43	3.42	3.40	3.39	3.38
1.59	3.72	3.73	3.74	3.75	3.75	3.76	3.76	3.77	3.52	3.49	3.47	3.45	3.43	3.42	3.40	3.39
1.67	3.72	3.73	3.74	3.74	3.75	3.76	3.76	3.76	3.54	3.50	3.48	3.46	3.44	3.43	3.41	3.40
1.76	3.71	3.72	3.73	3.74	3.75	3.75	3.76	3.76	3.55	3.52	3.49	3.47	3.45	3.44	3.42	3.41

Grain Quality Analysis

Hard red spring wheat genotypes were combined across the 2.96 million live seed ha^{-1} seeding rate for each environment, analyzed by ANOVA, and single degree of freedom contrasts were performed (Table 1.25). Quality contrasts were designed to determine if hybrid wheat has any grain quality characteristic advantages compared to the inbred genotypes Ingmar and Valda.

Table 1.25. Combined ANOVA and single degree of freedom contrasts for HRSW quality.

SOV	TW†	S	M	L	KWT	GPC	FN	ME	MS	PMT	BEM	TE	LV
	kg ha^{-1}		%		g	g kg^{-1}	s	g kg^{-1}	1-8‡	s	AU§	Nm	cc
Environment [E]	***	***	***	***	***	***	***	ns	***	***	***	***	**
Genotype [G]	***	***	***	***	***	***	***	ns	ns	**	ns	ns	**
E*G	***	***	***	***	*	***	***	ns	ns	ns	ns	ns	ns
Contrast¶													
I vs Hybrids	***	***	***	***	*	**	**	**	ns	*	ns	ns	ns
V vs Hybrids	***	**	ns	ns	***	***	***	ns	ns	*	*	*	**
IV vs Hybrids	***	***	***	***	***	***	***	**	*	ns	ns	ns	ns
Means													
I	70	0.5	26	74	38	14.0	354	54	3	116	55	1533	178
V	71	0.7	34	66	37	15.3	366	52	3	142	58	1615	205
IV	71	0.6	30	70	37	14.6	360	53	3	129	56	1574	191
Hybrids	69	0.9	33	66	40	14.1	330	49	2	129	55	1543	187

†TW, Test Weight; S, M, L, Small, Medium, and Large Kernel Distribution; KWT, 1000 Kernel Weight, GPC, Grain Protein Content; FN, Falling Number; ME, Milling Extraction; MS, Mixograph Score; PMT, Peak Max Time; BEM, Torque Maximum; TE, Total Energy; LV, Loaf Volume.
‡Mixograph score where 1 is low mixing tolerance and 8 is high mixing tolerance.
§Ambiguous units.
¶I, Ingmar; V, Valda.

The hybrids had significantly greater proportions of small and medium sized kernels and a greater kernel weight in general. However, when compared to Ingmar and Valda, wheat hybrids did not have superior end qualities. The hybrids had less grain protein content than Valda but were significantly greater than Ingmar. Ingmar and Valda had greater falling numbers although all genotypes had falling numbers which did not exceed the preferable time of 400 s. Hybrids also observed lesser milling extraction compared to Ingmar and Valda. These results correspond with those of Gaines et al. (1997) who found soft wheat milling extraction was less for smaller kernel sizes although other end quality characteristics were not affected by small kernel sizes.

Conclusions

Differences between cultivars and hybrids were somewhat irregular across five different environments. Overall, planting date did not impact yield. Genotype primarily affected HRSW agronomic characteristics more than planting date or seeding rate. Increased yield of hybrids likely comes from larger spikes. Within the hybrids tested, hybrids should be seeded at relatively similar rates as inbred cultivars. The optimum yield for H_D was reached at 0.45 million plants ha^{-1} higher in high yielding environments compared to low yielding environments which suggests targeting slightly higher stands in high yielding areas. The EOSR for Ingmar and Valda (4.08 to 4.15 million seeds ha^{-1}) was greater than the EOSR for the hybrids (3.67 to 3.85 million seed ha^{-1}). H_D had greater EOSR in high yield environments than low yield environments. In general, the wheat hybrids hold an agronomic and economic advantage over Ingmar and Valda if seed costs are within \$0.18 kg^{-1} or \$0.44 kg^{-1} when comparing H_D and Valda in high yielding environments. The EOSR tables can be used as a starting point for future hybrid wheat production recommendations. However, hybrid wheat economic implications are limited to the hybrids used in the experiment and future HRSW hybrids to be released will likely have greater yield benefits increasing economic return. Hybrid wheat can improve wheat yields in certain environments and wheat production would benefit from additional planting date and seeding rate exploration using commercially released hybrids. Heterosis did not increase end use quality therefore yield will determine the economic feasibility of hybrids and the EOSR does not need to consider quality.

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CHAPTER 2. PLANTING DATE, SEEDING RATE, ROW SPACING, AND RELATIVE MATURITY EFFECT ON SOYBEAN SEED YIELD AND CANOPY COVER

Abstract

Planting date (PD), seeding rate (SR), relative maturity (RM) of genotypes, and row spacing (RS) are primary management factors affecting soybean [Glycine max (L.) Merr.] yield. The individual and synergistic effects of PD, SR, RM, and RS effects on seed yield and agronomic characteristics and how well canopy measurements taken throughout the season can predict seed yield in North Dakota were investigated. Early and late PD, early and late RM genotypes, and two SR (408 000 and 457 000 seeds ha^{-1}) were evaluated in 14 environments and two RS (30.5 and 61 cm) were included in four environments in 2019-2020. Individual factors resulted in 245 and 189 kg ha^{-1} more yield for early PD and late RM, respectively. The improved treatment of combined early PD, late RM, and high SR factors had 16% yield and \$140 ha^{-1} more partial profit than the control. When including RS, 30.5 cm RS had 7% more yield than 61 cm RS. Adding 30.5 cm RS to the improved treatment in four environments resulted in 26% more yield and \$291 ha^{-1} compared to the control. A normalized difference vegetative index (NDVI) at R5 was the single best yield predictor, and stepwise regression using canopy measurements explained 69% of the variation in yield. North Dakota farmers are recommended to combine early planting, late RM cultivars, 457 000 seed ha^{-1} SR, and 31 cm RS to improve yield and profit compared to current management trends.

Introduction

The gap between potential and currently produced soybean [Glycine max (L.) Merr.] yields at the farm level has been investigated in the north-central US region. A soybean survey of 3568 fields including 524 fields in North Dakota by Rattalino Edreira et al. (2017) found yield differences between the highest and average yielding fields were due to three primary factors, which are planting date (PD) (Rattalino Edreira et al., 2017), relative maturity (RM) (Mourtzinis et al., 2018), and seeding rate (SR) (Gaspar et al., 2020). Mourtzinis et al. (2018) stated about 50% of the surveyed soybean fields in North Dakota had intermediate row spacing (RS) of approximately 38 cm and 25% was equally split between narrow (~25 cm) and wide (~76 cm) spacings. The effects of PD, RM, SR, and RS on soybean production have been well investigated individually. Current North Dakota management trends of mid-May planting, cultivars with sub-optimal RM, and 408 000 live seed ha^{-1} seeding rate can be improved upon (Stanley, 2017). The synergism between early planting, cultivars with longer RM (Stanley, 2017), and higher than 408 000 live seed ha^{-1} seeding rates effects require further exploration, especially in the most northern soybean production environments (Endres et al., 2020; Schmitz et al., 2020).

Planting date is considered the most important cultural management factor to soybean production (Cartter and Hartwig, 1963). Delaying Minnesota soybean planting from 1 May to 15 May decreased yields by 0.5% d^{-1} (Lueschen et al., 1992). Delaying soybean planting beyond late May resulted in declining yields in the north-central USA region (Anderson and Vasilas, 1985; Elmore, 1990; Oplinger and Philbrook, 1992; Pedersen and Lauer, 2003a; Rattalino Edreira et al., 2017; Robinson et al., 2009). In addition, Stanley (2017) reported a 0.4% d^{-1} yield loss when delaying planting beyond 1 May (up to June 1) in North Dakota. However, soybean response to PD can vary considerably from year to year depending on the magnitude of environmental constraints (Pederson and Lauer, 2003a, Robinson et al., 2009).

The length of the cropping season in the north-central US has increased by 5 to 20 d since the 1950s according to Kucharik et al. (2010) generating uncertain optimal soybean maturity recommendations (Gaspar and Conley, 2015). Soybean cultivar RM groups range from 000 to 10

(Boerma and Specht, 2004), with the suggested maturity groups for production North Dakota ranging from 00 to 1 (Kandel and Endres, 2019). Mourtzinis and Conley (2017) delineated optimal soybean maturity group zones noting a range of potential relative maturities (0.0 to 1.5) suited to North Dakota. Production recommendations currently suggest utilizing the longest cultivar maturity group suitable to the growing region to maximize yield (Mourtzinis et al., 2017).

With similar SR, the distance between soybean rows has an impact on plant density within the row, and soybean seed yield. Cooper (1977) in Illinois defined narrow row soybean as rows less than 50 cm apart where wide row spacing (RS) as rows equal or greater than 50 cm apart. Narrow rows create more equidistant plant spacing resulting in canopy cover earlier in the season (Shibles and Weber, 1966) and results in greater light interception compared to wider row spacing (Andrade et al., 2002; Bullock et al., 1998). Narrow row spacing has been found to increase yields in conditions with adequate rainfall and appropriate air temperatures (Alessi and Power, 1982; De Bruin and Pedersen, 2008b; Bullock et al., 1998; Cooper, 1977; Cox and Cherney, 2011; Devlin et al., 1995; Ethredge et al., 1989; Schmitz et al., 2020). In contrast, wide soybean RS improves yields under soil water deficit conditions (Alessi and Power, 1982; Devlin et al., 1995) and reduce Soybean Cyst Nematode (SCN) and Sudden Death Syndrome (SDS) effects (Pedersen and Lauer, 2003b; Swoboda et al., 2011).

Soybean SR describes the number of seeds planted in a given area. Seeding rates below 560 197 seeds ha^{-1} (De Bruin and Pedersen, 2008a), between 284 050 to 573 000 seeds ha^{-1} in high yield conditions (Devlin et al., 1995), and between 444 600 to 494 000 seeds ha^{-1} (Schmitz et al., 2020) have been found to produce the greatest yield. Soybean branching characteristics can minimize yield response from increased SR (Carpenter and Board, 1997). Increasing plant stand from 300 000 to 600 000 plants ha^{-1} reduced plant chlorosis and increased seed yield in iron deficiency (IDC) prone North Dakota soils (Goos and Johnson, 2001). Optimal SR in Kentucky for planting in May were as low as 171 000 seed ha^{-1} (Lee et al., 2008) and as high as 741 000 seeds ha^{-1} in Wisconsin producing similar yields around 3600 kg ha^{-1} (Oplinger and Philbrook, 1992). Gaspar et al. (2020) found SR below the agronomical optimum seeding rate exponentially increase risk and potential yield loss. Reducing soybean yield loss risk may be circumvented by optimizing canopy cover through management and predicting their effect on the canopy would be useful.

Canopy cover is a useful proxy measurement for light interception and crop productivity. Maximum photosynthesis is achieved when plants maximize light interception and utilization of photosynthetic radiation (Lee, 2006; Wells, 1991). Light interception can be quantified with methods such as quantum line sensors (Egli, 1994), approximated by fractional green canopy cover (FGCC) from pictures using the Canopeo app as demonstrated by Patrignani and Ochsner (2015), and leaf area index (LAI). Light interception measurements using quantum line sensors are considerably more time consuming compared to measuring FGCC using the Canopeo app. In addition, precise LAI measurements require plant destruction in order not to overestimate the LAI in dense canopies (Wilhelm et al., 2000). Normalized difference vegetation index (NDVI) can also be used to approximate fractional canopy coverage but is not a useful substitute for above ground biomass measurements (Perry et al., 2012).

Estimating and predicting crop yields using canopy cover measurements is of high interest for producers. Crop growth stage (Goodwin et al., 2018), RS (Singer, 2001), and canopy structure (Gardner and Auma, 1989) can affect light interception, FGCC, and NDVI. Measurements like NDVI and FGCC can predict yields for wheat (*Triticum aestivum*, L. emend.

Thell.) (Goodwin et al., 2018), rice (*Oryza sativa* L.) (Chang et al., 2005), and soybean (Ma et al., 2001). Light interception, green canopy cover quantification, and NDVI may allow for better yield prediction and a useful application in soybean production when combined.

Objectives

The objectives of the research were to determine how PD, SR, RM, and RS, as individual factors and when combined affect seed yield and agronomic characteristics, and if combining factors are more economical than current practices. The second objective was to determine if canopy development measurements could be used to predict soybean yield and if canopy measurements can predict yield, determine the most accurate and most practical strategy for yield prediction.

Materials and Methods

Location Description

The field experiments were conducted in 2019 and 2020 across eastern North Dakota in prominent soybean grown areas (Table 2.1). Experiments were conducted near Casselton, Fargo (two experiments each year), Finley, Grand Forks, Gwinner, Lisbon, and Prosper, North Dakota. Location and year were combined and are called ‘environment,’ for a total of 14 environments. The Fargo location was divided into tile and non-tile drained environments.

Table 2.1. Soil series, soil taxonomy, previous crop and productivity index for 14 environments in North Dakota, in 2019 and 2020.

Location	Year	Soil Series†	Soil Taxonomy	PC‡	GPS
Casselton	2019 2020	Kindred	Fine-silty, mixed, superactive, frigid Typic Endoaquolls	SB	46.882, -97.251
		Bearden	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls	W	
Fargo§	2019 2020	Fargo	Fine, smectitic, frigid Typic Epiaquerts	W	46.932, -96.859
		Ryan	Fine, smectitic, frigid Typic Natraquerts	W	
Finley	2019	Wyard	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls	W	47.526, -97.534
		Fram	Fine-loamy, mixed, superactive, frigid Typic Endoaquolls		
Grand Forks	2020	Bearden	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls	DB	47.790, -97.065
Gwinner	2019	Hamerly	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls	SB	46.210, -97.608
	2020	Tonka	Fine, smectitic, frigid Argiaquic Argialbolls	C	
Lisbon	2019 2020	Barnes	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls	SB	46.440, -97.800
		Svea	Fine-loamy, mixed, superactive, frigid Pachic Hapludolls	SB	
Prosper	2019 2020	Bearden	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls	W	47.001, -97.112
		Lindaas	Fine, smectitic, frigid Typic Argiaquolls	W	

†Soil data from (USDA, 2020). PC, Previous Crop; GPS, GPS Coordinates.
‡C, Corn [*Zea mays* (L.)]; DB, Dry Bean [*Phaseolus vulgaris* (L.)]; SB, Soybean; W, Wheat [*Triticum aestivum* L. emend. Thell.]
§Two experiments were conducted in Fargo, each year.

Experimental Design and Treatments

Each experiment was a randomized complete block with a split-plot arrangement with four replicates. The whole plot was PD and the sub-plots were a factorial combination RM of cultivars and SR. Planting dates were at an optimal time, which is no earlier than 5 days before the last projected spring frost, in mid-May and a late PD of two weeks thereafter. Seeding rates were 407 500 and 457 000 pure live seeds ha^{-1}. Cultivars used were 0.2 RM units apart and from the same company and will be described as early or late RM relative to the cultivars grown in that environment (Table 2.2). The Fargo location was partitioned into tile and non-tile drained environments and had a whole plot was PD and sub-plots were a factorial combination of RM, SR, and RS. The Fargo environments had narrow-intermediate 30.5 (narrow) and an intermediate-wide 61 cm (wide) RS while all other environments RS was 30.5 cm. The PD, RM, and SR data were combined with the similar treatments in all 14 environments. The four factors PD, RM, SR, and RS were combined over 2019 and 2020 with the main effects analyzed individually. To answer if a combination of factors provided higher yield compared to the conventional practices (control), individual factors were combined into treatments, combined across environments, and analyzed by treatment (Table 2.3).

Table 2.2. Soybean cultivars used and descriptive features.

		NDSU	Company				
Cultivar	Maturity	IDC†	IDC	SCN‡	Canopy	Height	Location in North Dakota
AG 03X7	0.3	-	3	R	Medium	Medium	Finley, GF
AG 05X9	0.5	2.4	3	R	Medium	Medium	Casselton, Fargo, Finley, GF, Gwinner, Lisbon, Prosper
AG 08X8	0.8	-	4	R	Medium	Medium Tall	Casselton, Fargo, Gwinner, Lisbon, Prosper,

†IDC, iron deficiency chlorosis. NDSU IDC scored on 1-5 scale (1=green, 5=dead) from Goos and Johnson (2001). Company IDC scored on 1-9 scale (1=green 9=dead).
‡SCN, soybean cyst nematode; R, resistant; GF, Grand Forks.

Table 2.3. Improved and current soybean management treatments and planting date (PD), relative maturity (RM), and seeding rate (SR) combinations.

Treatment	PD	RM	SR
Improved	Early	Late	457 000
Control	Late	Early	408 000
1	Early	Early	408 000
2	Early	Early	457 000
3	Early	Late	408 000
4	Late	Early	457 000
5	Late	Late	408 000
6	Late	Late	457 000

General Procedures

A ragdoll germination test using a moist paper towel at room temperature for 5 d was used to find seed germination percentage. Seeds with radicle formation were considered germinated. Proper planting rates were determined from the germination results to achieve the targeted live seed SR.

Early PD treatments were seeded once soil temperatures reached 10°C in early to mid-May, but not earlier than five d prior to the last historical projected frost date, using a Hege 1000 no-till planter (Hege Company, Waldenberg, Germany) with 30.5 cm RS at all locations and 30.5 and 61 cm at the Fargo location. The second PD was delayed by two to three weeks depending on field conditions (Table 2.4). Seeds were sown to a depth of approximately 3 cm. Plot size for the experimental unit was 1.52 m by 5.47 m. Soils were tested for plant essential nutrients before seeding to ensure fertility was not a limiting factor, and test levels for each environment are presented in Table 2.5 (Kandel and Endres, 2019).

The experiments were managed according to North Dakota State University extension recommendations regarding cultivation, fertilization, and herbicide and pesticide applications.

Table 2.4. Important dates and environment information for 2019 and 2020 soybean environments.

	SCN†		Seeding Date				Harvest	
			2019		2020			
Environment	2019	2020	1	2	1	2	2019	2020
	eggs 100 cc^{-1}				DOY			
Casselton	0	450	137	154	142	153	303	279
Fargo	0	0	137	154	133	149	302	275
Finley	-	-	133	149	-	-	303	-
Grand Forks	-	0	-	-	133	149	-	279
Gwinner	0	0	134	150	136	150	301	281
Lisbon	0	0	134	150	136	150	301	281
Prosper	-	3700	136	149	143	153	304	279

†SCN, Soybean cyst nematode; DOY, Day of year. DOY 135 is 15 May and DOY 280 is 7 October.

Table 2.5. Soil test results for soybean environments in 2019 and 2020.

Environment	Depth	NO_3-N	P	K	pH	OM
	cm	kg ha^{-1}	mg kg^{-1}			g kg^{-1}
			- - - - - - 2019 - - - - - -			
Casselton	0 - 15	19	18	360	7.5	4.8
	15 - 61	18	7	279	7.8	4.5
Fargo	0 - 15	-	4	377	7.7	5.4
Prosper	0 - 15	21	30	269	7.2	4.5
	15 - 61	24	17	216	7.4	3.2
Lisbon	0 - 15	13	25	293	6.7	4.2
	15 - 61	24	14	241	6.7	3.5
Gwinner	0 - 15	11	8	247	7.6	4.6
	15 - 61	8	3	195	7.6	3.1
Finley	0 - 15	27	18	273	7.2	4.7
	15-61	25	13	218	7.4	4.2
			- - - - - - 2020 - - - - - -			
Casselton	0-15	16	8	368	7.4	5.2
	15-61	37	7	303	7.5	3.9
Grand Forks	0-15	29	7	306	7.7	5.0
	15-61	87	5	202	7.8	4.3
Fargo	0-15	-	19	347	7.8	5.2
	15-61	179	-	-	-	-
Prosper	0-15	35	20	232	7.9	3.4
	15-61	57	6	176	8.2	2.5
Lisbon	0-15	93	29	283	6.3	5.0
	15-61	114	19	220	6.6	4.1
Gwinner	0-15	22	18	367	6.8	5.4
	15-61	57	7	284	7.3	3.8

Data Collection

Weather data were collected using the North Dakota Agricultural Weather Network (NDAWN) providing weekly maximum and minimum air temperature and rainfall. Weather data for Fargo, Grand Forks, Gwinner, Lisbon, and Finley used the Fargo, Grand Forks, Lisbon, Oakes, and Mayville NDAWN weather stations, respectively. Casselton and Prosper weather data were collected from the Prosper NDAWN location.

After planting, established plants were recorded at the V2 (two trifoliolate stage [Fehr et al., 1971]). Established plant density was recorded by counting a 0.91 m length from the middle soybean rows and the final plant density was recorded from the same length prior to harvest.

During the growing season, soil cover percent (Canopeo, Oklahoma State University, Stillwater, OK) was recorded. Fractional green canopy cover photos were processed providing canopy coverage percentage (Patrignani and Ochsner, 2015). Canopy pictures were taken approximately 1.5 m from the soil surface in the center of each plot using an iPad (Apple). Matlab software (MathWorks, Inc., Natick, MA) was used to calculate canopy cover by FGCC. Canopy photosynthetically active radiation (PAR) interception measurements were collected randomly in the front, middle, and back third of each experimental unit using an Accupar LP-80 (METER Group Inc, Pullman, WA) with the sensor perpendicular to the plot at a height of 2 cm above the soil surface. The PAR was averaged for each unit. Normalized difference vegetative index (NDVI) was recorded using a RapidSCAN CS-45 (Holland Scientific, Lincoln, NE) with NDVI being averaged across the unit. Fractional green canopy coverage, Accupar, and RapidSCAN measurements were recorded when the soybean plants in the early PD were at the V2, V4, R1, R3, R5, or R7 growth stage for a total of 18 canopy measurements. Fractional green canopy cover, NDVI, and PAR measurements were limited to Casselton, Prosper, and Fargo in 2019 and 2020 due to time limitation and resources.

Plant heights were measured prior to harvest at physiological maturity by making three separate measurements from the soil surface to the uppermost node on the plant and then averaging the measurements for each experimental unit. The plots were harvested, after physiological maturity (Fehr et al., 1971), using a Wintersteiger Classic plot combine (Wintersteiger Ag, Ried, Austria). Seed samples were cleaned, weighed, and analyzed for oil and protein content using a Perten Instruments DA 7250 NIR analyzer (Perten Instruments, Inc., Springfield, IL). Moisture and test weight were determined using a GAC 2100 moisture tester (DICKEY-John Corp., Minneapolis, MN) and observations were corrected to 13% moisture content. Seed weights were obtained by counting 1000 seeds using an electric counter and weighing them.

A partial net profit economic analysis for the combined treatment packages was performed by subtracting seed cost (price per seed × live seeding rate) from gross revenue (seed yield × market price). Price per seed was calculated by dividing a $50 seed cost unit^{-1} by 140 000 seeds (soybean unit), and gross revenue calculations used a market price of $0.0149 kg^{-1}.

Statistical Analysis

Analysis of variance was performed for 2019 and 2020 environments using the GLIMMIX procedure in SAS 9.4 (SAS Institute, SAS Circle, Cary, NC). Using fixed and random effect designations described by Carmer et al. (1989), PD, RM, SR, and RS were considered fixed effects while replicate and environment were considered random. Analysis of variance of dependent variables for the treatment packages, including the improved and control treatments (PD, RM, and SR or PD, RM, SR, and RS combinations at the Fargo environments) were performed considering treatment as a fixed effect and environment as a random effect using the GLIMMIX procedure. Orthogonal contrasts were made using Proc GLIMMIX to compare the improved and control management. Normality and homogeneity of variance assumptions of ANOVA were met, as determined by residual histograms and the ratio of the highest and lowest error mean square being less than 10 (Tabachnick and Fidell, 2001). A F-protected LSD ($P \leq 0.05$) was used to identify significant differences between treatment LSMEANS.

Model Preparation

A total of 12 environments were used from the 2019 and 2020 Casselton, Prosper, and Fargo environments. The data from Fargo was separated by tile and non-tile drained environments and by 30.5 and 61 cm RS. Fractional green canopy cover, PAR interception, and

NDVI measurements at each growth stage and the established plant density recorded at Casselton, Fargo, and Prosper in 2019 and 2020 were used for multiple linear regression analysis for a total of 6688 of data points. Measurements greater than 3 standard deviations of the mean in each environment for each measurement type and stage combination were removed (165 data points) from the data. The Reg procedure in SAS was used to analyze the relationship between each individual measurement and yield. Variable variance inflation factors (VIF) were reviewed to ensure VIF values were below 5 (Burnham and Anderson, 1998). The Glmselect procedure was used for stepwise and lasso multiple linear regression methods. Models were compared using the lowest root mean square error (RMSE) and highest adjusted R^2 (Kumar et al., 2019) and lowest Akaike Information Criterion (AIC) (Lollato et al., 2019). Stepwise regression using a 0.15 *F* statistic significance level selection criteria was used to build a model to best predict soybean seed yield using the 18 canopy measurement variables for 6523 total data points. The Validate statement was used to randomly select 20% of the data and adjusted R^2 was averaged over 50 iterations to validate the model for both regression methods.

Results and Discussion

Daily temperatures were close to normal throughout the growing season (Figures 2.1 and 2.2). In 2019, heavy rainfall occurred in Finley (Mayville NDAWN) between the early and late PD causing soil crusting and reduced plant emergence (Figure 2.1). The 2020 growing season had adequate rainfall, but a late season frost occurred in eastern North Dakota, which was especially damaging to the crop at Lisbon on 9 September (253 DOY) when the minimum air temperatures reached -1°C (Figure 2.2). The frost reduced the longer maturing cultivar’s yield potential which was transitioning from the R6 to R7 stage (Fehr et al., 1971).

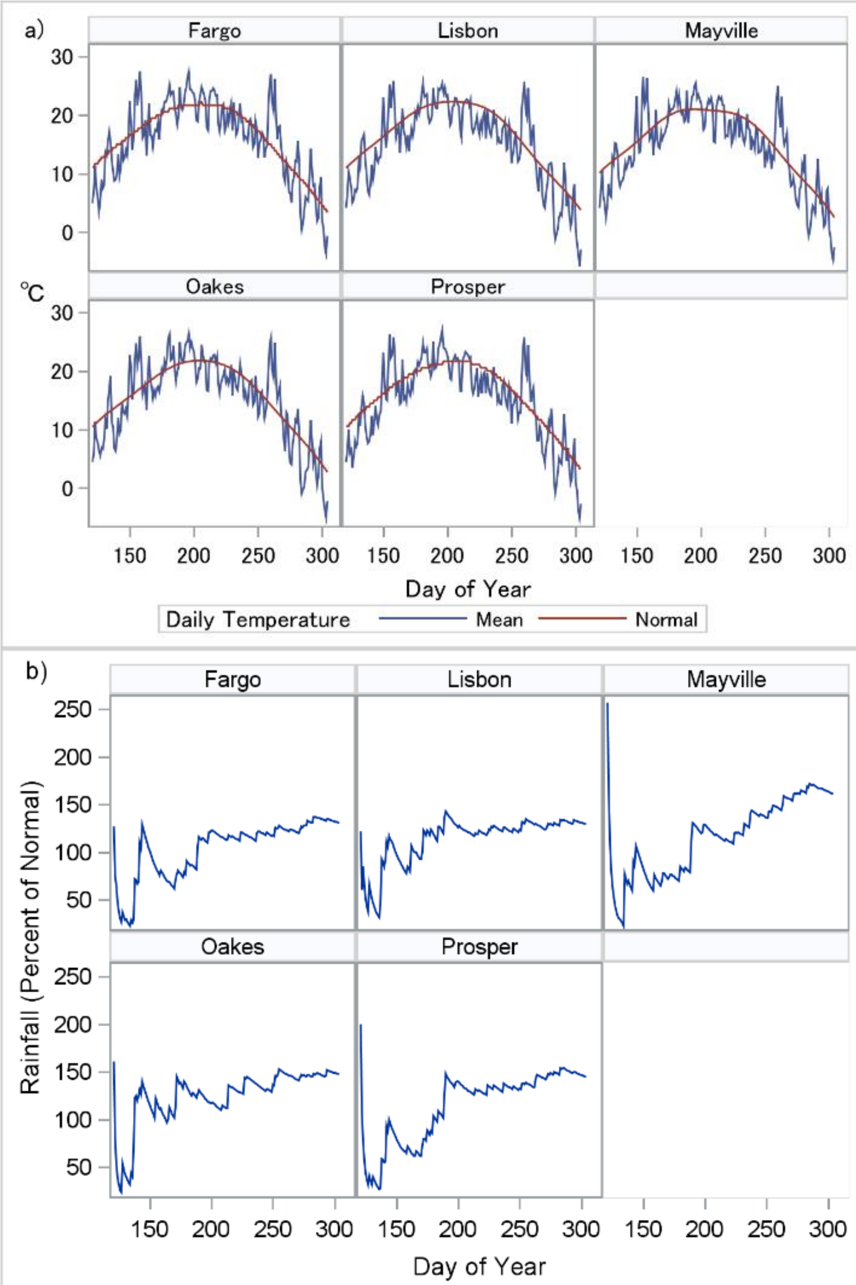

Figure 2.1. Soybean growing season a) daily mean and normal temperatures and b) daily rainfall as a percent of the normal for 2019 environments.

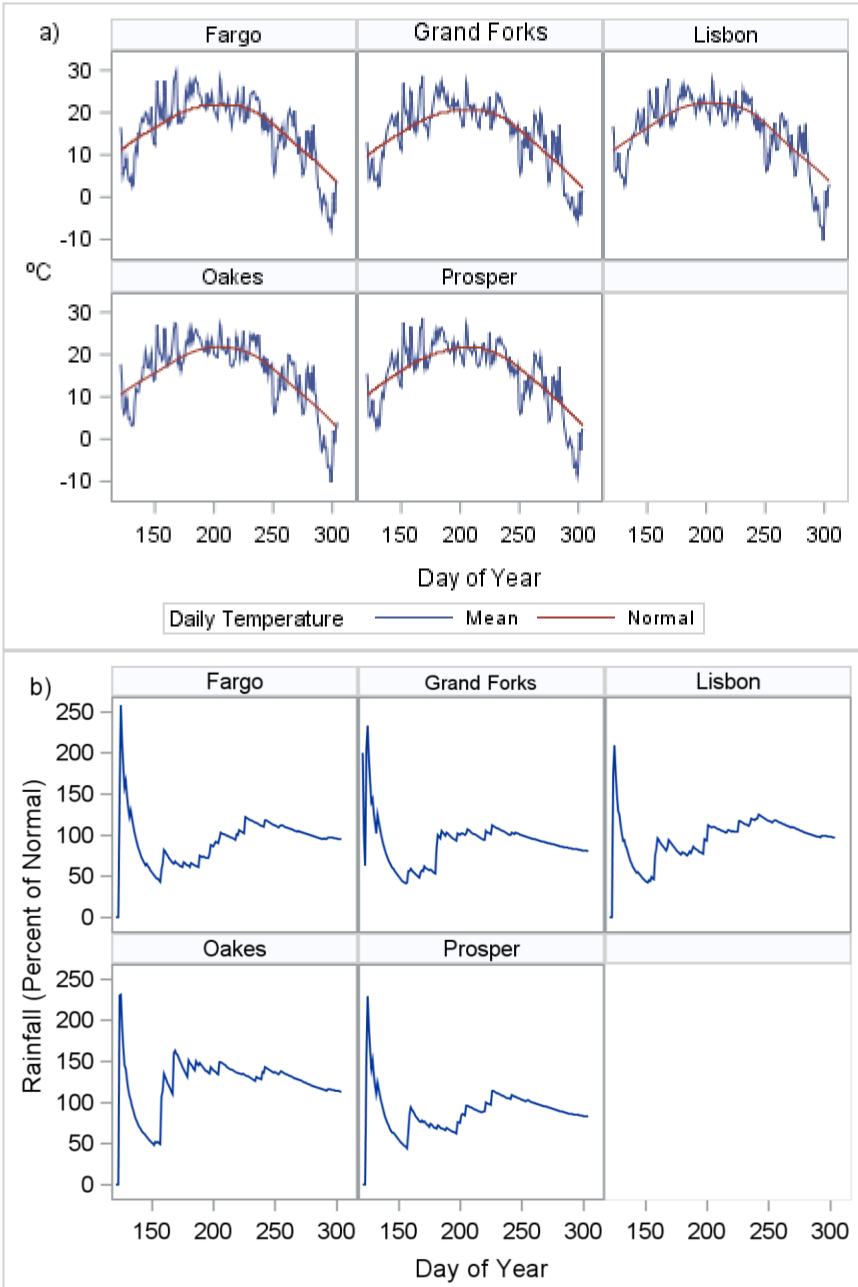

Figure 2.2. Soybean growing season a) daily mean and normal temperatures and b) daily rainfall as a percent of the normal for 2020 environments.

Agronomic Characteristics

Data from 14 environments were combined and analyzed by ANOVA. The initial combined analysis resulted in a non-significant RM effect (P=0.085) for yield, but removing the frost affected 2020 Lisbon environment resulted in a RM significance (P=0.014) for yield (Table

2.6). The early RM yielded 13% greater than the late RM in Lisbon in 2020 compared to the 6% late RM yield advantage when averaged across the other 13 environments.

Table 2.6. Probability (*P*) level for combined ANOVA across 14 environments for soybean agronomic characteristics.

SOV	df†	df	ES‡	FS	HT	PC	Oil	SWT	Yield§
Environment	12	13	- - - - - - - - - - - - - - - - - -	-	-	*P*	- -		
Planting Date [PD]		2	0.016	0.012	0.741	0.241	0.010	0.207	0.015
Relative Maturity [RM]		2	0.134	0.071	<0.001	0.159	0.012	0.122	0.014
Seeding Rate [SR]		2	<0.001	<0.001	0.399	0.924	0.192	0.269	0.243

†Environment degrees of freedom for yield with the 2020 Lisbon environment removed due to significant frost damage.
‡ES, Established Stand; FS, final stand; HT, height; PC, protein content; SWT, 1000 seed weight.
§Yield is based on 13 environments, excluding Lisbon due to early season frost in 2020.

Established and final plant density was affected by PD and SR (Table 2.6). Late planting resulted in greater established and final stands of 16 and 18% greater, respectively (Table 2.7). Plant mortality rates from established to final stands were 16.7 and 14.5%, respectively for early and late PD, which are slightly higher compared to other reports in North Dakota of 6.6 (Schmitz et al., 2020) and 12.3% (Stanley, 2017). Late planting dates often improve plant establishment due to an increase in soil temperature (Oplinger and Philbrook, 1992). Lueschen et al. (1992) found plant density was inconsistently affected by planting date and can vary by environment and tillage practice. As expected, the 457 000 seed ha^{-1} SR had greater plant densities than the lower SR (Table 2.7).

Plant height was 8 cm greater for the late RM compared to the early RM (Table 2.7), but this may be explained by genetic differences between cultivars. Planting date and seeding rate had no influence on plant height. Akhter and Sneller (1996) found reduced soybean plant height when planted before May in Arkansas. In the upper Midwest such as Illinois and Wisconsin, earlier planting dates often result in an increase in plant height relative to later planting dates (Pedersen and Lauer, 2003a; Osler and Cartter, 1954).

Table 2.7. Agronomic trait observation means averaged across planting date, relative maturity, and seeding rate and 14 environments.

Treatment	ES[†]	FS	HT	PC	Oil	SWT	Yield[‡]
Planting Date	plants ha^{-1}		cm	g kg^{-1}		g	kg ha^{-1}
Early	378 121b	323 763b	76	370	185a	134	3317a
Late	439 265a	383 588a	76	380	183b	133	3072b
Relative Maturity							
Early	402 543	347 096	72b	377	182b	135	3100b
Late	414 843	360 255	80a	373	186a	133	3289a
Seeding Rate seeds ha^{-1}							
408,000	391 418b	340 191b	76	374	184	134	3177
457,000	425 967a	367 161a	76	377	184	134	3213

[†]ES, Established Stand; FS, final stand; HT, height; PC, protein content; SWT, 1000 seed weight. Yield is based on 13 environments, excluding Lisbon due to early season frost in 2020.
[‡]Within columns, means for each treatment followed by a different letter are significantly different using pairwise comparisons at an $\alpha = 0.05$.

Soybean oil content was significantly different for PD and RM and kernel weight differences were not significant (Table 2.6). The difference associated with RM was likely different due to genetic differences between the two cultivars. Cultivar and climate both contribute to geographic protein and oil content differences (Piper and Boote, 1999). Longer maturing cultivars are more likely to have higher temperatures during the R5 to R8 growth stages favoring greater oil content (Mourtzinis et al., 2017). Other research showed delayed planting increased seed protein content and decreased oil content by positioning the seed-fill stage during higher temperature periods in the growing season (Helms et al., 1990; Kane et al., 1997).

Yield data were combined across 13 environments, excluding the 2020 Lisbon environment, showed greater seed yields for the early PD (Table 2.7). Early planting offers 245 kg ha^{-1} greater yield compared to late planting and a 0.6% d^{-1} yield loss when delaying planting two weeks. Similarly, Stanley (2017) reported 0.4% d^{-1} yield loss occurred when delaying planting beyond 1 May (up to June 1) in North Dakota. Delayed planting dates reduced yields from 70 to 360 kg ha^{-1} wk^{-1} in May in Iowa (De Bruin and Pedersen, 2008a), 25 to 31% from 1 to 15 May and 31% from 15 to 30 May, respectively in Wisconsin (Grau et al., 1994), 464 kg ha^{-1} from early to mid-May in Minnesota (Lueschen et al., 1992), and a 6% from 1 to 15 May in North Dakota (Stanley, 2017).

Longer maturing soybean cultivars had significantly greater yield (189 kg ha^{-1}) than the earlier RM cultivars tested (Table 2.7). Mourtzinis et al. (2017) reported the greatest soybean seed yield was achieved when combining early planting and longer season RMs in the north-central US region including North Dakota. In this study, early PD provided 8% yield benefit compared to late planting and late RM gave 6% greater yield than a cultivar whose RM is 0.2 units earlier. Although the two SRs had similar yields in this study, only two SR were evaluated limiting potential inferences. Previous research in the same region found the highest yields at 444 600 and 494 000 seed ha^{-1} (Schmitz et al., 2020). Results of this experiment suggest that PD and RM relationships affect yield in the northern soybean growing region.

Analysis by Treatment Package

Individual treatments were analyzed to identify if synergism between PD, RM, and SR factors translate as a 'package' of management practices into better performance of the improved treatment compared to the control (Table 2.8). The effects of PD and RM are known (Table 2.7); however, when favored management strategies are combined, the improved strategy has significantly greater yield (16%) than the control (Table 2.8). Planting date appears to have the greatest impact on yield followed by RM whereas SR is a minor yield contributor. The yield advantage for the improved treatment provides \$23 ha^{-1} greater partial net profit than the control when subtracting a constant seed cost ha^{-1} from the product of yield and a constant market price. The improved strategy provides similar economic returns as treatment 3, which only differ by a lower seeding rate. Using seeding rates above the rate providing the maximum yield reduce the chance of a farmer losing profits compared to seeding at or below the optimum rate (Gaspar et al., 2020).

Table 2.8. Soybean yield, partial net profit, and orthogonal contrast of treatments for soybean yield averaged across 13 environments in 2019 and 2020.

Treatment	PD[†]	RM	SR	Yield	Partial Net Profit
			seeds ha^{-1}	kg ha^{-1}	\$ ha^{-1}
Improved	Early	Late	457 000	3464a[‡]	1364a
Control	Late	Early	408 000	2980c	1224c
1	Early	Early	408 000	3192b	1290b
2	Early	Early	457 000	3205b	1270bc
3	Early	Late	408 000	3406a	1357a
4	Late	Early	457 000	3027bc	1222c
5	Late	Late	408 000	3122bc	1259bc
6	Late	Late	457 000	3159bc	1261bc
P				<0.001	<0.001
Improved vs Control				<0.001	<0.001

[†]PD, Planting Date; RM, Relative Maturity; SR, Seeding Rate. Partial net profit accounts for \$50 per 140 000 seeds and a \$0.0149 kg^{-1} market price.
[‡]Means within the column followed by the same letter are not significantly different. Comparisons were made using pairwise comparisons between all treatments at an $\alpha = 0.05$.

Planting Date, Relative Maturity, Seeding Rate, and Row Spacing Study

The Fargo location consisted of two environments, one with controlled tile drainage and the other is naturally drained, which were used in both 2019 and 2020. Planting date, RM, and RS affected most dependent variables (Table 2.9). Early planting resulted in reduced established plant density compared to late planting and therefore final plant densities comparatively (Table 2.6 and Table 2.10). Seeding rate had a similar impact on comparable established and final plant densities. Above normal rainfall events prior to the early PD created poor seeding and emergence conditions. The reduced stand may be the primary reason for the reduced yield obtained with the early planting.

The RM of the cultivar significantly affects FGCC, (Table 2.9). Late RM provided 6 and 3% greater FGCC compared to the earlier RM at the V4 and R5 growth stages, respectively. Others also found that longer maturing cultivars are able to collect a greater proportion of the total PAR throughout the season often resulting in greater seed yield and oil content and reduced protein content (Monteith, 1972; Rattalino Edreira et al., 2020) (Table 2.10).

Table 2.9. Probability (P) level for combined ANOVA for soybean agronomic characteristics for Fargo tile drainage and natural drainage environments in 2019 and 2020.

			FGCC		PAR		NDVI				
SOV†	ES	FS	V4	R5	V4	R5	V4	R5	Protein	Oil	Yield
	- *P* -										
Planting Date [PD]	0.017	0.009	0.054	0.749	0.256	0.515	0.508	0.422	0.985	0.084	0.016
Relative Maturity [RM]	0.680	0.125	0.018	0.010	0.385	0.431	0.188	0.201	0.017	0.005	0.099
Seeding Rate [SR]	0.048	0.050	0.236	0.553	0.379	0.402	0.193	0.354	0.352	0.855	0.133
Row Spacing [RS]	0.171	0.122	0.047	0.026	0.037	0.464	0.041	0.300	0.088	0.094	0.007

†SOV, source of variation; ES, established stand; FS, final stand; FGCC, fractional green canopy cover; PAR, Photosynthetically Active Radiation Interception; NDVI, Normalized Difference Vegetative Index;V4, four trifoliolate stage; R5, pod fill stage.

Narrow rows were found to be superior to wider rows Row spacing results show the benefit of narrow RS (30.5 cm) in the northern US soybean growing region (Table 2.9 and 2.10). At the V4 and R5 soybean growth stages the narrower row spacing treatments had 6 and 3 % greater FGCC, respectively (Table 2.10). Lee et al. (2008) reported complete canopy cover at the R5 growth stage was required for maximum yield potential. The higher percent FGCC for the 30.5 cm RS can partially explain the yield difference (265 kg ha^{-1}) between the narrow and wide RS (Table 2.10). Previous research in the northern US soybean growing region deemed RS a major yield contributing factor with narrow RS (30.5 cm) providing 6% greater yield than 61 cm RS (Schmitz et al., 2020).

Row spacing significantly impacted light interception where narrow rows intercepted 5.4% more PAR interception at V4 (Table 2.10). However, as the season progressed, there were no differences in PAR or NDVI between narrow and wide RS. If growing conditions are favorable, late season canopy differences between narrow and wide RS can be negligible. However, narrow RS yielded greater than wide RS therefore it is possible the early season difference in FGCC, PAR interception, or NDVI can explain the greater yield.

Table 2.10. Mean agronomic trait observations for planting date, relative maturity, seeding rate, and row spacing averaged across controlled tile drainage and naturally environments in 2019 and 2020 for a total of 4 environments.

			FGCC		PAR		NDVI				
SOV†	ES	FS	V4	R5	V4	R5	V4	R5	Protein	Oil	Yield
PD	plants ha^{-1}				%		0 to 1		g kg^{-1}		
Early	380 608b	344 881b	51a	90a	36a	92a	0.50a	0.86a	335a	173a	3883a
Late	432 649a	403 757a	42a	90a	33a	92a	0.49a	0.86a	335a	171a	3570b
RM											
Early	409 419a	362 826a	43b	88b	34a	92a	0.49a	0.86a	339a	168b	3585a
Late	403 838a	385 812a	49a	91a	35a	92a	0.49a	0.86a	331b	176a	3868a
SR											
seeds ha^{-1}											
408 000	392 081b	360 607a	45a	90a	34a	93a	0.50a	0.86a	334a	172a	3685a
457 000	421 176a	388 031a	47a	90a	36a	93a	0.49a	0.86a	335a	172a	3767a
RS											
cm											
30.5	424 782a	395 411a	49a	91a	38a	93a	0.52a	0.86a	334a	173a	3859a
61	388 475a	353 227a	43b	88b	32b	93a	0.47b	0.86a	336a	171a	3594b

Within columns, means for each treatment followed by the same letter are not significantly different using pairwise comparisons at an $\alpha = 0.05$.
†SOV, source of variation; ES, established stand; FS, final stand; FGCC, fractional green canopy cover; PAR, photosynthetically active radiation interception; V4, four trifoliolate stage; R5, beginning seed stage; PD, planting date; RM, relative maturity; SR, seeding rate; RS, row spacing.

Previous analysis in this study reported PD and RM to be critical components affecting yield. Moreover, narrow RS improved yields by 7% compared to wider spacings. Many previous studies have confirmed the importance of soybean row spacing particularly due to increased light interception (Andrade et al., 2002; Bullock et al., 1998). Evaluating these individual effects within an improved management package of early planting, a late maturing cultivar, high (457 000 seed ha^{-1}) SR, and narrow (30.5 cm) RS permits assessment of the synergism between four yield benefitting factors.

The improved management strategy had superior yields (26% greater) and partial net profit (\$291 ha^{-1}) compared to conventional practices (Table 2.11). Comparing the control to treatment 8, the change in RS did have a non-significant yield increase suggesting that a change in RS does not impact yield or partial net profit if a late RM soybean is planted late at a lower

SR. In this case, changing the SR of the improved treatment to the lower SR (Treatment 5) results in similar profits but would likely buffer plant density reducing events. Schmitz et al. (2020) found increased yields associated with narrow RS compared to wide in the same growing region. In North Dakota, wide RS can result in incomplete canopy closure in the absence of ideal temperature and rainfall, and narrow RS improves the potential to maximize PAR interception and therefore an increase in grain yield (Andrade et al., 2002).

Table 2.11. Soybean yield, partial net profit, and orthogonal contrast of treatments averaged across controlled tile drainage and naturally drained environments in 2019 and 2020.

Treatment	PD†	RM	SR	RS	Yield	Partial Net Profit‡
			seeds ha^{-1}	cm	kg ha^{-1}	\$ ha^{-1}
Improved	Early	Late	457 000	30.5	4162a	1345a
Control	Late	Early	408 000	61.0	3316h	1054h
1	Early	Early	408 000	30.5	3867bcd	1256abcde
2	Early	Early	457 000	30.5	3844bcde	1228cdef
3	Early	Early	408 000	61.0	3639defg	1173defg
4	Early	Early	457 000	61.0	3581efgh	1131fgh
5	Early	Late	408 000	30.5	4085ab	1336ab
6	Early	Late	408 000	61.0	3832bcde	1243bcde
7	Early	Late	457 000	61.0	4013abc	1290abc
8	Late	Early	408 000	30.5	3489gh	1117gh
9	Late	Early	457 000	30.5	3670defg	1164efg
10	Late	Early	457 000	61.0	3356h	1048h
11	Late	Late	408 000	30.5	3783cdef	1225cdef
12	Late	Late	457 000	30.5	3948abc	1266abcd
13	Late	Late	408 000	61.0	3437gh	1098gh
14	Late	Late	457 000	61.0	3542fgh	1117gh
		P			<0.001	<0.001
		Improved vs Control			0.008	0.001

Within the column, means for each treatment followed by the same letter are not significantly different using pairwise comparisons at an $\alpha = 0.05$.

†PD, planting date; RM, relative maturity; SR, seeding rate; RS, row spacing.

‡Partial net profit accounts for \$50 per 140 000 seeds and \$0.0149 kg^{-1} market price.

Yield Prediction Using Canopy Measurements

Individual canopy measurements combined across narrow RS in Prosper and Casselton and both RS in Fargo moderately describe the variation in yield with FGCC and NDVI being better descriptors on average (Table 2.12). Through the R1 to R3 growth stages soybean is actively producing more trifoliolates and producing seed, and FGCC was consistently (R^2 from 0.43 to 0.52) related with yield at these stages. Canopy PAR interception was poorly related to seed yield throughout the season (R^2 from 0.01 to 0.30). The best time to record FGCC and NDVI is at R5. At R5, the PAR interception relationship with yield is considerably lower than at the other reproductive stages. This is likely due to most experimental units having similar PAR interception values regardless of the yield potential of the unit. Narrow RS (30.5 cm) typically have improved PAR interception capacity and yield potential compared to wide rows for soybean (Andrade et al., 2002), as was the case at V4 (Table 2.10).

Table 2.12. Coefficients of determination (R^2) of soybean seed yield in relation to green canopy cover, light interception, and a vegetative index sampled over growth stages for Casselton and Prosper and both row spacings in Fargo in 2019 and 2020.

	FGCC†		PAR		NDVI	
Stage	R^2‡	RMSE	R^2	RMSE	R^2	RMSE
V2	0.05	710	0.01	728	0.01	725
V4	0.21	646	0.21	647	0.19	653
R1	0.43	551	0.24	635	0.41	560
R3	0.49	519	0.30	608	0.05	708
R5	0.52	507	0.01	724	0.65	434
R7	0.16	668	0.23	637	0.01	728

†FGCC, Fractional Green Canopy Cover; PAR, Photosynthetically Active Radiation Interception; NDVI, Normalized Difference Vegetative Index.
‡Coefficients of determination and RMSE from Proc Reg.

The R5 NDVI measurement was the best single observation (R^2=0.65) explaining yield differences. NDVI relationship to yield was expected to increase from planting until R6. The poor relationship between NDVI and yield (R^2=0.05) at R3 may have been due to experimental units absorbing comparable amounts of visible light at that stage. Ma et al., (2001) found soybean NDVI and seed yield relationships improved from the R2 to R5 stages and can discern between high and low yielding genotypes when measured at R5. The NDVI is strongly related to above soybean ground biomass (Ma et al., 1996), and soybean seed production potential increases as plant growth increases (Vega et al., 2001). Therefore, the R5 NDVI results which best describe yield in this study are similar to those found by Ma et al. (2001).

The stepwise and Lasso regression model parameters were comparable with stepwise having a slight advantage with lesser deviation from the regression line (Table 2.13). The primary difference between the two methods are the variables used in the models with Lasso variable selection typically minimizing overfitting of models compared to stepwise regression (Tibshirani, 1997). Within the models, the importance of NDVI at R1, R3, and R5 and FGCC at R3 are similar (Table 2.13). In this case, the variable combination produced by the stepwise (Adj. R^2=0.69) model is similar to the Lasso (Adj. R^2=0.67) model. However, the Lasso variable selection provides a more practical use as only NDVI and FGCC measurements are necessary with a relatively negligible Adj. R^2 reduction. Previous soybean canopy measurements studies relate yield to canopy reflectance (Ma et al., 2001; Mourtzinis et al., 2014) and PAR interception (Andrade et al., 2002). However, incorporating NDVI, FGCC, and PAR interception across early and late PD, early and late RM, 408 000 and 457 000 live seed ha^{-1} SR, and narrow (30.5 cm) and wide (61 cm) RS allows for a yield prediction model with a marginally greater inference and, in this case, a greater explanation of yield compared to a single canopy measurement.

Table 2.13. Stepwise and Lasso regression parameter comparison.

Parameter†	Stepwise Regression	Lasso Regression
Adj. R^2	0.68	0.66
Validated Adj. R^2	0.69	0.67
RMSE	411	425
AIC	3346	3362
Variables Used	NDVI.R1	NDVI.R1
	PAR.R1	NDVI.R3
	NDVI.R3	FGCC.R3
	FGCC.R3	NDVI.R5
	NDVI.R5	FGCC.R5
	PAR.R5	

†Adj. R^2, Adjusted R^2; RMSE, Root Mean Square Error; AIC, Akaike Information Criterion; FGCC, Fractional Green Canopy Cover; PAR, Photosynthetically Active Radiation Interception; NDVI, Normalized Difference Vegetative Index.

Understanding the practical use of these models can provide researchers different estimates depending on which equation is used. For Example, Ma et al. (2001) suggests measuring NDVI between the R4 and R5 stages to screen and rank soybean genotypes. Using the stepwise model in Table 2.14 with data from the improved treatment with an actual yield of 3723 kg ha^{-1} and measurements of 0.72, 57.8, 0.82, 92.8, 0.84, and 85.7 for NDVI R1, PAR R2, NDVI R3, FGCC R3, NDVI R5, and PAR R5, respectively, the estimated yield is 3711 kg ha^{-1}. Using the Lasso model in Table 2.14 and values of 0.72, 0.82, 92.8, 0.84, and 93.3 for NDVI R1, NDVI R3, FGCC R3, NDVI R5, and FGCC R5, respectively, the estimated yield is 3554 kg ha^{-1}. The yield predictions display how the stepwise model can provide higher yield values than the Lasso model. The behavior of the models is important to note to better understand the yield prediction of the regression equations.

Table 2.14. Stepwise and Lasso regression equations to best predict soybean yield.

Method	Equation[†]
Stepwise	$\hat{Y}$=874×NDVI.R1 - 8×PAR.R1 + 1913×NDVI.R3 + 9×FGCC.R3 + 9357×NDVI.R5 - 13×PAR.R5-5604
Lasso	$\hat{Y}$=40×NDVI.R1 + 562×NDVI.R3 + 7×FGCC.R3 + 8185×NDVI.R5 + 5×FGCC.R5 - 4921

[†]FGCC, Fractional Green Canopy Cover expressed in percent; PAR, Photosynthetically Active Radiation Interception expressed in percent; NDVI, Normalized Difference Vegetative Index expressed as 0 to 1; $\hat{Y}$ is estimated yield kg ha^{-1}.

Combining established plant density with a canopy measurement could be a simple means to improve yield prediction. However, established plant density was not a strong predictor of yield within the range of plant density we encountered in these experiments and did not improve R^2 values (Table 2.15) compared to canopy measurements alone (Table 2.12). A single canopy measurement, especially FGCC at R3 or R5, is a more effective use of time to predict yield.

Table 2.15. Coefficients of determination (R^2) of soybean seed yield in relation to established plant density, green canopy cover, light interception, and a vegetative index sampled over growth stages for Casselton and Prosper and both row spacings in Fargo in 2019 and 2020.

	Established Plant Density					
	FGCC†		PAR		NDVI	
Stage	Adj. R^{2}‡	RMSE	Adj. R^2	RMSE	Adj. R^2	RMSE
V2	0.05	711	0.01	729	0.01	726
V4	0.22	643	0.21	647	0.20	654
R1	0.44	548	0.24	636	0.42	557
R3	0.49	519	0.30	609	0.05	710
R5	0.52	508	0.01	725	0.65	435
R7	0.16	669	0.23	638	0.01	729

†ES, Established Plant Density; FGCC, Fractional Green Canopy Cover; PAR, Photosynthetically Active Radiation Interception; NDVI, Normalized Difference Vegetative Index.
‡Adjusted coefficients of determination (Adj. R^2) and RMSE from Proc Reg.

The model which best predicts yield may not always be the most practical to use. Instruments for NDVI and PAR measurement can be expensive and may not be practical for every farmer or agronomist to own. However, FGCC can easily be obtained by using a cell phone with the Canopeo application in a few seconds. Table 2.12 provides R^2 values for the relationship between FGCC and yield at several growth stages, and Table 2.16 displays simple and multiple regression equations which were most predictive of yield. The relationship between FGCC and yield slightly improves when both the R3 and R5 measurements are included. The best yield prediction model using FGCC includes observations at V2, R1, R3, and R5 with the R5 observation having the greatest effect on the seed yield. It is important to note that the FGCC only explains at most 56% of the variation in yield encountered. Using a single FGCC measurement at the R5 growth stage is likely the most efficient way to collect data that give a reasonable prediction. However, given the only moderate R^2 values, FGCC should primarily be used to monitor soybean progress throughout the season rather than predicting yield per se. Incorporating weather variables such as total August rainfall or monthly minimum and maximum air temperature in July and August may improve model performance (Joshi et al., 2020).

Improving the soybean prediction model would benefit from a wider array of genotypes, additional years of data, and inclusion of weather data to expand inferences beyond the two-week planting window, RM groups, SRs, and RS used in the study.

Table 2.16. Regression parameters using fractional green canopy cover measured at various growth stages throughout the growing season to predict yield at Casselton and Prosper and both row spacings in Fargo in 2019 and 2020.

FGCC†	Adj. R^2	RMSE	Equation
Growth Stage			
R3	0.49	510	$\hat{Y} = 33.4 \times FGCC.R3 + 662.3$
R5	0.52	510	$\hat{Y} = 50.3 \times FGCC.R5 - 868.2$
R3 R5	0.54	479	$\hat{Y} = 18.8 \times FGCC.R3 + 29.4 \times FGCC.R5 - 603.2$
V2 R1 R3 R5	0.56	470	$\hat{Y} = -7 \times FGCC.V2 + 7 \times FGCC.R1 + 13 \times FGCC.R3 + 25 \times FGCC.R5 - 132$‡

†FGCC Fractional Green Canopy Cover, Adj. R^2, Adjusted R^2; RMSE, Root Mean Square Error.
‡Equation derived using stepwise regression. $\hat{Y}$ = yield in kg ha^{-1} FCGC is expressed as percent cover.

Conclusions

Planting as early as appropriate and using genotypes with later RMs adapted to the area can increase yields. However, environmental influences like soil crusting before emergence or a killing frost before physiological maturity could reverse or nullify early planting or late RM benefits. Combining the best soybean production factors for North Dakota provides greater yield and partial net profit compared to standard regional practices. In addition, using a narrow RS compared to a relatively wider RS in North Dakota improves yield. Adding narrow RS to the recommended management package provides a substantial yield and partial net profit compared to standard practices. These findings display a synergistic effect when combining favorable management strategies. Growers in eastern North Dakota and similar soybean production areas are recommended to combine favorable production practices like early planting, late maturing cultivars adapted to the area, and to use narrow row spacings when possible to maximize yield potential. Combining multiple linear regression techniques showed 69% of soybean seed yield can be explained by canopy measurements throughout the growing season, and a NDVI measurement at the R5 stage is the single observation most closely predicted yield. Measuring the FGCC at R5 is an easily accessible and reasonable measurement explaining 52% of yield variation and could be used by farmers and agronomists to evaluate soybean yield potential.

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OVERALL CONCLUSIONS

This research was intended to explore planting date, seeding rate, and genotype or relative maturity in soybean on HRSW and the aforementioned factors including row spacing on soybean production in North Dakota. The results describe varying degrees of response of these factors between HRSW and soybean, but overall, using wheat hybrids require similar seeding rates as cultivars and combining advantageous planting date, seeding rate, relative maturity, and row spacing management practices in soybean greatly improved yield and partial net profit compared to standard North Dakota practices.

A uniform crop management approach is not apparent for wheat production as differences between environments were evident. Planting as soon as conditions were appropriate did not impact wheat yield compared to delaying planting two weeks. Separating individual planting dates into high (>5000 kg ha^{-1}) and low (<5000 kg ha^{-1}) yielding environments resulted in the hybrid optimal yield requiring slightly increased seeding rates compared to cultivars. In addition, improved hybrid yields are likely from increased spike size. However, the increase in hybrid yield may be offset by higher seed prices compared to conventional cultivars unless seed prices are relatively similar. Heterosis did not improve end use quality for the hybrid tested suggesting the economic practicality should only consider yield and related price factors.

Compared to wheat, the planting date, seeding rate, relative maturity, and row spacing factors have a larger effect on soybean yield and agronomic characteristics. Early planting and using late relative maturity cultivars typically increase yield but this can be negated by early season stand reducing events or killing frosts prior to physiological maturity. The results from combining factors into management packages indicated the improved treatment greatly improved yield and partial net profit compared to common North Dakota management practices. Predicting soybean yield using canopy measurements could explain nearly 70% of the yield variation. Instead of multiple measurements throughout the season, a fractional green canopy cover measurement using the Canopeo application at the R5 growth stage explains over half of yield variation and is easily accessible for farmers, agronomists, or researchers. Adding soil and weather data into the prediction model would likely improve precision and utility.

Nonetheless, hybrid wheat has the potential to improve wheat production in North Dakota. Results in this study were limited to the experimental hybrids tested, and additional testing using commercially released hybrids would likely result in more clear relationships and trends. Soybean producers in eastern North Dakota are recommended to plant early while using late relative maturity cultivars adapted to the area while being seeded at 457 000 live seed ha^{-1} and to use narrow row spacings if possible.

APPENDIX

Table A 1. Linear and quadratic regression analysis for Hard Red Spring Wheat (*Triticum aestivum* L. emend. Thell.) yield and grain protein response to established plant density averaged across seeding rate for each planting date within each environment in 2019 and 2020.

Environment	PD†	R^2	OPD	Yield	Order	Regression Equation
			Million plants ha^{-1}	kg ha^{-1}		
Grand Forks	Early	0.25			L	$\hat{y}$= 3913.9 + 316.5x
		0.68	2.19	4692	Q	$\hat{y}$= 2221.8 + 2250.0x - 512.4x^2
	Late	0.38			L	$\hat{y}$= 4401.8 + 96.3x
		0.53	2.58	4730	Q	$\hat{y}$= 3207.7 + 1180.0x - 228.7x^2
Hettinger	Early	0.65			L	$\hat{y}$= 4845.9 + 142.6x
		0.74	2.66	5272	Q	$\hat{y}$= 2757.1 + 1880.0x - 351.4x^2
	Late	0.39			L	$\hat{y}$= 4336.3 + 105.9x
		0.53	2.88	4635	Q	$\hat{y}$= 3873.0 + 529.6x - 92.0x^2
Langdon	Early	0.01			L	$\hat{y}$= 5710.6 + 29.7x
		0.01	2.38	5775	Q	$\hat{y}$= 5935.8 - 135.0x + 28.3x^2
	Late	0.31			L	$\hat{y}$= 5993.4 - 15.4x
		0.34	2.01	5960	Q	$\hat{y}$= 5926.6 + 33.2x - 8.3x^2
Minot	Early	0.59			L	$\hat{y}$= 4109.7 - 99.8x
		0.60	3.77	3749	Q	$\hat{y}$= 4402.9 - 347.2x + 46.1x^2
	Late	0.01			L	$\hat{y}$= 3458.7 + 123.2x
		0.12	5.19	3992	Q	$\hat{y}$= 3183.2 + 311.5x - 29.9x^2
Prosper	Early	0.55			L	$\hat{y}$= 5301.8 + 1.1x
		0.70	2.08	5282	Q	$\hat{y}$= 5513.4 - 223.2 x + 53.8x^2
Environment	PD	R^2	OPD	Protein		Regression Equation
			Million plants ha^{-1}	g kg^{-1}		
Grand Forks	Early	0.00			L	$\hat{y}$= 157 + 0.01 x
		0.40	1.89	158	Q	$\hat{y}$= 145 + 1.39 x - 0.37x^2
	Late	0.35			L	$\hat{y}$= 148 + 0.13 x
		0.62	2.10	150	Q	$\hat{y}$= 159 - 0.84 x + 0.2x^2
Hettinger	Early	0.41			L	$\hat{y}$= 148 - 0.22 x
		0.46	2.83	141	Q	$\hat{y}$= 167 - 1.81 x + 0.32x^2
	Late	0.85			L	$\hat{y}$= 156 - 0.30 x
		0.95	1.66	150	Q	$\hat{y}$= 143 + 0.83 x - 0.25x^2
Langdon	Early	0.10			L	$\hat{y}$= 137 - 0.05 x
		0.46	2.77	136	Q	$\hat{y}$= 125 + 0.83 x - 0.15x^2
	Late	0.61			L	$\hat{y}$= 138 - 0.05 x
		0.69	2.50	137	Q	$\hat{y}$= 135 + 0.15 x - 0.03x^2
Minot	Early	0.58			L	$\hat{y}$= 142 + 0.24 x
		0.60	1.41	145	Q	$\hat{y}$= 146 - 0.09 x + 0.06x^2
	Late	0.98			L	$\hat{y}$= 148 - 0.12 x
		0.99	2.02	146	Q	$\hat{y}$= 147 - 0.05 x - 0.01x^2
Prosper	Early	0.85			L	$\hat{y}$= 160- 0.47 x
		0.87	1.34	155	Q	$\hat{y}$= 150 + 0.67 x - 0.27x^2

†PD, planting date; OPD, optimum plant density for maximum yield based on regression from PROC REG. L, Linear; Q, Quadratic; ŷ, Predicted Yield; x, plant density (million plants ha^{-1}).

Table A 2. Significance levels for planting date, seeding rate, and genotype effects and orthogonal polynomial contrasts on Hard Red Spring Wheat (*Triticum aestivum* L. emend. Thell.) yield and protein for Grand Forks, Hettinger, Langdon, and Minot North Dakota environments in 2019 and 2020.

		GF	H	L	M		GF	H	L	M
SOV[†]	df	Yield				df	Protein			
Seeding rate (SR)	4	ns	ns	ns	ns	4	ns	ns	ns	ns
Linear (SR_L)	1	ns	ns	ns	ns	1	ns	*	ns	ns
Quad (SR_Q)	1	*	ns	ns	ns	1	ns	ns	ns	ns
Cubic SR	1	ns	ns	ns	ns	1	ns	ns	ns	ns
Quartic SR	1	ns	ns	*	*	1	ns	ns	ns	ns
Planting Date (PD) x SR	4	**	ns	ns	**	4	**	ns	ns	**
SR_L x PD	1	ns	ns	ns	*	1	ns	ns	ns	**
SR_Q x PD	1	ns	ns	ns	ns	1	ns	ns	ns	ns
Cubic SRxPD	1	ns	ns	ns	ns	1	ns	ns	ns	ns
Quintic SRxPD	1	ns	ns	ns	ns	1	ns	ns	ns	ns
SR x Genotype	24	ns	ns	ns	ns	24	ns	ns	ns	ns
SR-L Ingmar (I) vs Hybrids	1	ns	ns	ns	ns	1	ns	ns	ns	ns
SR-Q I vs Hybrids	1	ns	*	ns	ns	1	ns	ns	ns	ns
SR_L Valda (V) vs Hybrids	1	*	ns	ns	ns	1	ns	ns	ns	ns
SR_Q V vs Hybrids	1	ns	ns	ns	ns	1	ns	ns	*	ns
SR_L x IV vs Hybrids	1	*	ns	ns	ns	1	ns	ns	ns	ns
SR_Q x IV vs Hybrids	1	ns	ns	ns	ns	1	ns	ns	*	ns
SR_L I vs Best	1	ns	ns	ns	ns	1	ns	ns	ns	ns
SR_Q I vs Best	1	ns	**	ns	ns	1	ns	ns	ns	ns
SR_L V vs Best	1	ns	ns	ns	ns	1	ns	ns	ns	ns
SR_Q V vs Best	1	ns	ns	ns	ns	1	ns	ns	ns	ns
SR_L IV vs Best	1	ns	ns	ns	ns	1	ns	ns	ns	ns
SR_Q IV vs Best	1	ns	*	ns	ns	1	ns	ns	ns	ns
SR-L I vs Hybrids	1	ns	ns	ns	ns	1	ns	ns	ns	ns
SR-Q I vs Hybrids	1	ns	*	ns	ns	1	ns	ns	ns	ns

[†]SOV = Source of variation; df = degrees of freedom; GF = Grand Forks; H = Hettinger; L = Langdon; M = Minot.

Table A 3. Hard Red Spring Wheat (*Triticum aestivum* L. emend. Thell.) genotypes Valda and H_D yield response standardized across four high (>5000 kg ha^{-1}) and five low (<5000 kg ha^{-1}) yield environments (YE) and averaged across seeding rate in 2019 and 2020.

YE	Genotype	*P*	R^2	OSR†	Yield	Equation
				Million seeds ha^{-1}	kg ha^{-1}	
High	Valda	0.329	0.67	3.34	5551	$\hat{y} = 5411.1 + 83.5x – 12.5x^2$
	H_D	0.156	0.84	3.86	5847	$\hat{y} = 4801.3 + 541.6x – 70.1x^2$
Low	Valda	0.304	0.70	3.82	4366	$\hat{y} = 3510.6 + 447.2x – 58.5x^2$
	H_D	0.163	0.84	3.23	4282	$\hat{y} = 4493.7 – 131.1x + 20.3x^2$

†OSR, Optimum Seeding Rate; ŷ, predicted yield; x, seeding rate (million seeds ha^{-1}).

Table A 4. Hard Red Spring Wheat (*Triticum aestivum* L. emend. Thell.) genotypes Valda and H_D yield response standardized across four high (>5000 kg ha^{-1}) and five low (<5000 kg ha^{-1}) yield environments (YE) and established plant density averaged across seeding in 2019 and 2020.

YE	Genotype	*P*	R^2	OPD†	Yield	Equation
				Million plants ha^{-1}	kg ha^{-1}	
High	Valda	0.544	0.46	2.25	5547	$\hat{y} = 5362 + 164.3x – 36.5x^2$
	H_D	0.068	0.93	2.76	5857	$\hat{y} = 4369 + 1077.0x – 194.9x^2$
Low	Valda	0.023	0.98	2.46	4379	$\hat{y} = 3221 + 942.0x – 191.6x^2$
	H_D	0.136	0.86	2.31	4282	$\hat{y} = 4518 – 205.0x + 44.3x^2$

*, **, ***, and ns indicate significance at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$, and not significant, respectively.
†OPD, Optimum Plant Density.

Table A 5. Combined Ingmar and Valda Hard Red Spring Wheat (*Triticum aestivum* L. emend. Thell.) seeding rate providing the maximum economic return based on seed cost and grain price combined over early and late planting dates for Grand Forks, Hettinger, Langdon, and Minot, North Dakota in 2019 and 2020.

	Early Planting Date								Late Planting Date							
	Market Price ($ kg^{-1})															
Seed Cost	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29
($ kg^{-1})	Million Seeds ha^{-1}								Million Seeds ha^{-1}							
0.35	3.99	3.99	3.99	3.99	3.99	3.99	3.99	3.99	4.52	4.52	4.53	4.53	4.53	4.53	4.53	4.53
0.44	3.98	3.99	3.99	3.99	3.99	3.99	3.99	3.99	4.51	4.52	4.52	4.52	4.53	4.53	4.53	4.53
0.53	3.98	3.98	3.98	3.99	3.99	3.99	3.99	3.99	4.51	4.51	4.52	4.52	4.52	4.52	4.52	4.53
0.62	3.98	3.98	3.98	3.98	3.98	3.99	3.99	3.99	4.50	4.51	4.51	4.51	4.52	4.52	4.52	4.52
0.70	3.97	3.98	3.98	3.98	3.98	3.98	3.98	3.99	4.49	4.50	4.50	4.51	4.51	4.51	4.52	4.52
0.79	3.97	3.97	3.98	3.98	3.98	3.98	3.98	3.98	4.49	4.49	4.50	4.50	4.51	4.51	4.51	4.51
0.88	3.97	3.97	3.97	3.98	3.98	3.98	3.98	3.98	4.48	4.49	4.49	4.50	4.50	4.51	4.51	4.51
0.97	3.96	3.97	3.97	3.97	3.97	3.98	3.98	3.98	4.47	4.48	4.49	4.49	4.50	4.50	4.50	4.51
1.06	3.96	3.96	3.97	3.97	3.97	3.97	3.98	3.98	4.47	4.48	4.48	4.49	4.49	4.50	4.50	4.50
1.15	3.96	3.96	3.96	3.97	3.97	3.97	3.97	3.98	4.46	4.47	4.48	4.48	4.49	4.49	4.50	4.50
1.23	3.95	3.96	3.96	3.96	3.97	3.97	3.97	3.97	4.45	4.46	4.47	4.48	4.48	4.49	4.49	4.50
1.32	3.95	3.95	3.96	3.96	3.97	3.97	3.97	3.97	4.45	4.46	4.47	4.47	4.48	4.48	4.49	4.49
1.41	3.95	3.95	3.96	3.96	3.96	3.97	3.97	3.97	4.44	4.45	4.46	4.47	4.47	4.48	4.48	4.49
1.50	3.94	3.95	3.95	3.96	3.96	3.96	3.97	3.97	4.43	4.45	4.46	4.46	4.47	4.48	4.48	4.48
1.59	3.94	3.95	3.95	3.95	3.96	3.96	3.96	3.97	4.43	4.44	4.45	4.46	4.47	4.47	4.48	4.48
1.67	3.94	3.94	3.95	3.95	3.96	3.96	3.96	3.96	4.42	4.43	4.44	4.45	4.46	4.47	4.47	4.48
1.76	3.93	3.94	3.94	3.95	3.95	3.96	3.96	3.96	4.41	4.43	4.44	4.45	4.46	4.46	4.47	4.47

Table A 6. Combined hybrid Hard Red Spring Wheat (*Triticum aestivum* L. emend. Thell.) seeding rate providing the maximum economic return based on seed cost and grain price combined over early and late planting dates for Grand Forks, Hettinger, Langdon, and Minot, North Dakota in 2019 and 2020.

	Early Planting Date								Late Planting Date							
	Market Price ($ kg^{-1})								Market Price ($ kg^{-1})							
Seed Cost	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29	0.17	0.18	0.20	0.22	0.24	0.26	0.28	0.29
($ kg^{-1})	Million Seeds ha^{-1}								Million Seeds ha^{-1}							
0.35	4.93	4.94	4.95	4.95	4.96	4.96	4.96	4.96	3.33	3.34	3.34	3.34	3.34	3.34	3.34	3.35
0.44	4.92	4.92	4.93	4.94	4.94	4.95	4.95	4.95	3.33	3.33	3.33	3.34	3.34	3.34	3.34	3.34
0.53	4.90	4.91	4.92	4.92	4.93	4.94	4.94	4.94	3.32	3.32	3.33	3.33	3.33	3.33	3.34	3.34
0.62	4.88	4.89	4.90	4.91	4.92	4.92	4.93	4.93	3.31	3.32	3.32	3.33	3.33	3.33	3.33	3.33
0.70	4.86	4.88	4.89	4.90	4.91	4.91	4.92	4.92	3.31	3.31	3.32	3.32	3.32	3.33	3.33	3.33
0.79	4.84	4.86	4.87	4.88	4.89	4.90	4.91	4.91	3.30	3.31	3.31	3.32	3.32	3.32	3.32	3.33
0.88	4.83	4.84	4.86	4.87	4.88	4.89	4.90	4.90	3.29	3.30	3.31	3.31	3.31	3.32	3.32	3.32
0.97	4.81	4.83	4.84	4.86	4.87	4.88	4.89	4.89	3.29	3.29	3.30	3.31	3.31	3.31	3.32	3.32
1.06	4.79	4.81	4.83	4.84	4.86	4.87	4.88	4.88	3.28	3.29	3.30	3.30	3.31	3.31	3.31	3.32
1.15	4.77	4.80	4.81	4.83	4.84	4.86	4.87	4.87	3.27	3.28	3.29	3.30	3.30	3.31	3.31	3.31
1.23	4.75	4.78	4.80	4.82	4.83	4.84	4.85	4.86	3.27	3.28	3.28	3.29	3.30	3.30	3.30	3.31
1.32	4.74	4.76	4.78	4.80	4.82	4.83	4.84	4.85	3.26	3.27	3.28	3.29	3.29	3.30	3.30	3.30
1.41	4.72	4.75	4.77	4.79	4.81	4.82	4.83	4.84	3.25	3.26	3.27	3.28	3.29	3.29	3.30	3.30
1.50	4.70	4.73	4.76	4.78	4.79	4.81	4.82	4.83	3.25	3.26	3.27	3.28	3.28	3.29	3.29	3.30
1.59	4.68	4.71	4.74	4.76	4.78	4.80	4.81	4.82	3.24	3.25	3.26	3.27	3.28	3.28	3.29	3.29
1.67	4.66	4.70	4.73	4.75	4.77	4.79	4.80	4.81	3.23	3.25	3.26	3.27	3.27	3.28	3.28	3.29
1.76	4.65	4.68	4.71	4.74	4.76	4.77	4.79	4.80	3.23	3.24	3.25	3.26	3.27	3.28	3.28	3.29