SOYBEAN SEEDING RATE AND ROW SPACING EFFECTS ON PLANT ESTABLISHMENT AND YIELD

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Soybean Seeding Rate and Row Spacing Effects on Plant Establishment and Yield

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

MASTER OF SCIENCE

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ABSTRACT

North Dakota soybean [*Glycine max* (L.) Merrill] management varies across the state, resulting in yield differences. Eight soybean seeding rates (starting at 197600 and increasing by 49400 live seed ha^{-1} increments) and row spacing (30 and 61 cm) were evaluated in 15 North Dakota environments in 2017-2018 to determine plant densities, seed yield, and plant loss, which were compared with soybean producer field data. Planting 30 cm row spacing yielded 183 kg ha^{-1} greater than 61 cm row spacing. On farm, maximum yields occurred at 414000 live seed ha^{-1} and final plant densities of 352000 plants ha^{-1}. In research plots, 494000 live seed ha^{-1} had the highest yield. On farm, 8.9% plant loss occurred after plant establishment while research data observed 6.9% plant loss. North Dakota soybean producers should use narrow row spacing, use final plant density to estimate yields, and 444600 live seed ha^{-1} provided the highest net revenue.

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INTRODUCTION

Soybean [*Glycine max* (L.) Merr.] is a dicotyledonous legume, which has been grown in northeast China since the 11th century B.C. The profitability from soybean derived oil, biodiesel, animal feed, and human nutrition, supports soybean demand. With various seed planting machinery and production methods, it is common for farmers to use different row spacings and seeding rates to maximize profit. Different soybean management practices often result in yield gaps between yield potential and reported farm yields (Cassman et al., 2003).

Due to multiple factors contributing to the soybean yield gap, producer reported yield and management data can identify yield-limiting factors (Grassini et al., 2011). To identify soybean yield-limiting factors for North Dakota, management and yield data were collected from 1122 producer fields from 2014 to 2017. Survey field data from 2014 and 2015 generated curiosity about the differences in reported seeding rates and established plant densities that prompted field visits in subsequent years. In 2016 and 2017, 214 producer fields were visited once during the early and again in late season to confirm established and harvested soybean plant densities, respectively. Field visit observations indicated additional plant loss after plant establishment. To understand plant density yield-limiting factors reported from producer fields, it is common to replicate management factors in research trials to quantify the factor's effect (Villamil et al., 2012).

The varying management factors and strategies that North Dakota soybean producers reported requires further investigation on the effects of row spacing and seeding rate and their relation to plant density and yield.

LITERATURE REVIEW

Soybean History

Soybean has been raised in Europe as well as North and South America dating back to the 1700s (U.S. Soybean Export Council, 2015). Soybean has since been adapted to various environments by natural selection and breeding methods. The adoption and increase of soybean production worldwide is mainly due to end use product utility (U.S. Soybean Export Council, 2015). Soybean is utilized by Midwestern agriculture producers to increase soil health, which is a soil's capacity to sustain a living ecosystem (Doran and Parkin 1994), and provide biologically fixed N (Patterson and LaRue, 1983). Increasing soil health benefits farmer's future productivity and overall soil quality.

The life cycle of soybean is separated into two growth phases, vegetative and reproductive, where the stages are further broken down into sub stages (Fehr et al., 1971). Growth between the different stages of the soybean plants is determined by temperature and the amount of light energy received per stage (Kandel, 2014). Photosynthesis is crucial for the growth of plants. In the northern United States, soybean is considered a short-day plant. Short-day plants do not begin reproductive growth until after the critical night length (photoperiod) is achieved, which is after 21 June in North America. After soybean emergence, the vegetative growth advances to the next stage every five days on average and advances each reproductive stage about every ten days until full maturity (Fehr et al., 1971).

Increase in global population raises the demand for more food production and other related products. Demand for food products also creates a need for increase production of soybean. World soybean use increased from 312 million Mg in 2016 to 336 million Mg in 2017 (USDA, 2017). Soybean oil consumption increased 40% a year from 1998 to 2008 in China. The

USA biodiesel demand increased 3% from 2016 to 2017, with the demand driven by state and federal financial incentives (Hanson, 2017). After oil extraction, about 98% of global soybean production is used as animal feed (U.S. Soybean Export Council, 2015). The diverse and multifaceted soybean market requires a large amount of soybean production to provide for the increasing need in feed. Improved soybean production is being implemented through new breeding strategies, genetic modifications, and management practices (Tester and Langridge, 2010). As a crop in North Dakota, an increase in soybean production and expansion in area can be attributed to its relative profitability compared to small grains as well as improved soybean varieties (Bangsund et al., 2011).

Producing soybean in North Dakota provides challenges due to an often adverse climate. In North Dakota, it is recommended to plant soybean of a 0 group maturity when the soil temperature is 10˚C, between 10 and 25 May, and with a target of 370 000 established plants per ha^{-1} regardless of row spacing. Soybean emerge by an elongating hypocotyl leaving the plant vulnerable to frost damage (Kandel, 2014). The maturity group of the soybean variety planted determines the duration of the plant's life. Plants typically mature in September and October. Depending on maturity and planting date, harvested soybeans contain approximately 36% protein and 20% lipids (USDA, 2016). The average soybean yields in North Dakota for the years 2014 to 2017 were 2320, 2387, 2790, and 2281 kg ha^{-1}, respectively (USDA, 2018a).

North Dakota Soybean Survey

Communication between soybean producers and agriculture educators such as NDSU Extension is vital to educate producers and improve management practices. Providing resources and information from relevant research aids local and regional soybean production. NDSU Extension gains soybean management information from the North Dakota Soybean Survey

(NDSS). The NDSS is a paper survey delivered to participating soybean producers, and inquires about soybean information such as seeding rate, plant density, variety planted, soil management practices, and disease presence. Management recommendations based on the NDSS can be used to increase soybean production in North Dakota (Rattalino Edreira et al., 2017).

Seeding Rate and Plant Density

The relationship between seeding rates, yield, and iron deficiency chlorosis (IDC) have been explored in several soybean related studies (De Bruin and Pedersen, 2008b; Cox and Cherney, 2011; Devlin et al., 1995; Ethredge et al., 1989; Goos and Johnson, 2001). Soybean seeding rate describes the number of seeds planted in a given area. Soybean plants display variable amounts of branching depending on the amount of space for growth, which may result in no yield response from increased seeding rates (Carpenter and Board, 1997). Planting soybean seeds at variable rates may result in different plant responses. Increasing seeding rates to 516 000 seeds ha^{-1} has been found to increase soybean chlorophyll levels, reduce plant chlorosis, and increase seed yield in iron (Fe) deficient soils (Goos and Johnson, 2001). Varying soybean seeding rates have produced similar yield levels with rates as low as 76 000 seeds ha^{-1} in Kentucky and as high as 388 000 seeds ha^{-1} in Wisconsin (Oplinger and Philbrook, 1992; Lee et al., 2008).

Plant density is defined as the number of plants per unit area (Bonham, 2013). The number of established plants are different from seeding rates due to the multitude of causes preventing emergence such as moisture, temperature, planting depth, salinity, pH, light stress, or the ability of the seed to germinate. Seeding rates (seeds planted) are adjusted for germination percent, anticipated mortality of live seeds, and the desired established plant density (Kandel, 2014). Currently, North Dakota State University recommends an established soybean plant density of 370 500 plants ha^{-1}.

Row Spacing

The distance between soybean rows has an impact on plant density and soybean seed yield. Cooper (1977) in Illinois defined narrow row soybean as rows < 50 cm apart where wide row spacing as rows $\geq$ 50 cm apart. Planting soybean in narrow rows leads to quicker canopy closure, which may result in greater light interception (Andrade et al., 2002; Bullock et al., 1998). In narrow rows, soybean plants are at more equidistant plant spacing, resulting in early season canopy cover as compared with plants in wider row spacings (Shibles and Weber, 1966). Narrow row spacing has been found to increase yields in favorable weather 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). However, the use of narrow soybean row spacing can reduce yields under soil water deficit conditions (Alessi and Power, 1982).

Wide row soybean spacings are more common outside of the northern Midwest. Soybean in wide rows have better water use efficiency, are more tolerant to water deficit conditions, and have higher yields during water deficit conditions (Alessi and Power, 1982; Devlin et al., 1995). Agricultural environments experiencing drought and water deficiency are likely to have soybean planted in wide rows. However, soybean row spacing is largely dependent on the preference of the grower. Planting wide row widths of soybean can reduce disease stress and reduce the effects of Soybean Cyst Nematode (SCN) and Sudden Death Syndrome (SDS) (Pedersen and Lauer, 2003; Swoboda et al., 2011). However, without the presence of disease pressure, wide row spacing does not result in a significant yield improvement over narrow spacing.

Emergence Rate

Various external factors such as soil moisture, temperature, and soil salinity affect the soybean seedling. According to Helms et al. (1996a), soil water content and temperature during germination greatly influences soybean emergence. Adequate soil moisture during soybean imbibition paired with rapid soil drying or high temperatures will considerably reduce soybean emergence (Helms et al., 1996b). In addition, increasing soil salinity and electrical conductivity (EC), which is a measure of the amount of soil salts, reduce soybean seedling emergence by limiting the amount of water available to the seedling which, in turn, reduces the seedling vigor (Vieira et al., 2004).

An emergence index (EI) can be used to describe the rate at which seedlings emerge from the soil. Anfinrud and Schneiter (1984) found a significant correlation between the EI and sunflower (*Helianthus annuus* L.) early planting compared with late planting. The EI can be influenced by soil type and seeding depth (Berti and Johnson, 2013), and the emergence rate may be related to the germination percent of the seed.

Tile Drainage

Tile drainage has a multitude of positive benefits when installed in agricultural fields. According to Gardner et al. (1994), tile drainage reduces waterlogging of the soil which increases soil structure and positively benefits soil health. Soils with tile drainage require less time to warm up in the spring depending on soil texture (Lieffers and Rothwell, 1987). Increased spring soil temperatures allows for timely crop management operations during otherwise unfavorable conditions. Excess soil moisture fills pores within the soil reducing the amount of atmospheric oxygen (O_2) and N gas.

Iron Deficiency Chlorosis in Soybean

Soils in North Dakota usually contain sufficient amounts of Fe to sustain plant growth, but the genetic makeup of the plant determines the use of Fe by an adapted mechanism (Brown et al., 1972). The Fe acquisition occurs in plants using one of two mechanisms which are classified as either strategy I or strategy II plants (Romheld and Marschner, 1986). Dicot species are under the classification of strategy I plants.

Soybean acquire Fe, utilizing the same strategy (I) as other dicot plants. Strategy I plants take up Fe by increasing membrane-bound reductase activity, increase H^+ concentration in the root zone, chelate Fe, and reduce Fe^{3+} to Fe^{2+} for uptake (Marschner et al., 1989). Multiple factors such as excessive N fertilization (Caliskan et al., 2008), high soil pH (Moraghan and Mascagni Jr., 1991), amount of bicarbonates and soluble salts in the soil (Franzen and Richardson, 2000), and seed iron content (Wiersma, 2005; 2010) can interrupt and interfere with the strategy I Fe acquisition. Soybean iron deficiency chlorosis (IDC) symptoms are often associated with multiple stresses and not just soil Fe availability (Hansen et al., 2003).

The likelihood of IDC increases as soil electrical conductivity (EC) increases, and soils containing higher concentrations of chelated Fe have been found to mitigate IDC (Hansen et al., 2003). Soybean plants respond to soil conditions in different ways. Soybean nodulation decreases with increasing $CaCO_3$ in the soil (Franzen and Richardson, 2000). The amount of $CaCO_3$ in a soil can be measured by the $CaCO_3$ Equivalent (CCE), which represents the neutralizing ability of the soil as compared to pure $CaCO_3$. The influence these soil characteristics have on soybean plant nodulation requires further analysis. Iron deficiency chlorosis negatively affects the soybean productivity by reducing seed production. Seeding rates have been documented to influence the severity of IDC, seed yield, and plant chlorophyll levels in soybean (Goos and Johnson, 2001).

Research Objectives

Increased demand for soybean supports further research into soybean production and management practices. The objective of this research was to determine the effect of row spacing and seeding rate on soybean plant establishment, plant density, plant loss, vigor, canopy coverage, plant height, seed yield, seed protein, and seed oil content. Concurrent research utilized the NDSS to examine the relationship between reported and observed plant densities from fields as well as in season plant loss. Results will increase the understanding of soybean management practices and provide an economic analysis to optimize profits and practicality of management decisions for North Dakota soybean producers.

MATERIALS AND METHODS

Experimental Design and Treatments

The experiment was conducted at five locations in 2017 and duplicated at four locations in 2018. The primary research location was at North Dakota State University's (NDSU) NW22 research station north of Fargo, ND (46.932124° -96.858941°). Remaining locations were at Casselton, ND (46.883932°, -97.237001°), Prosper, ND (47.003138°, -97.105581°), Ransom county (46.441170°, -97.802049°), Sargent county (46.211173°, -97.654191°), and Steele county (47.440210°, -97.650868°) research sites. Casselton, ND and Prosper, ND will be referred to by their respective town name. Ransom, Sargent, and Steele counties will be referred to by its respective county name. NW22 is divided into two separate environments because the site has tile drainage with control boxes able to simulate tile and non-tile drained soils, hence a tiled and a non-tiled environment. Location by year will be called environment. The experiment was designed as a randomized complete block design (RCBD) with a 2 × 7 factorial arrangement of row spacing and seeding rates. There were four replications per environment and each replication was composed of 14 treatments. The treatments had a soybean variety of adapted maturity for the environment, two different row spacings, and seven soybean seeding rates. The NW22 location tested two different adapted soybean varieties due to sufficient area for experimentation. Important crop management and observation dates are presented in Table 1.

Soybean seeds planted in 2017 and 2018 were treated with fungicide and insecticide as Acceleron Standard (pyraclostrobin [methyl N-{2-[1-(4-chlorophenyl)pyrazol-3-yloxymethyl] phenyl}(N -methoxy)carbamate], metalaxyl [methyl N-(2,6-dimethylphenyl)-N-(methoxyacetyl)-DL-aalaninate], fluxapyroxad [1H-Pyrazole-4-carboxamide, 3-(difluoromethyl)-1-methyl-N-(3’,4’,5’-trifluoro[1,1’-biphenyl]-2-yl)], imidacloprid [N-[1-[(6-

chloropyridin-3-yl)methyl]-4,5-dihydroimidazol-2-yl]nitramide]) (Acceleron Seed Applied Solutions, Monsanto Company, St. Louis, MO). Seeds were inoculated with *Bradyrhizobium japonicum* in the form of Vault SP (BASF, Ludwigshafen, Germany) at a rate of 1.8 g kg^{-1} seed, to promote root nodulation for N fixation.

Weeds were controlled using (a.i. 48.8% glyphosate, N-(phosphonomethyl) glycine, in potassium salt form) Roundup WeatherMAX (Monsanto Co., St. Louis, MO) and (12.6% (E)-2-[1-[[(3-chloro-2-propenyl)oxy]imino]propyl]- 5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) SelectMax (Valent U.S.A. Corporation, Walnut Creek, CA). In 2017 and 2018, (a.i. 9.15% S-Cyano(3-phenoxyphenyl)methyl (+/-)-cis/trans-3-(2,2-dichloethenyl)-2,2-dimethylcyclopropanecarboxylate) Mustang Maxx (FMC Corporation, Philadelphia, PA) was applied at a rate of 1.75 L ha^{-1} to environments surpassing soybean aphid (*Aphis glycines* Matsumura) and grasshopper (Orthoptera: Acrididae) thresholds as described by NDSU.

Soil series taxonomy and land information is shown in Table 2. The soil at the NW22 location is a complex of Fargo and Ryan silty clay (USDA, 2018b). Both are naturally poorly or very poorly drained and slowly permeable. The soil without tile drainage has a relatively low crop productivity index rating and is not considered prime farmland. The soil’s natural fertility is somewhat limited, and nutrient leaching is rated as very limited. The parent material of the soil is clayey glaciolacustrine deposits.

Table 1. Dates of important measurements and field operations at NW22, Casselton and Prosper, ND, and Ransom, Sargent, and Steele counties, ND, in 2017 and 2018.

	Fargo	Casselton	Prosper	Ransom	Sargent	Steele
	---------------------------------Date---------------------------------					
			2017			
Soil test/fertilize/plant	8-May	10-May	-	12-May	12-May	15-May
First herbicide application	12-Jun	12-Jun	-	16-Jun	16-Jun	16-Jun
Second herbicide application	15-Jul	15-Jul	-	15-Jul	15-Apr	15-Jul
Insecticide 1	18-Aug	18-Aug	-	18-Aug	18-Aug	18-Aug
Insecticide 2	24-Aug	-	-	24-Aug	24-Aug	-
Stand count 1	24-May	26-May	-	31-May	31-May	1-Jun
Stand count 2	25-May	27-May	-	7-Jun	7-Jun	7-Jun
Stand count 3	26-May	30-May	-	14-Jun	17-Jun	14-Jun
Stand count 4	27-May	1-Jun	-	-	-	-
Stand count 5	29-May	2-Jun	-	-	-	-
Stand count 6	30-May	5-Jun	-	-	-	-
Stand count 7	1-Jun	8-Jun	-	-	-	-
Stand count 8	2-Jun	16-Jun	-	-	-	-
Stand count 9	5-Jun	-	-	-	-	-
Stand count 10	8-Jun	-	-	-	-	-
Stand count 11	16-Jun	-	-	-	-	-
Fall stand count	19-Sep	27-Sep	-	22-Sep	22-Sep	24-Sep
Vigor 1	26-Jun	30-Jun	-	29-Jun	29-Jun	29-Jun
Vigor 2	13-Jul	13-Jul	-	11-Jul	11-Jul	11-Jul
Canopeo	13-Jul	7-Jul	-	11-Jul	11-Jul	11-Jul
IDC	26-Jun	-	-	-	-	-
Height measurement	19-Sep	27-Sep	-	22-Sep	22-Sep	24-Sep
Harvest	9-Oct	4-Oct	-	5-Oct	30-Sep	4-Oct
			2018			
Soil test/fertilize/plant	14-May	-	11-May	-	11-May	15-May
First herbicide application	13-Jun	-	4-Jun	-	4-Jun	5-Jun
Second herbicide application	2-Jul	-	21-Jun	-	28-Jun	21-Jun
Insecticide 1	12-Jul	-	2-Aug	-	24-Jul	2-Aug
Insecticide 2	11-Aug	-	-	-	-	-
Stand count 1	23-May	-	23-May	-	23-May	27-May
Stand count 2	24-May	-	24-May	-	25-May	30-May
Stand count 3	25-May	-	25-May	-	27-May	1-Jun
Stand count 4	26-May	-	26-May	-	6-Jun	6-Jun
Stand count 5	27-May	-	27-May	-	-	-
Stand count 6	29-May	-	29-May	-	-	-
Stand count 7	31-May	-	31-May	-	-	-
Stand count 8	6-Jun	-	7-Jun	-	-	-
Stand count 9	-	-	-	-	-	-
Stand count 10	-	-	-	-	-	-
Stand count 11	-	-	-	-	-	-
Fall stand count	7-Sep	-	13-Sep	-	13-Sep	14-Sep
Vigor 1	28-Jun	-	Jun-18	-	28-Jun	2-Jun
Vigor 2	17-Jul	-	17-Jul	-	28-Jun	17-Jul
Canopeo	14-Jul	-	28-Jun	-	17-Jul	2-Jul
IDC	14-Jul	-	-	-	-	-
Height measurement	7-Sep	-	21-Sep	-	13-Sep	26-Sep
Harvest	18-Sep	-	24-Sep	-	1-Oct	28-Sep

Table 2. Soil series, soil taxonomy, previous crop and productivity index for NW22, Casselton and Prosper, ND, and Ransom, Sargent, and Steele counties, ND, in 2017 and 2018.

Location	Soil Series†	Soil Taxonomy†	Prev. Crop†	PI†
Fargo	Fargo-Ryan	Fine, smectitic, frigid Typic Epiaquerts	‡Wheat	67
		Fine, smectitic, frigid Typic Natraquerts		
Casselton	Kindred-Bearden	Fine-silty, mixed, superactive, frigid Typic Endoaquolls	Soybean	92
		Fine-silty, mixed, superactive, frigid Aeric Calciaquolls		
Prosper	Bearden-Lindaas	Fine-silty, mixed, superactive, frigid Aeric Calciaquolls	Wheat	94
		Fine, smectitic, frigid Typic Argiaquolls		
Ransom	Barnes-Svea	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls	§Corn	85
		Fine-loamy, mixed, superactive, frigid Pachic Hapludolls		
Sargent	Hamerly-Tonka	Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls	Corn	64
		Fine, smectitic, frigid Argiaquic Argialbolls		
Steele	Fram-Wyard	Coarse-loamy, mixed, superactive, frigid Aeric Calciaquolls	¶Dry Bean	48
		Fine-loamy, mixed, superactive, frigid Typic Endoaquolls		

†Soil data from (USDA, 2018b). Prev. Crop = Previous Crop, PI = Crop Productivity Index.
‡*Triticum aestivum* (L.) emend. Thell.
§*Zea mays* (L.).
¶*Phaseolus vulgaris* (L.).

The Casselton experiment site was located to the west of Casselton, ND. The soil is a mixture of Kindred and Bearden silty clay loams with 0 to 2 percent slopes. Both are naturally somewhat poorly drained and are considered prime farmland. The parent material of the soil is fine-silty glaciolacustrine deposits (USDA, 2018b).

The Prosper environment is a complex of Bearden and Lindaas silty clay loams with 0 to 2 percent slopes. It is considered prime farmland if drained with a crop productivity index of 94. The parent material of the soil are fine-silty glaciolacustrine deposits (USDA, 2018b).

Ransom county experimental location is a Barnes and Svea loam. This soil complex has a fine-loamy till parental material. The soils have a 0 to 3 percent slope, are well drained, and are prime farmland (USDA, 2018b).

The Sargent county experimental site is a Hamerly and Tonka complex with 0 to 3 percent slopes. It is somewhat poorly drained yet still considered prime farmland if drained. The parent material is fine-loamy till and local alluvium over till (USDA, 2018b).

The Steele county research location is a Fram and Wyard complex soil series. This complex has 0 to 3 percent slopes, somewhat poorly drained, and is considered prime farmland. The parent material is coarse-loamy till and local alluvium over till (USDA, 2018b).

Row Spacing and Seeding Rate Study

Soybean seed used was from a single company to reduce maturity group inconsistencies between varieties. A ragdoll germination test was conducted using a moist paper towel at room temperature for 5 d to find seed germination percentage. Seeds with radicle formation were considered germinated. Proper planting rates were determined from the results to achieve the targeted live seed seeding rates. Soybean seeds were counted with a seed counter to ensure precise live seed seeding rates. The soybean seeding rates used for the factorial arrangement were 197 600, 247 000, 296 400, 345 800, 395 200, 444 600, and 494 000 live seed ha^{-1}. A 543 400 live seed ha^{-1} rate was also used, but was not applied to each row spacing equally in all environments due to lack of experimental area. Table 3 displays soybean variety information and related agronomic descriptions.

Table 3. Soybean varieties used and descriptive features.

Variety	Company	Maturity	NDSU IDC†	Company IDC	SCN‡	Canopy	Height	Location§
0434	Asgrow	0.4	2	4	S	Medium	Medium	Steele 2017
0536	Asgrow	0.5	2	2	R	Medium	Medium Tall	NW22 2017
0835	Asgrow	0.8	1.9	3	R	Bushy	Medium Tall	NW22 2017, Casselton, 2017, Ransom 2017
0934	Asgrow	0.9	-	4	R	Medium	Medium Short	Sargent 2017 and 2018
05X8	Asgrow	0.5	-	3	R	Medium	Medium Tall	NW22 2018
08X8	Asgrow	0.8	-	4	R	Medium	Medium Tall	NW22 2018, Prosper 2018
03X7	Asgrow	0.3	-	3	R	Medium	Medium	Steele 2018

† IDC = iron deficiency chlorosis. NDSU IDC scored on 1-5 scale (1=green, 5=dead) from Goos and Johnson (2008). Company IDC scored on 1-9 scale (1=green 9=dead).
‡SCN = soybean cyst nematode. R=resistant.
§Casselton and Prosper, ND. Ransom, Sargent, and Steele counties, ND.

Plots were planted as soon as field conditions were favorable in early to mid-May using a four row plot planter with a 30 cm row spacing or using two rows with 61 cm row spacing. The plots were planted with a Hege 1000 no-till planter (Hege Company, Waldenberg, Germany). Seeds were sown to a depth of approximately 3 cm.

After planting the treatments, soybean emergence was routinely observed beginning as soon as the first plants emerged (Table 1). Emerged plants were counted by selecting a length of 1 m along the planted soybean row. In order to maintain consistent plant density observations within the experimental unit, two stakes were placed 1 m apart within the soybean rows. Soybean plants emerging right next to the stake, and that were in the same horizontal plane of the stake, were not considered as part of the emergence count. Soybean emergence counts were performed on the 2 innermost rows of each treatment (4 row plots) or in each of the rows of the two row (61 cm row spacing). The selected area was away from the border of the trial to eliminate the border effect. Emerging plants were not considered emerged until soybean cotyledons were no longer in contact with the soil surface. Emergence data in the NW22, Casselton, and Prosper environments were recorded as regularly and consistently as possible at one to two d intervals until emergence was completed, which was approximately 40 d after planting. Soybean emergence from county locations were recorded 7, 14, and 21 d after planting. The emergence index (EI) was calculated using the formula $EI = A\left(\frac{1}{x}\right) + \cdots + A\left(\frac{1}{N}\right)$ where A is the number of emerged cotyledons, X is the number of days after intial emergence, and N is the number of days to the last day emergence was counted, as described by Anfinrud and Schneiter (1984). Emergence was defined as at least one plant emerged in the observed area.

Growing degree days (GDD), which depend on daily minimum and maximum temperatures, were used to explain emergence. Soybean GDD were retrieved from the corn GDD model supplied by (NDAWN, 2018). The corn GDD model uses base threshold temperature of 10°C to calculate GDD for each day. GDD were accumulated beginning at soybean planting.

Throughout the growing season, plant density reducing events were also observed and recorded. Soybean plant densities were observed again before harvest to determine final harvestable plant density. Using plant densities from plant establishment, percent plant loss was determined using the formula $L = \frac{E - F}{(E/100)}$ where L is percent plant loss, E is established plant density, and F is final plant density.

During the growing season, vigor, IDC, and Canopeo (Canopeo, Oklahoma State University, Stillwater, OK) were recorded. Vigor scores were recorded at the V2-V3 (2 to 3 leaf trifoliolate stages [Fehr et al., 1971]) and the V5 to V6 stages. Vigor scores were on a scale ranging from 1 to 9 with 1 being the lowest score and 9 being the highest obtainable score. The scores were a visual assessment for potential yield of the soybean plots. The scores were based on relative vigor within a replicate meaning only one plot achieved the maximum and minimum score. Remaining plots were scored relative to the best and worst plots for consistency.

IDC ratings were made visually on a 1 to 5 scale, with 1 representing no chlorosis and 5 the most severe chlorosis (Rodriguez de Cianzio et al., 1979). IDC ratings were taken from the V2 to V3 stages. Canopeo measures the fractional green canopy cover (FGCC) through an image processed through the Canopeo application providing a green canopy coverage percentage (Patrignani and Ochsner, 2015). Canopeo pictures were taken approximately 1.5 m from the soil surface. Images were captured in the middle of the plot to retain consistency. Matlab (MathWorks, Inc., Natick, MA) was used to measure the canopy cover by FGCC. The Canopeo canopy coverage data was recorded at the V5 to V6 stage, before the reproductive phase.

Plant heights were obtained prior to harvest at physiological maturity. Three separate measurements from the soil surface to the uppermost node on the plant were recorded within each plot. Measurements were then averaged.

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 using a Clipper seed cleaner (Ferrell-Ross, Bluffton, IN), and the seed samples were then weighed for yield on a Mettler Toledo XS6001S scale (Mettler-Toledo, LLC, Columbus, OH). A Perten Instruments DA 7250 NIR analyzer was utilized to measure the oil and protein content (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.

Weather data for the 2017 and 2018 growing seasons were obtained from the North Dakota Agricultural Weather Network (NDAWN) to provide monthly maximum and minimum air temperatures and total precipitation amounts. Weather data for the NW22 (Fargo) location was collected from the NDAWN in Fargo, ND (46.897°, -96.812°). Weather data for Casselton and Prosper, ND were collected from NDAWN weather station near Prosper, ND (47.002°, -97.115°). Ransom, Sargent, and Steele county locations collected weather data at NDAWN weather stations Lisbon, ND (46.445°, -97.721°), Oakes, ND (46.074°, -98.093°), and Mayville, ND (47.498°, -97.262°), respectively.

Statistical analysis was conducted for a randomized complete block design (RCBD) with a two-factor (row spacing and seeding rate) factorial arrangement. Data and dependent variables were analyzed PROC GLM and Type 3 ANOVA tests were used to analyze treatment data with statistical software SAS (SAS Institute Inc., Cary, NC). Row spacing and seeding rates were analyzed as fixed factors. Row spacing levels were 30 and 61 cm. Seeding rate levels were 197 600, 247 000, 296 400, 345 800, 395 200, 444 600, and 494 000 live seed ha^{-1}. All other factors such as rep and environment were random variables. In order to combine the RCBD factorial data at NW22 with other environments, NW22 research location was separated into naturally drained (NAD) and controlled tile drainage (CTD) data. The drained and undrained data was further divided into individual varieties at the NW22 location, creating four environments at NW22 per year. The environments at NW22 are NAD 1, NAD 2, CTD 1, and CTD 1. A 543 400 live seed ha^{-1} rate was applied to both row spacing levels for the NAD 1 and CTD 1 environments in 2017 and 2018. Each environment was first analyzed independently, and the data for 2017 and 2018 was analyzed separately. Homogeneity of variance was confirmed by comparing the error means squared for each measured agronomical trait observation to ensure they were within a factor of 10. Combinable data was analyzed over all environments possible, using procedures described by Carmer et al. (1989).

Table 4. ANOVA of factorial study for row spacing and seeding rate at Casselton and Prosper, ND, and Ransom, Sargent, and Steele counties, ND.

SOV†	df‡ equation	df
Rep	(r-1)	3
Row Spacing [RS]	(RS-1)	1
Seeding Rate [SR]	(SR-1)	6
RS*SR	(RS-1)(SR-1)	6
Error	(r-1)[(RS)(SR)-1)]	39
Total	r(RS)(SR)-1	55

†SOV=Source of variation.
‡df=Degrees of freedom.

Treatment means were separated using a Fisher's protected least significant difference (LSD) at a 95% level of confidence (α=0.05). Means separation for environments and combined data used their respected LSD values. The ANOVA table displays the source of variation (SOV) and degrees of freedom (df) in the factorial study at NW22 (Table 4). The ANOVA table also represents other environments tested. The 543 400 live seed ha^{-1} seeding rate is not included in the factorial analysis, but the mean is used for comparison between seeding rates and regression analysis.

North Dakota Soybean Survey Field Observations

The NDSS paper survey was distributed to participating soybean producers throughout North Dakota. The survey requested information on various management decisions to represent the differing soybean production techniques currently used in North Dakota. In addition, the survey provided soybean yield to the corresponding fields submitted. Participating soybean producers were recruited through the extensive networks of the county extension agents, North Dakota Soybean Council, and North Dakota Soybean Growers Association representatives. The survey was conducted for the 2014 to 2017 growing seasons.

Completed and returned surveys were input into an Excel database (Microsoft Office 2013, Redmond, Washington). US legal land description (Public Land Survey System, US Bureau of Land Management) was converted to global positioning system (GPS) coordinates using Earth Point Software (Earth Point, Boise, Idaho). Fields were assigned identification numbers relative to their submission order. Submitted soybean fields were visited on two occasions during the 2016 and 2017 growing season to estimate plant densities and obtain a Canopeo reading. Producers were contacted prior to field visits to confirm field visits were allowed on their property. The first field visit took place prior to flowering (R1) while the late season visit was between the R4 and R6 stages. Observations were recorded in three representative sample locations throughout each field. Sampled Locations within each field were >36 m from a field border or other sample site, and headland rows were avoided. Plant densities were estimated by counting all established and living plants within a 2.74 m row length regardless of row spacing in three sample locations within each field. The row spacing was measured in cm for each field to calculate the field's established plant density.

During the early season observation, three photographs were taken at each sample location, approximately 1.5 m from the soil surface, and images were processed using Canopeo App. Canopeo data were recorded at the V1 to V5 stage using Matlab for conversion to canopy cover. The three Canopeo readings were then averaged to record mean Canopeo readings for each field.

Data was collected from 214 North Dakota soybean producer fields in 2016 (n=99) and 2017 (n=115). The number of field visit data points used for seeding rate, established plant density, final plant density, and in-season loss were 195, 197, and 205, and 191, respectively. Number of observed fields varied due to incomplete paper surveys from the NDSS or a low number of observation points per grouping. Seeding rate data were grouped in 10 000 live seed ha^{-1} increments beginning at 360 000 live seed ha^{-1}, and plant density data was grouped in 10 000 plants ha^{-1} increments. Groupings were considered in the regression analysis with a minimum of 5 observations. Number of observations per grouping for seeding rate, established plant density, final plant density, and in-season loss ranged from 10 to 33, 5 to 36, 10 to 37, and 6 to 28, respectively. Both established and final plant density grouping increments began at 220 000 live seed ha^{-1}. Field data used means from grouped increments. Experimental research data was grouped similarly for seeding rate, established and final plant density, and in-season loss. Experimental seeding rates and plant densities were grouped in 49 400 live seed ha^{-1} and plant ha^{-1} increments. Experimental research data used means to express seeding rate and plant densities for regression. Experimental research seeding rates contained 120 observations each aside from the 543 400 live seed ha^{-1} having 60 observations. SAS (PROC REG) analyzed linear and quadratic least squares regression analysis on least squares means only and evaluated relationships between soybean seeding rates, plant establishment, stand loss, Canopeo readings, and yield field visit data. Seeding rates and yield information were obtained from reported NDSS forms. Plant densities and Canopeo readings were obtained from field visits. Regression models used the coefficient of regression (r^2), to explain variation around the trendline.

Economic Analysis

An economic analysis will provide North Dakota soybean producers with estimated net revenue for row spacing and seeding rate. Soybean market prices used represent a range of expected grain prices currently and into the future. The market prices used do not consider any basis and solely reflect market value. Seed costs were obtained from Duffy (2018) who estimated herbicide tolerant seed prices to be $52 per soybean unit (140 000 seeds). Price per seed was calculated and multiplied by seeding rate to obtain seed costs. Net revenue was calculated by subtracting seed cost from gross revenue (yield multiplied by estimated market price). Net revenue in dollars was analyzed using PROC GLM and Type 3 ANOVA tests were used to analyze treatment data with statistical software SAS. Row spacing and seeding rate were considered fixed effects. Means were separated using a Fisher's protected LSD at a 95% level of confidence (α=0.05). Environments were combined as error mean squares for net revenue in each environment were homogenous and within a factor of 10. The data was analyzed over 15 environments from 2017 and 2018 using procedures described by Carmer et al. (1989).

RESULTS AND DISCUSSION

Weather Data

In 2017, Fargo received less than normal precipitation in May, June, July, and August (Table 5). Rainfall in 2017 was above normal in September. The 2017 mean monthly average maximum and minimum air temperatures were above normal in June and July, but August of 2017 was cooler than normal. The 2018 growing season was warmer than normal and experienced higher than normal rainfall in comparison to the historical data (Table 5). Although the 2018 growing season experienced above average rainfall, the above normal minimum air temperatures caused crops to show above ground drought symptoms in August.

The 2017 Casselton experimental site had less than normal precipitation throughout the season until September (Table 5). Lack of rainfall accompanied less than normal air temperatures after planting in May as well as in August. Air temperatures were normal in June and July. Prosper experimental site had less than normal precipitation throughout the growing season except for August 2018. Air temperatures were higher than normal in May and June except for August 2018, which was cooler than normal.

Ransom County had less than normal precipitation in the early season for 2017 from May to July (Table 5). August and September of 2017 had higher than normal precipitation amounts. Air temperatures for June were above normal whereas August was below normal in 2017.

Sargent County had less than normal precipitation from May, June, July, and September of 2017 (Table 5). Air temperatures in 2017 were similar to normal aside from June being above normal and August observing less than normal temperatures. Precipitation in 2018 was less than normal in May and August while June and July were above the normal rainfall amount. The early season air temperatures were higher in 2018 than normal while the late season temperatures were less than normal.

Table 5. Mean monthly air temperatures and precipitation during the growing season in 2017 and 2018 for each environment.

	Max Air Temp			Min Air Temp			Precipitation		
Month	2017	2018	Norm.†	2017	2018	Norm.	2017	2018	Norm.
	------ºC------			------ºC------			------mm------		
				Fargo					
May	21	25	21	7	10	7	27	44	71
June	26	27	25	13	16	13	58	123	99
July	29	28	28	16	16	15	23	81	71
Aug	25	27	27	13	15	14	58	101	65
Sept	22	21	22	11	9	9	70	65	65
Total							235	414	371
				Casselton and Prosper					
May	21	25	21	6	9	6	17	54	77
June	26	27	25	12	14	12	88	79	100
July	28	27	28	14	14	14	50	65	88
Aug	25	27	28	11	12	13	53	79	67
Sept	22	21	22	8	7	8	152	71	66
Total							359	348	398
				Sargent					
May	20	25	21	7	10	7	32	24	75
June	27	27	26	13	15	13	51	91	80
July	29	27	29	15	15	15	17	96	80
Aug	25	27	28	13	13	14	97	21	54
Sept	22	21	22	9	8	8	54	52	65
Total							251	283	354
				Steele					
May	20	25	20	6	8	6	25	38	68
June	26	28	25	12	14	12	89	64	95
July	28	28	27	14	13	14	65	56	82
Aug	25	27	27	11	11	13	9	80	65
Sept	22	18	21	9	7	7	99	36	54
Total							287	274	364
				Ransom					
May	21	25	21	6	10	6	37	24	75
June	27	27	25	12	15	12	54	90	96
July	29	27	29	15	15	14	22	96	82
Aug	25	27	28	12	13	13	98	21	60
Sept	22	21	22	9	8	7	72	45	64
Total							284	276	377

†Norm = Normal, represents a 30-yr average from 1981-2010. Data obtained from North Dakota Agricultural Weather Network.

The Steele County experimental site had less than normal monthly rainfall for the 2017 growing season except for September (Table 5). The 2017 air temperatures were higher than normal in June, July, and September while August was less than normal. The 2018 growing season observed less than normal precipitation in the early to mid-growing season. Air temperatures in 2018 were higher on average for the first half of the growing season.

Soybean Emergence Study

Soybean growing seasons in 2017 and 2018 were considerably different between the years from planting to establishment. Precipitation in May, 2017 was less than in May, 2018 which was observed in soybean emergence differences. Soybean emergence plant density observations from 2017 and 2018 were combined within their respective year.

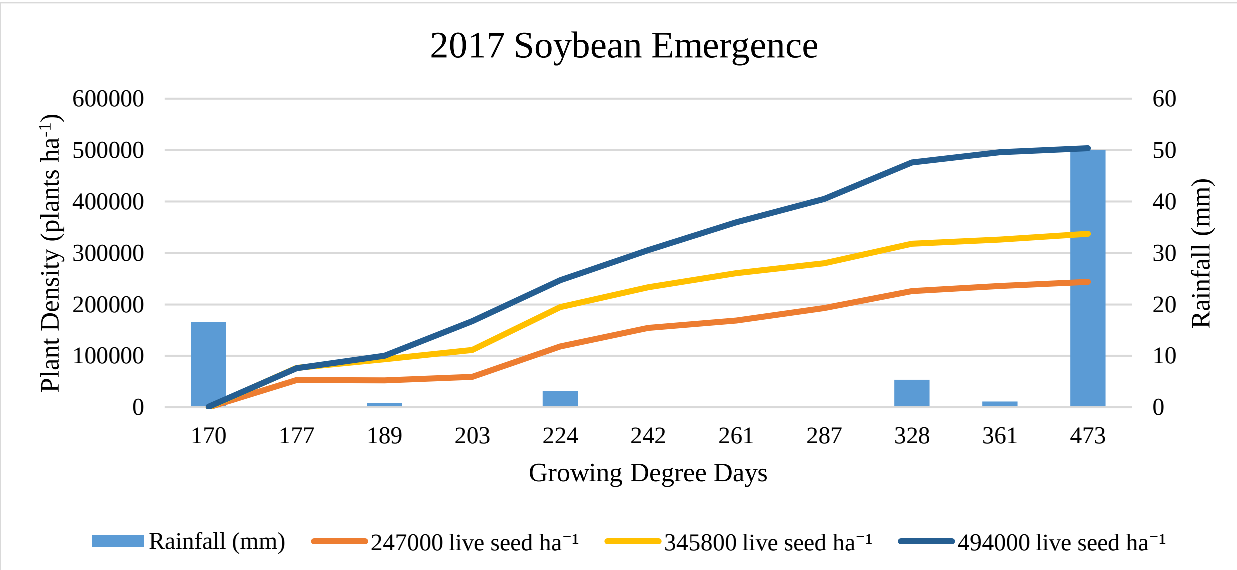

Figure 1. Soybean emergence in 2017.
Soybean plant densities observed with corresponding growing degree days (GDD) and recorded rainfall events in 2017.

Soybean emergence advanced at a slow rate (Figure 1) likely due to reduced soil (0 to 3 cm) moisture extending from the previous growing season through soybean emergence in 2017. The first soybean emergence was observed 16 d after planting in 2017 and after receiving 15mm rainfall. Emergence slowly progressed with limited soil moisture and the slow accumulation of GDD observed in an EI of 12, averaged across all seeding rates (Table 6). In general, higher EI values represent higher emergence rates. Overall, 90% emergence occurred from 287 to 328 GDD in 2017 (Table 7). Absolute plant densities observed during emergence differentiated between seeding rates with additional GDD. Plant densities as a percent of the established density did not differ between seeding rates (Figure 2).

Table 6. Mean emergence index (EI) averaged across seeding rates for combined environments in 2017 and 2018.

live seed ha^{-1}	2017		2018	
197 600	7	c†	11	d
247 000	7	cd	13	d
296 400	9	bc	17	c
345 800	12	b	20	c
395 200	15	a	24	b
444 600	14	a	26	ab
494 000	16	a	27	a
Mean	12		22	
LSD (0.05)	3		3	

†Means in a column, within a year, followed by the same letter are not significantly different at ($P \leq 0.05$).

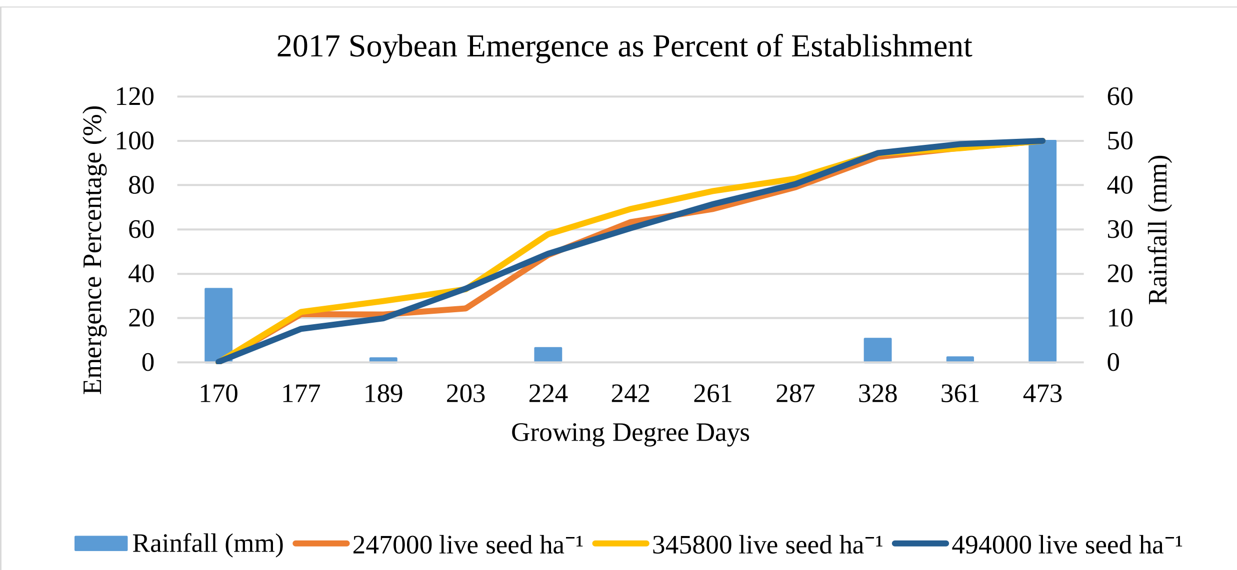

Figure 2. Soybean emergence as percent of establishment in 2017.
Soybean plant densities as a percentage of established plant density observed with corresponding growing degree days (GDD) and recorded rainfall events in 2017.

Growing conditions in 2018 were considered more conducive for plant establishment (Figure 3). Approximately 35mm precipitation between soybean planting and the first recorded emergence resulted in a mean EI of 22 (Table 6). Plant densities quickly established with max air temperatures 4°C above normal. Rapid GDD accumulation resulted in 90% emergence observed between 151 to 162 GDD (Table 7). Similar to 2017, 2018 did not show any differences between seeding rates as a percent of established plant density (data not shown).

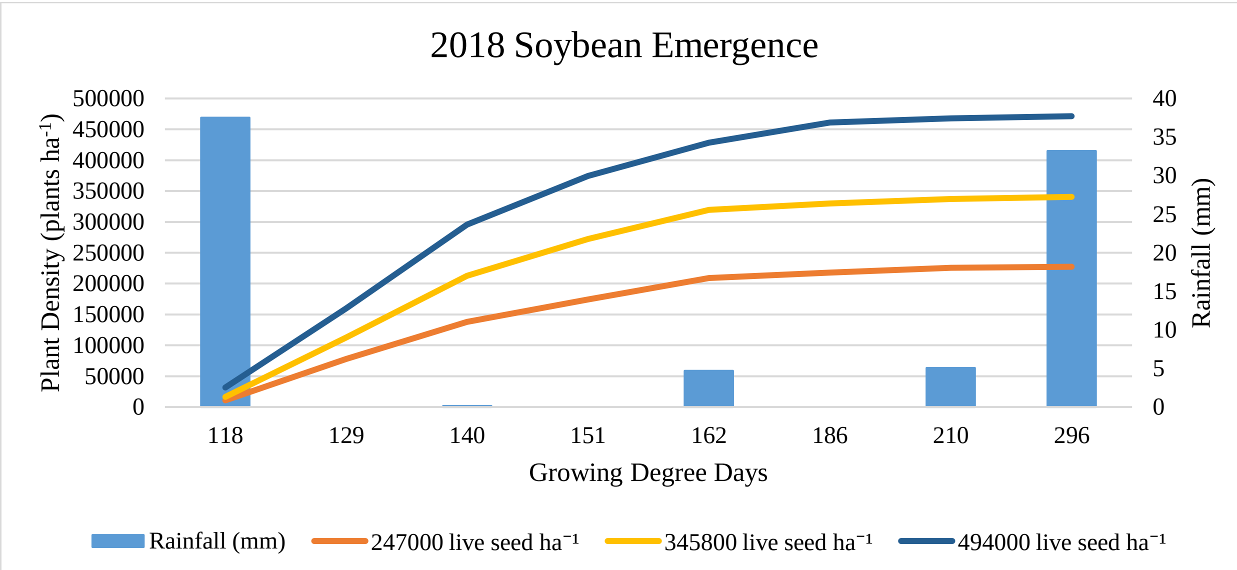

Figure 3. Soybean emergence in 2018.
Soybean plant densities observed with corresponding growing degree days (GDD) and recorded rainfall events in 2018.

Table 7. Mean accumulated growing degreed days (GDD) required to 50% and 90% soybean emergence in 2017 and 2018 experimental locations.

		% Emergence	
Location	Year	50	90
	2017	GDD	
NW22		239 - 264	277 - 318
Casselton		185 - 221	245 - 257
Combined		203 - 224	287 - 328
	2018		
NW22		126 - 137	148 - 172
Prosper		131 - 142	164 - 176
Combined		129 - 140	151 - 162

Differing early-growing season environments in 2017 and 2018 allows for soybean emergence comparisons between environments with less than normal and similar to normal rainfall. Soybean emergence in 2017 required more time for plant establishment than in 2018 and experienced an EI 10 units less (Table 6). Emergence in 2017 required over 60 GDD more to achieve 50% emergence than in 2018 (Table 7). Furthermore, an additional 100 GDD were needed for 90% emergence in 2017 compared to 2018 (Table 7). Dry conditions considerably lengthened time to soybean establishment compared to a year experiencing sufficient quantities of rain between planting and establishment.

Emergence in 2018 required 129 to 140 GDD to achieve 50% emergence and 151 to 162 GDD to 90% emergence (Table 7). This information is similar to Conley and Gaska, (2008) who found 50% and 90% emergence to occur at 130 and 155 GDD, respectively. This data suggests environments experiencing early season drought or limited soil moisture should expect greater lengths and additional GDD to plant establishment. Alternatively, environments with adequate and well-timed rainfall prior to and during soybean establishments should experience more rapid plant establishment.

Row Spacing and Seeding Rate Experiment

Agronomic data from the 15 environments were analyzed, and residual mean squares were homogenous for all environments. Therefore, all environments were combined for analysis. Levels of significance for row spacing, seeding rate, and their interactions are provided in Table 8.

Row Spacing

Table 8 indicates there were no significant differences between established plant density and final plant density for row spacing in combined environments. Previous research in the upper Midwest observed that narrow row spacing can have greater plant establishment at similar seeding rates due to less competition within a row than in a wide row spacing (Oplinger and Philbrook, 1992; Elmore, 1998).

Early vigor (V2 to V3) and late vigor (V5 to V6) were significantly different between row spacing (Table 8 and 9). Plants in the 61 cm row spacing were more vigorous than the 30 cm row spacing for both early and late vigor scoring. Early vigor scores were similar between row spacing in 2017 (data not shown). Late vigor scores 5.0 for 30 cm, and 5.9 for 61 cm row spacing treatments, were significantly different across all 2017 environments. The late vigor score in 2018 for the 61 cm row spacing (5.6), observed a higher score than the 30 cm treatment (5.3). Plants in 61 cm row spacing are closer together within the row increasing the observed heights. Row spacing differences can also be attributed to less than normal early season precipitation prior to vigor score observations. Dry environmental conditions limited plant growth allowing row spacing differences to be undistinguishable in 2017. Above normal temperatures and well-timed early season precipitation created an environment more conducive to growth in 2018, which was observed in the difference of row spacing vigor scores.

Canopeo ratings were significantly greater for 30 cm row spacing (Table 9) and observed 6% more canopy coverage when compared with the 61 cm row spacing soybean at V5 and V6 Narrow row spacing as a management practice attempts to maximize light interception and soybean crop yield (Board et al., 1990; Wells, 1991). Plants within the 30 cm row spacing observed more spacing between plants within the row allowing for more branching. In turn, increased branching in narrow row spacing resulted in more canopy coverage in 30 cm row spacing than the 61 cm row spacing.

Narrow row spacing caused plants just before harvest to be 2 cm shorter than in wide row spacing. Soybean grain yield was 183 kg ha^{-1} greater in narrow row spacing than wide row spacing. These findings are similar to Oplinger and Philbrook, (1992) who found yield decreased as row spacing increased.

Table 8. Sources of variation, degrees of freedom, and levels of significance for the ANOVA of agronomic traits for 15 environments in 2017 and 2018.

SOV[†]	df	df[‡]	df[§]	ES	FS	EV	LV	IDC[¶]	CP	HT	Yield	PC	OC	2017 EI[§]	2018 EI[§]	Loss
Env [Environment]	14	7	4													
Rep(Env)	42	21	15													
Row [Row Spacing]	1	1	1	ns	ns	***	**	ns	***	*	***	ns	ns	***	*	**
Env*Row	14	7	4	ns	ns	*	***	ns	***	***	***	ns	ns	***	*	ns
Rate [Seeding Rate]	6	6	6	***	***	***	***	***	***	***	***	***	***	***	***	ns
Env*Rate	84	42	24	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns
Row*Rate	6	6	6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns
Env*Row*Rate	84	42	24	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CV %				27.3	17.8	29.3	24.7	21.4	11.8	6.7	11.0	1.7	1.8	36.7	19.0	100.1
Residual Error	588	315	195													

ns, *, **, *** = not significant, significant at ($P \leq 0.05$), ($P \leq 0.01$), and ($P \leq 0.001$), respectively.

[†]SOV = source of variation, df = degrees of freedom, ES = established stand, FS = final stand, EV = early vigor, LV = late vigor, IDC = iron deficiency chlorosis, CP = canopeo, HT = plant height, PC = protein content, OC = oil content, EI = emergence index.

[‡]df for eight combined environments at NW22 due to no visual IDC differences at other environments.

[§]df for five combined environments in both 2017 and 2018.

[¶]IDC is averaged over eight environments at NW22 due to no visual differences at other environments.

Table 9. Mean agronomic trait observations for two row spacings averaged across seven seeding rates and 15 environments.

Row Spacing	ES[†]		FS		EV		LV		IDC[‡]		CP		HT		Yield		PC		OC		2017 EI		2018 EI		Loss	
cm	plants ha^{-1}				1 - 9[§]				1 - 5[¶]		%		cm		kg ha^{-1}		g kg^{-1}								%	
30	333 872	a	314 399	a	5.2	b	5.2	b	2.3	a	68	a	76	b	3145	a	331.3	a	181.3	a	8	b	13	b	5.6	b
61	340 077	a	312 003	a	5.5	a	5.7	a	2.3	a	62	b	78	a	2962	b	331.3	a	181.3	a	15	a	27	a	7.6	a

Within columns, means followed by the same letter are not significantly different at ($P \leq 0.05$).

[†]ES = established stand, FS = final stand, EV = early vigor, LV = late vigor, IDC = iron deficiency chlorosis, CP = canopeo, HT = plant height, PC = protein content, OC = oil content, EI = emergence index, Loss = in-season plant loss.

[‡]IDC is averaged over eight environments at NW22 due to no visual differences at other environments

[§]Visual vigor score, with 9 being the most vigorous.

[¶]Visual scale from Goos and Johnson (2008), with 5 being the most chlorotic.

The emergence index was significantly greater in 2018 than 2017 for both 30 cm and 61 cm row spacing (Table 9). The 2018 environments (Fargo and Prosper) provided conditions more conducive for emergence as compared to 2017. Well timed rainfall in 2018 during emergence increased the emergence index for both 30 cm and 61 cm row spacing by 5 and 12, respectively, compared to 2017.

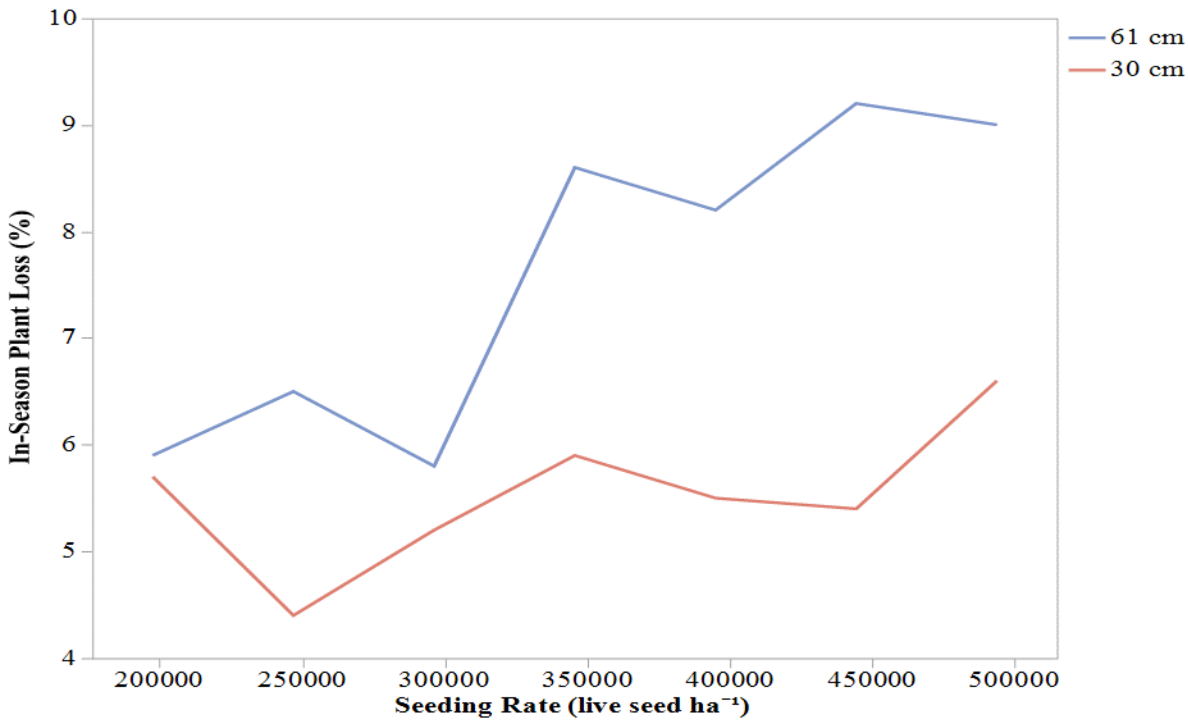

Figure 4. Row spacing and seeding rate effect on in-season plant loss for all 15 environments.

Plant loss was significantly different for row spacing with 61 cm row spacing experiencing 7.6% loss, which was 2.0% more than 30 cm row spacing although final plant densities were only 2000 plants apart and not significant (Table 9). Narrow row spacing observed less plant loss at all seeding rates compared to 61 cm row spacing (Figure 4). With a consistent seeding rate, intra-row plant distance is reduced as row spacing increase. Within 61 cm row plots, increased amounts of plants lacking pod formation, seed fill, and plant mortality were visually noted.

Environment x Row Spacing

Table 8 indicates that observations for row spacing were significantly different between environments for early vigor, late vigor, Canopeo readings, plant height, yield, and 2017 and 2018 emergence indices. The environment by row spacing interaction was determined to be due to differences in magnitude. Early vigor, late vigor, Canopeo percentages, plant heights, yields, and 2017 and 2018 emergence indices retained similar general trends in each environment (data not shown), but observations varied in magnitude between years. Environment was a key factor in determining the plant growth between the different experimental locations, which was observed in early and late vigor scores and Canopeo percentages. Due to the geographical locations of the experimental environments, weather patterns were unique between each environment across 2017 and 2018. Because vigor scores, Canopeo percentages, and plant heights all measure soybean vegetative growth, early season rainfall for each environment was a large factor contributing to the observed row spacing differences.

Seeding Rate

Seeding rate significantly influenced soybean plant growth as observed in established and fall plant densities, early and late vigor, and Canopeo percentage (Table 10). Increased seeding rates proportionally increased plant density at both the beginning and end of the growing season. In general, increasing seeding rates also resulted in greater vigor ratings. However, the mean for the 543 400 seeds ha^{-1} rate (data not shown) observed early vigor scores less than the 494 000 seeds ha^{-1} treatment. This decrease in vigor was confirmed by Canopeo readings indicating a reduction in canopy coverage with increased plant densities.

The 494 000 seeds ha^{-1} rate resulted in the significantly lowest IDC score while the 197 600, 247 000, and 296 400 seeds ha^{-1} rates experienced greater IDC stress (Table 10). Lower

IDC rating associated with more dense seeding rates is also supported by Goos and Johnson (2000).

Plant height at physiological maturity was the highest in the 494 000 live seed ha^{-1} seeding rate (Table 10). In general, plant height increased as the seeding rate increased. Oplinger and Philbrook, (1992) also noted the increase in plant height alongside seeding rate increases.

Soybean yield increased as seeding rate increased until a plateau was observed between 444 600 (Table 10) and 543 400 live seed ha^{-1} rates (data not shown). However, increased seeding rates reduces the spacing between plants within a row possibly causing yield reduction observed in the 543 400 live seed ha^{-1} seeding rate.

Soybean seed protein and oil content were significantly different for seeding rate. Data combined across 2017 and 2018 indicated increasing protein content as soybean seeding rate increased. These results are supported by Bellaloui et al., (2015) who found increasing seeding rate will increase seed protein content until a density of 400 000 plants ha^{-1} is achieved, thereafter protein contents are expected to decrease. Protein contents for 444 600, 494 000, and 543 400 live seed ha^{-1} seeding rates were 332, 334, and 333 g kg^{-1}, respectively. These protein contents show a protein increase as seeding rate increases. These findings contrast previous research reporting an inverse relationship between soybean yield and protein content (Hartwig and Hinson, 1972; Sebern and Lambert, 1984). According to Orlowski et al., (2017), early-season soybean stress can increase soybean protein content and reduce oil content.

Table 10. Agronomic observations averaged across seeding rate across all 15 environments.

Seeding Rate	ES[†]		FS		EV		LV		IDC‡		CP		HT		Yield		PC		OC		2017 EI		2018 EI		Loss
live seed ha^{-1}	plants ha^{-1}				1 - 9[§]				1 - 5[¶]		%		cm		kg ha^{-1}		g kg^{-1}								%
197 600	190 783	g	178 146	g	3.5	e	3.4	f	2.4	a	56	f	76	cd	2936	d	330	cd	182	a	6.7	d	11.2	d	5.8
247 000	232 086	f	217 701	f	4.2	d	4.3	e	2.5	a	60	e	77	bcd	2968	cd	330	d	181	ab	7.5	cd	13.3	d	5.5
296 400	281 676	e	266 110	e	4.8	c	5.0	d	2.4	a	63	d	76	d	3045	bc	330	cd	182	a	9.5	bc	17.0	c	5.5
345 800	327 937	d	302 733	d	5.2	c	5.7	c	2.3	ab	66	c	77	bc	3075	ab	332	bc	181	ab	11.7	b	19.7	c	7.3
395 200	399 970	c	372 525	c	6.0	b	6.2	b	2.2	cd	68	b	77	bc	3096	ab	331	cd	182	a	14.7	a	23.8	b	6.8
444 600	439 838	b	407 540	b	6.4	b	6.5	b	2.3	bcd	69	b	78	ab	3150	a	332	ab	181	bc	14.5	a	25.9	ab	7.3
494 000	486 536	a	447 648	a	7.1	a	7.0	a	2.1	d	72	a	79	a	3155	a	334	a	180	c	15.6	a	26.9	a	7.8
LSD (0.05)	6 036		6 231		0.5		0.4		0.2		2		1		101		1		1		2.7		2.7		ns

ns = not significant.

[†]ES = established stand, FS = final stand, EV = early vigor, LV = late vigor, IDC = iron deficiency chlorosis, CP = canopeo, HT = plant height, PC = protein content, OC = oil content, EI = emergence index.

[‡]IDC is averaged over eight environments at NW22 due to no visual differences at other environments.

[§]Visual vigor score, with 9 being the most vigorous.

[¶]Visual scale from Goos and Johnson (2008), with 5 being the most chlorotic.

Emergence indices for 2017 and 2018 were significantly different for seeding rate. The EI increased as seeding rate increased in both 2017 and 2018 despite environmental differences between the years. Emergence index was expected to increase due to seeding rates directly influencing plant density at establishment (Table 10).

Environment x Seeding Rate

Although Table 8 indicates the observations for seeding rate were significantly different between environments for the 2017 emergence index (Table 8), however, the relationship between the 2017 emergence index is sporadic and may not be a true interaction (data not shown). Environmental differences can be largely attributed to lack of rainfall before and after soybean planting (Table 5). Dry conditions provided inconsistent and varying emergence indices between environments and seeding rates obscuring the nature of the interaction.

Row Spacing x Seeding Rate

The interaction between row spacing x seeding rate significantly influenced 2018 EI. The EI describes the rate of emergence. The EI for the 444 600 live seeds ha^{-1} rate increased from 28 to 30 between the NAD 2 and CTD 2 environments. However, the 494 000 live seed ha^{-1} rate decreased from 32 to 29 between the NAD 2 and CTD 2 environments (data not presented). More research is required to better understand how EI responds to row spacing and seeding rate.

Soybean Survey Field Visits

Data from 2016-2017 soybean producer field visits were collected and compared to previously reported paper survey field data for 2014-2017. Soybean producers reported an average plant loss of 10% derived from seeding rate and established plant density data. This prompted further examination resulting in field observations conducted in 2016 and 2017 to confirm reported data.

Linear Regression Analysis for Canopeo and Yield

This section discusses field visit data for seeding rate and established plant density effects on Canopeo readings, and Canopeo reading effect on soybean yield. Soybean Canopeo readings were compared to seeding rate and established plant density from soybean survey field visit data. The three Canopeo readings per field were averaged, taken from VC to V3, were compared to grouped seeding rates from reported survey data and found a significant linear relationship (Table 11). As expected, Canopeo readings and seeding rate were highly related (r^2= 0.63). Increased seeding rates are likely to increase canopy coverage at early-season vegetative growth (Figure 5).

The effect of soybean established plant density on Canopeo percent was significant (Table 11). The positive relationship between established plant density and Canopeo readings was expected. However, Canopeo data was variable (Figure 6) as growth stages (VC to V3) and latitude (45.552° N to 48.977° N) varied between observed fields among many other variables such as planting date, varietal selection, and soil characteristics.

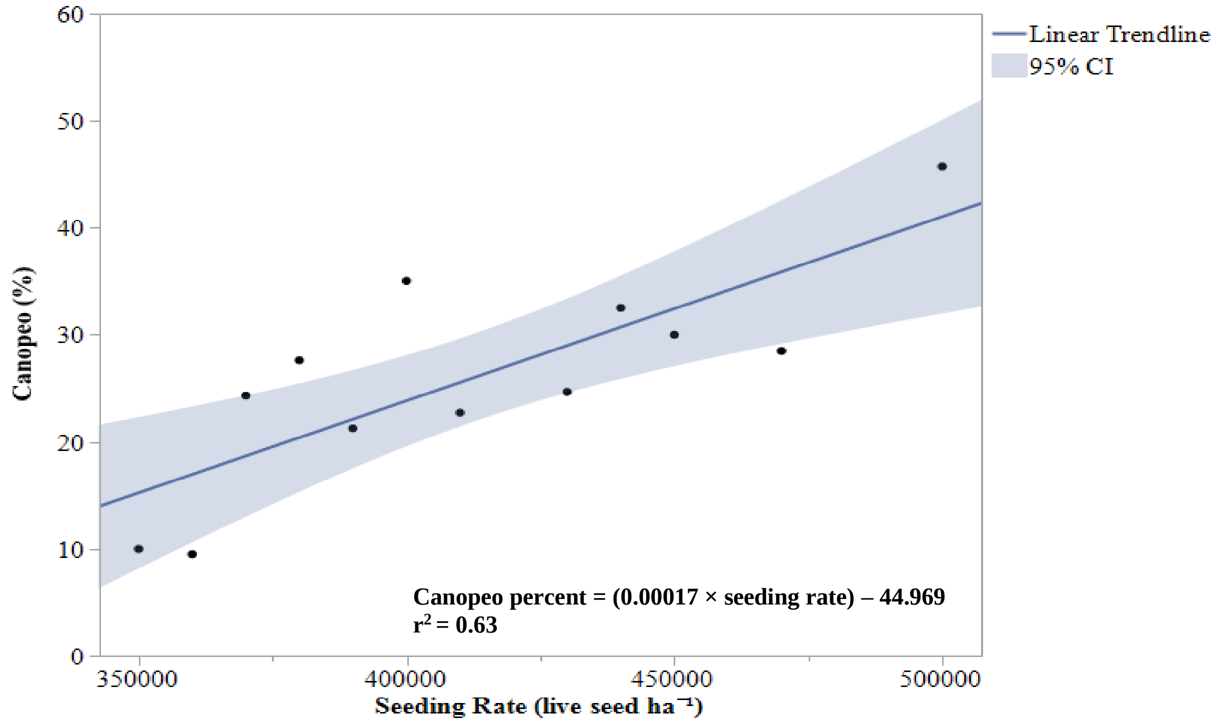

Figure 5. Seeding rate effect on Canopeo, 2016-2017.
Regression summary of soybean seeding rates and Canopeo readings in North Dakota Producer fields, 2016-2017.

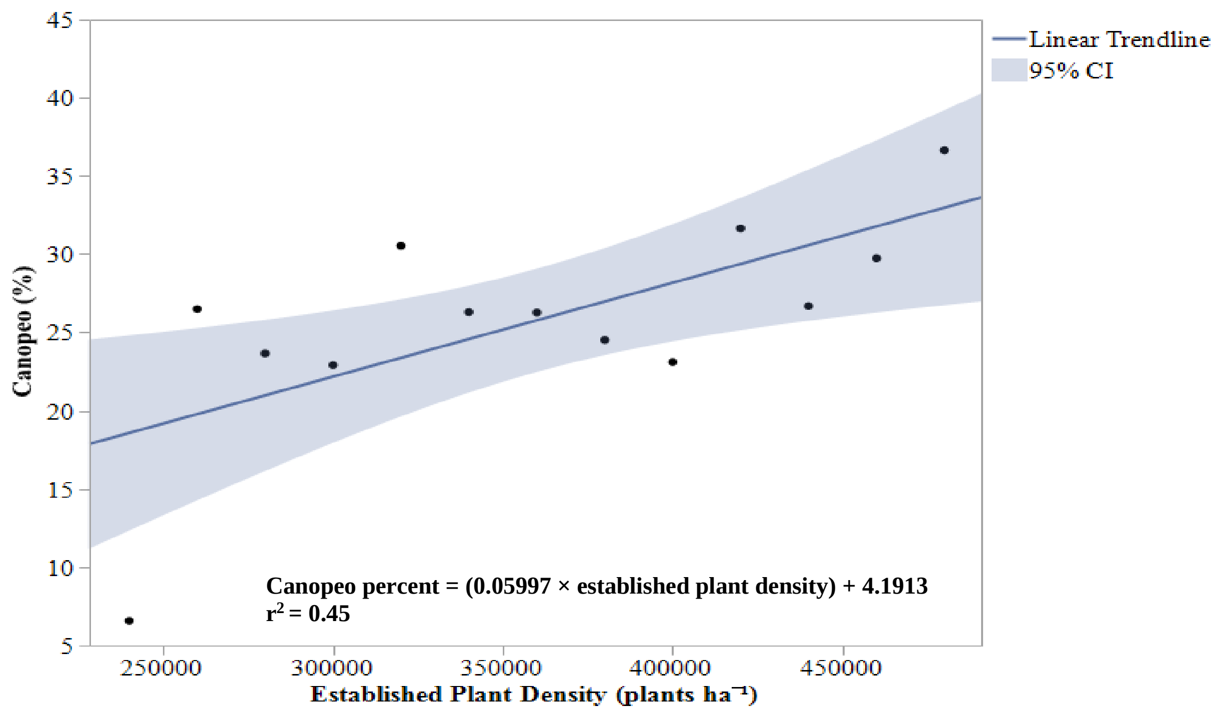

Figure 6. Established plant density effect on Canopeo, 2016-2017.
Regression summary of established soybean plant densities and Canopeo in North Dakota Producer fields, 2016-2017.

Table 11. Summary of linear regression models from field survey data predicting Canopeo readings for seeding rate and established plant density, and predicting yield based on Canopeo readings.

	Linear Equation†	$r^{2‡}$	CV	Significance Level
x = Seeding rate	Y_1= 0.00017x - 44.969§	0.63	24.5	**
x = Established Plant Density	Y_1= 0.05997x + 4.1913	0.45	21.0	*
x = Canopeo	Y_2= 9.71913x + 2562.5	0.09	20.7	***

†Equations from PROC REG. *, **, and *** indicate significance at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively.
‡r^2 = regression coefficient, CV = coefficient of variation.
§Y_1 = Canopeo, Y_2 = Yield.

The linear relationship between Canopeo and soybean yield was highly significant (Table 11). There is substantial variation between data points (r^2= 0.09), and the linear relationship shows that increases in Canopeo percentage are associated with greater yields (Figure 7). According to the linear equation, each Canopeo percent (recorded from VC to V3) results 9.7 kg ha^{-1} increase in yield. This data displays the importance of maximizing canopy coverage during early-season vegetative growth to achieve greater yields.

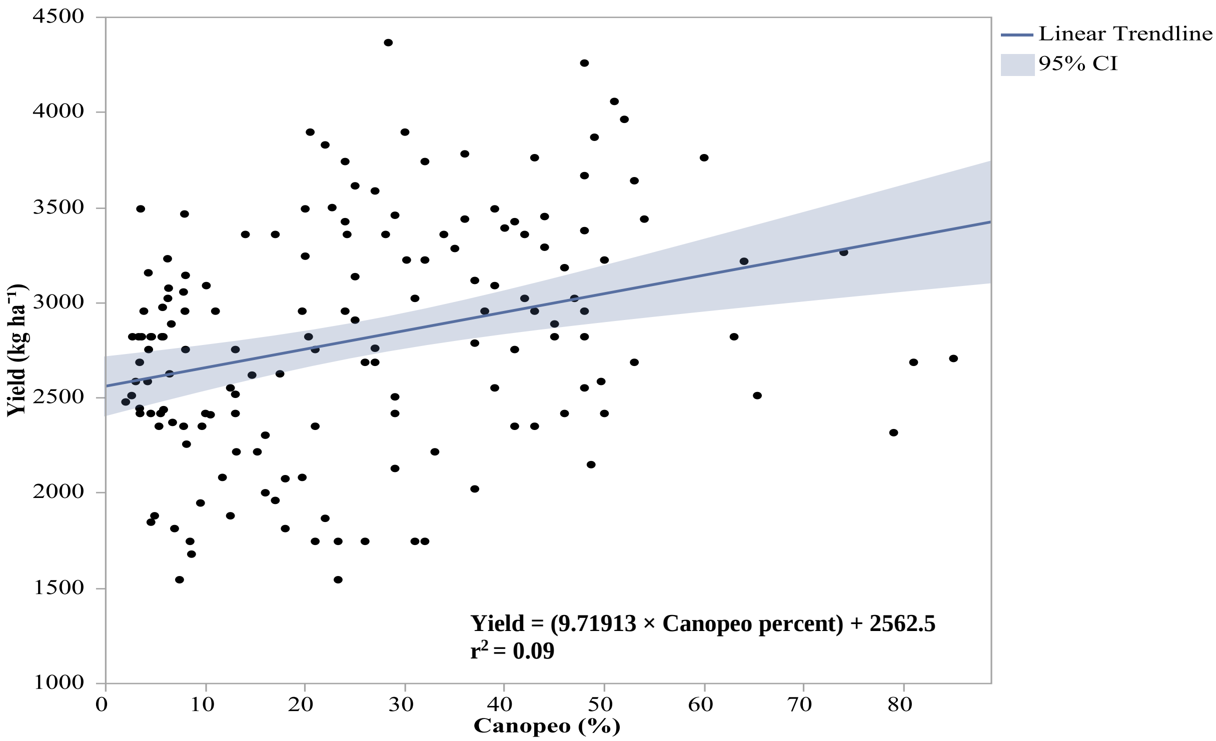

Figure 7. Canopeo effect on yield, 2016-2017.
Regression summary of yield and Canopeo readings recorded from soybean V1 to V5 stages in North Dakota Producer fields, 2016-2017.

Experimental research data was used for linear regression analysis for seeding rate and established plant density effects on Canopeo, and Canopeo effect on yield. Field visit data was verified using experimental research plots for comparison. Experimental plots found the linear relationship between seeding rate and Canopeo reading was significant (Table 12). Data from experimental plots found a strong relationship (r^2= 0.91) based on the linear equation where Canopeo readings increased with seeding rate increases (Figure 8).

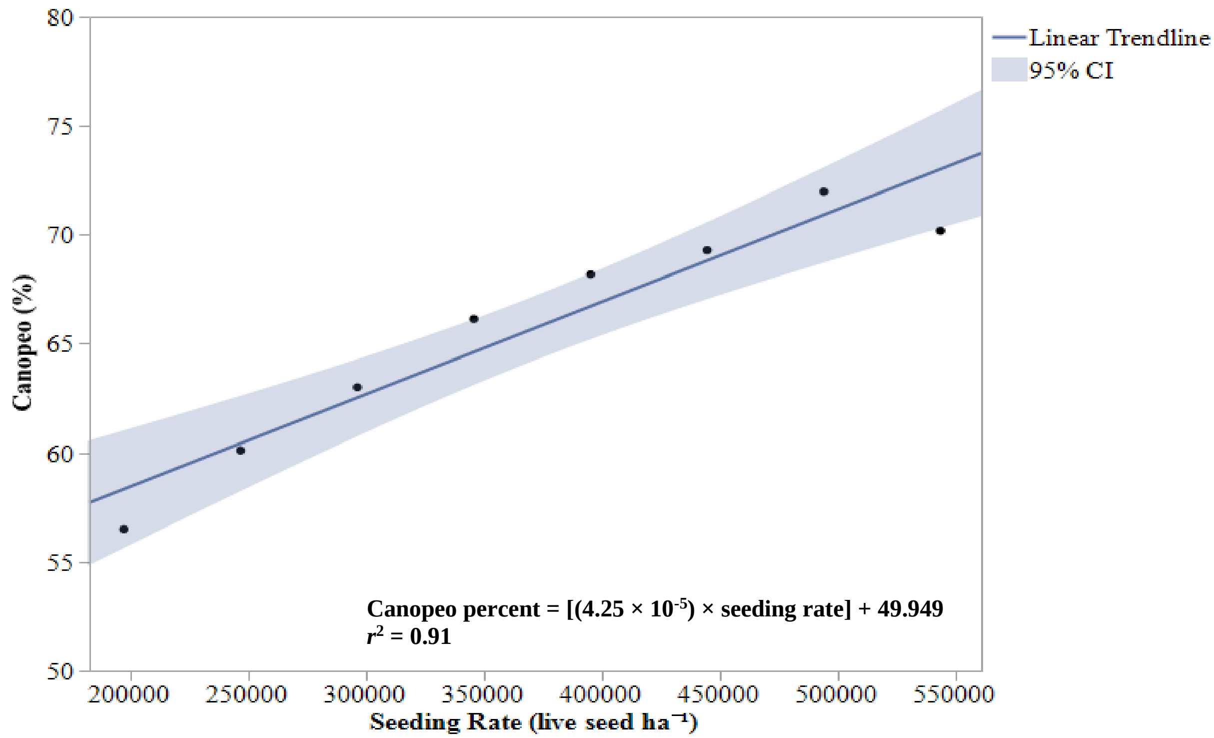

Figure 8. Seeding rate effect on Canopeo, 2017-2018.
Regression summary of Canopeo readings recorded from soybean V5 to V6 stages and seeding rate in experimental research, 2017-2018.

Table 12. Summary of linear regression models from experimental research data predicting Canopeo readings for seeding rate and established plant density, and predicting yield based on Canopeo readings.

	Linear Equation†	$r^{2‡}$	CV	Significance Level
x = Seeding rate	$Y_1 = (4.25 \times 10^{-5})x + 49.949$‡	0.91	2.6	***
x = Established Plant Density	$Y_1 = (4.27 \times 10^{-5})x + 50.298$	0.93	2.4	***
x = Canopeo	$Y_2 = 31.457x + 1002.251$	0.94	16.1	***

†Equations from PROC REG. All models significant at $P \leq 0.001$.
‡r^2 = regression coefficient, CV = coefficient of variation.
§Y_1 = Canopeo, Y_2 = Yield.

The relationship between established plant density and Canopeo reading in experimental plots was highly significant (Table 12). The linear equation had an r^2 of 0.93; data suggests greater established plant densities will likely result in greater canopy coverage (Figure 9).

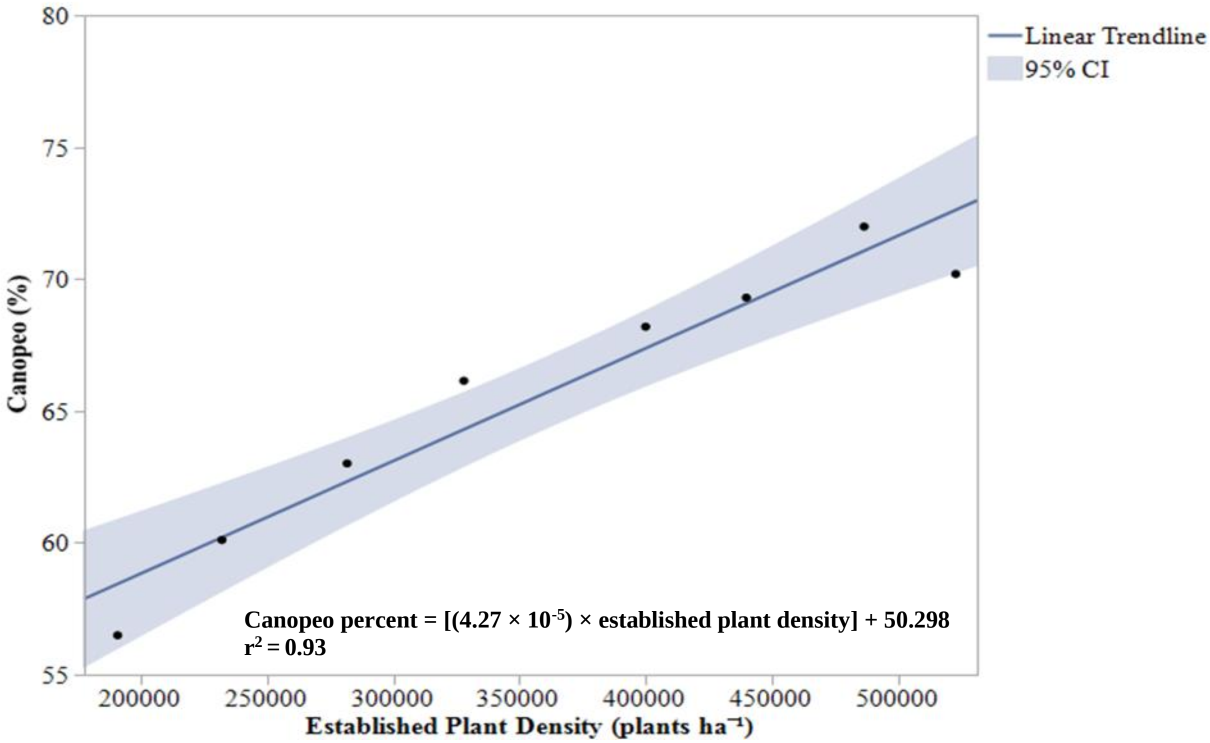

Figure 9. Established plant density effect on Canopeo, 2017-2018.
Regression summary of Canopeo readings recorded from soybean V5 to V6 stages and established soybean plant densities in experimental research, 2017-2018.

Linear regression for Canopeo percent effect on yield was highly significant (Table 12). As expected, experimental small plot data resulted in an increasing trend between Canopeo and yield (Figure 10). There was less variation for the linear trendline in experimental plots compared to findings from soybean field visits. The linear equation suggests yield increases 31.5 kg ha^{-1} per Canopeo percent increase.

The relationship between established plant density and Canopeo reading in experimental plots was highly significant (Table 12). The linear equation had an r^2 of 0.47, and the data suggests greater established plant densities will likely result in greater canopy coverage (Figure 9).

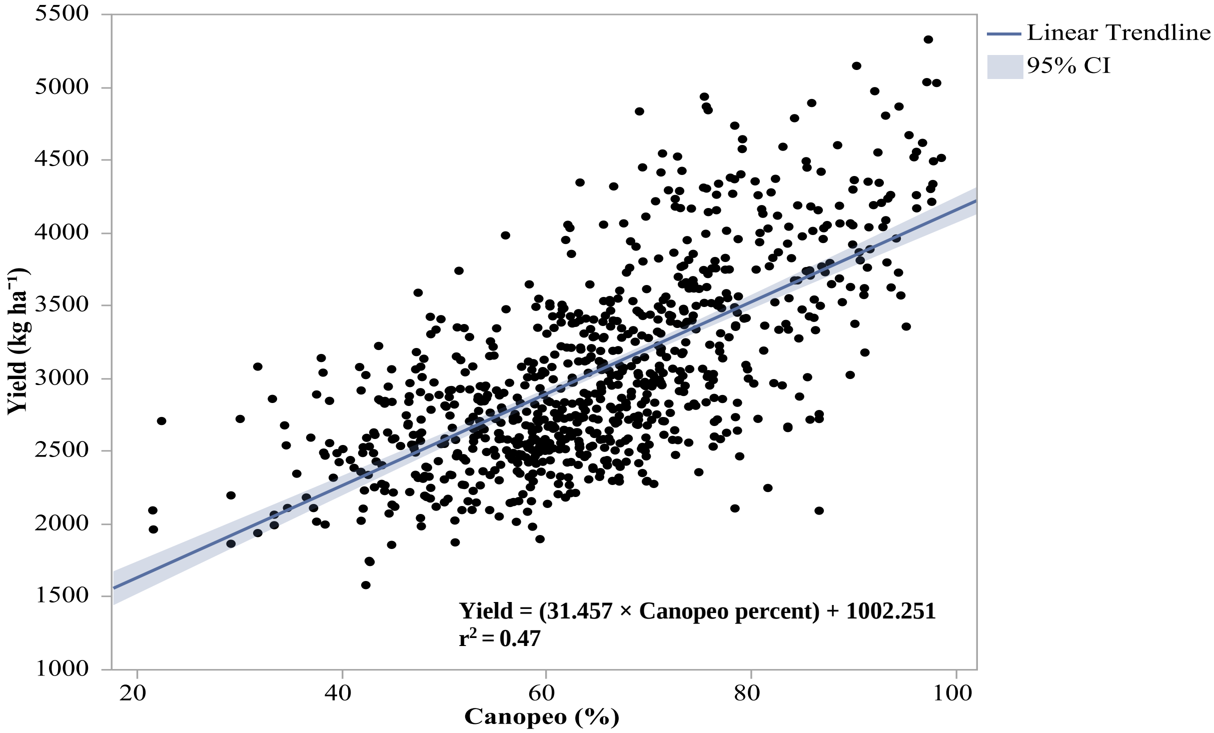

Figure 10. Canopeo effect on yield, 2017-2018.
Regression summary of yield and Canopeo readings recorded from soybean V5 to V6 stages in experimental research, 2017-2018.

Yield and Plant Loss Regression Analysis

A quadratic least squares regression analysis was used to evaluate seeding rate, established plant density, and final plant density. The analysis was performed for yield comparison between field visit data and experimental plots. Quadratic equations reported allowed for function maximum calculations. Linear regression analysis was evaluated for in-season plant loss for field visit and experimental plot data, separately.

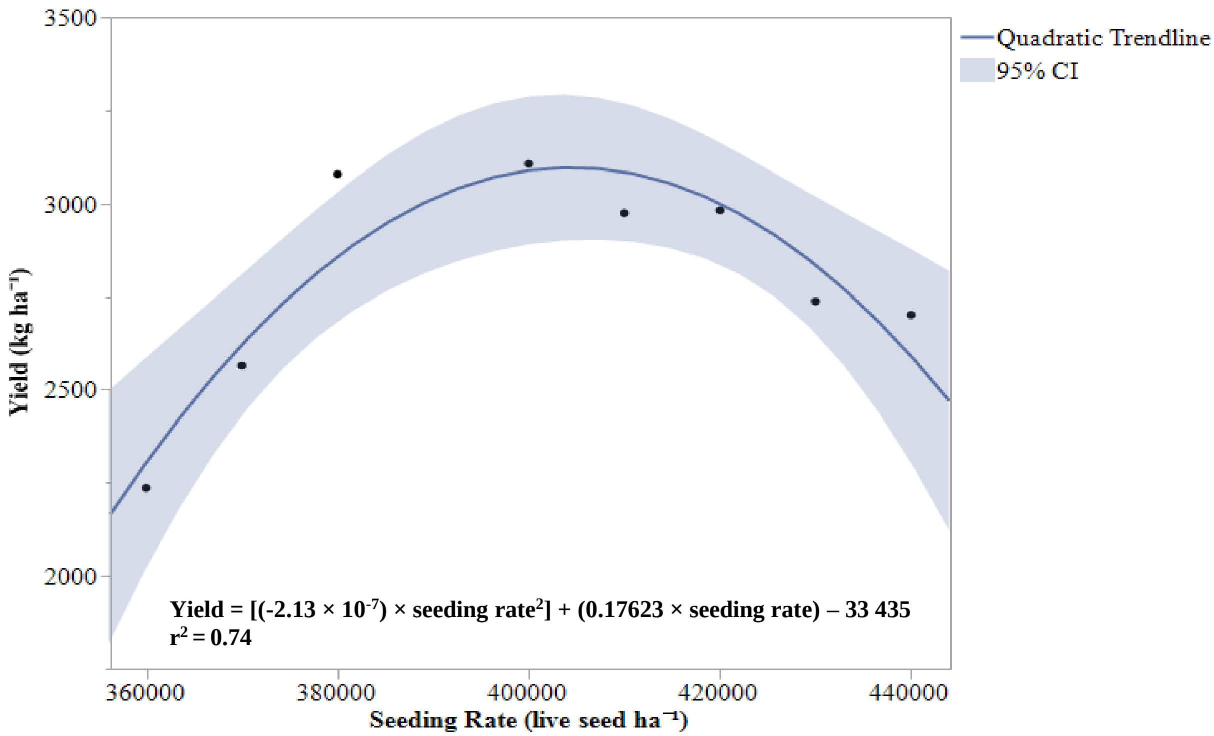

Figure 11. Seeding rate effect on yield, 2016-2017.
Regression summary of yield and soybean seeding rate in North Dakota Producer fields, 2016-2017.

Table 13. Summary of quadratic regression models from field survey data.

	Quadratic Equation[†]	$r^{2‡}$	CV	Function Maximum			Significance Level
				Seeding Rate	Plant Density	Yield	
				live seed ha^{-1}	plants ha^{-1}	kg ha^{-1}	
x = Seeding Rate	$Y = (-2.13 \times 10^{-7})x^2 + 0.17623x - 33\,435$‡	0.74	6.1	413 753	-	3023	**
x = Established Plant Density	$Y = (-1.70 \times 10^{-8})x^2 + 0.01261x + 619$	0.41	5.4	-	370 094	2953	*
x = Final Plant Density	$Y = (-2.86 \times 10^{-8})x^2 + 0.02014x - 614$	0.70	4.5	-	352 031	2931	***

[†]Equations from PROC REG. *, **, and *** indicate significance at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively.
[‡]r^2 = regression coefficient, CV = coefficient of variation.
[§]Y = yield in kg ha^{-1}.

Table 14. Summary of quadratic regression models from experimental research data.

	Quadratic Equation[†]	$r^{2‡}$	CV	Function Maximum			Significance Level
				Seeding Rate	Plant Density	Yield	
				live seed ha^{-1}	plants ha^{-1}	kg ha^{-1}	
x = Seeding Rate	$Y = (-2.84 \times 10^{-9})x^2 + 0.00267x - 2495$[§]	0.94	0.8	470 797	-	3123	***
x = Established Plant Density	$Y = (-2.90 \times 10^{-9})x^2 + 0.00265x + 2517$	0.94	0.7	-	456 753	3122	***
x = Fall Plant Density	$Y = (-3.35 \times 10^{-9})x^2 + 0.00285x - 2515$	0.94	0.8	-	425 612	3121	***

[†]Equations from PROC REG. *** indicates significance at $P \leq 0.001$.
[‡]r^2 = regression coefficient, CV = coefficient of variation.
[§]Y = yield in kg ha^{-1}.

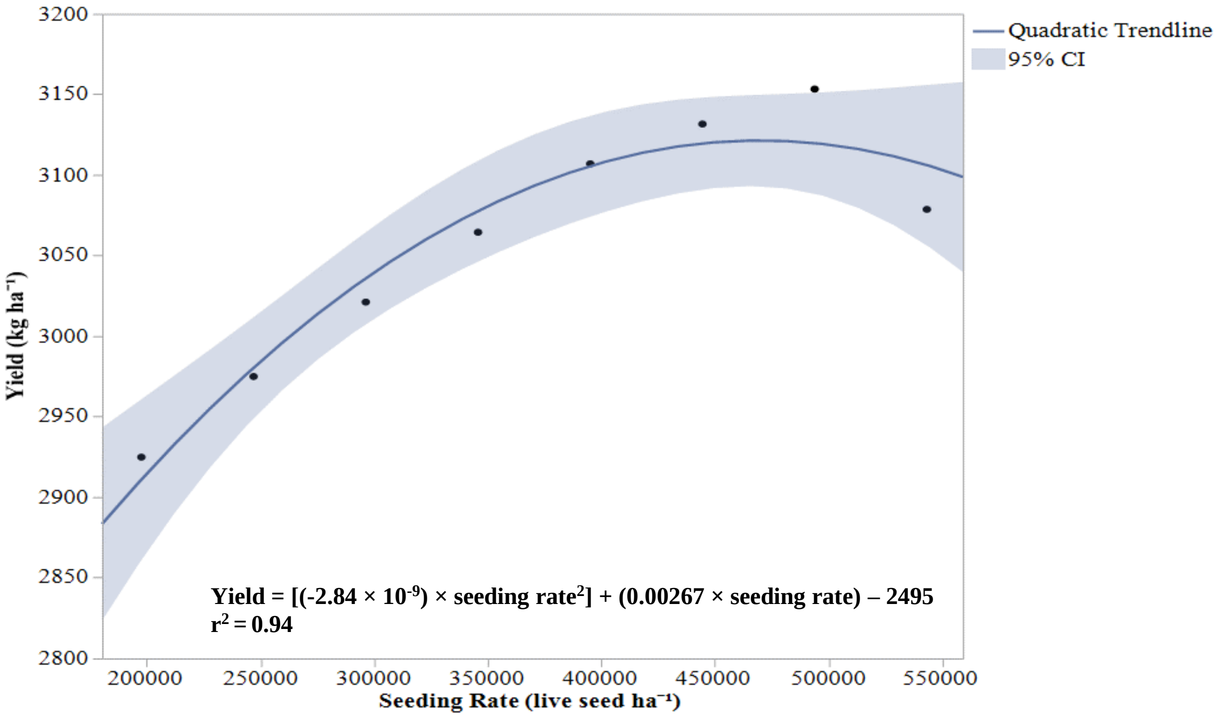

Figure 12. Seeding rate effect on yield, 2017-2018.
Regression summary of yield and soybean seeding rate in experimental research data, 2017-2018.

Reported seeding rates for fields visited were compared to yield (Figure 11). The quadratic relationship (r^2= 0.74) was significant between grouped seeding rates and yield (Table 13). Increase in seeding rate increased yield until 400 000 live seed ha^{-1} where the yield trend then decreased. The seeding rate quadratic equation for yield has a function maximum of 413 753 live seed ha^{-1}. At 413 753 live seed ha^{-1}, the corresponding calculated maximum yield is 3023 kg ha^{-1}. This information suggests seeding rates above or below 413 753 live seed ha^{-1} will experience suboptimal yields according to the quadratic regression analysis.

Similar findings were observed in experimental research data for the quadratic regressions analysis for seeding rate (Figure 12). Seeding rate highly influenced yield and explained 94% of yield variation (Table 14). For the research data, the maximum seeding rate and yield occurred at 470 797 live seed ha^{-1} and 3123 kg ha^{-1}, respectively. Both the maximum seeding rate and yield were greater in the experimental research compared with the field observations. The experimental data suggests the optimal yield is achieved at 57 044 live seed ha^{-1} more than the field visit data found. This is likely due to the increased precision in small plot research compared to field data.

Quadratic regression analysis of field visit data revealed yield was significantly influenced by established plant density with (r^2= 0.41) variance observed in reported yields (Table 13). The quadratic equation maximum yield was 2953 kg ha^{-1} at an established plant density of 370 094 plants ha^{-1} (Figure 13). This is consistent with the NDSU recommended soybean plant establishment of 370 500 plants ha^{-1}.

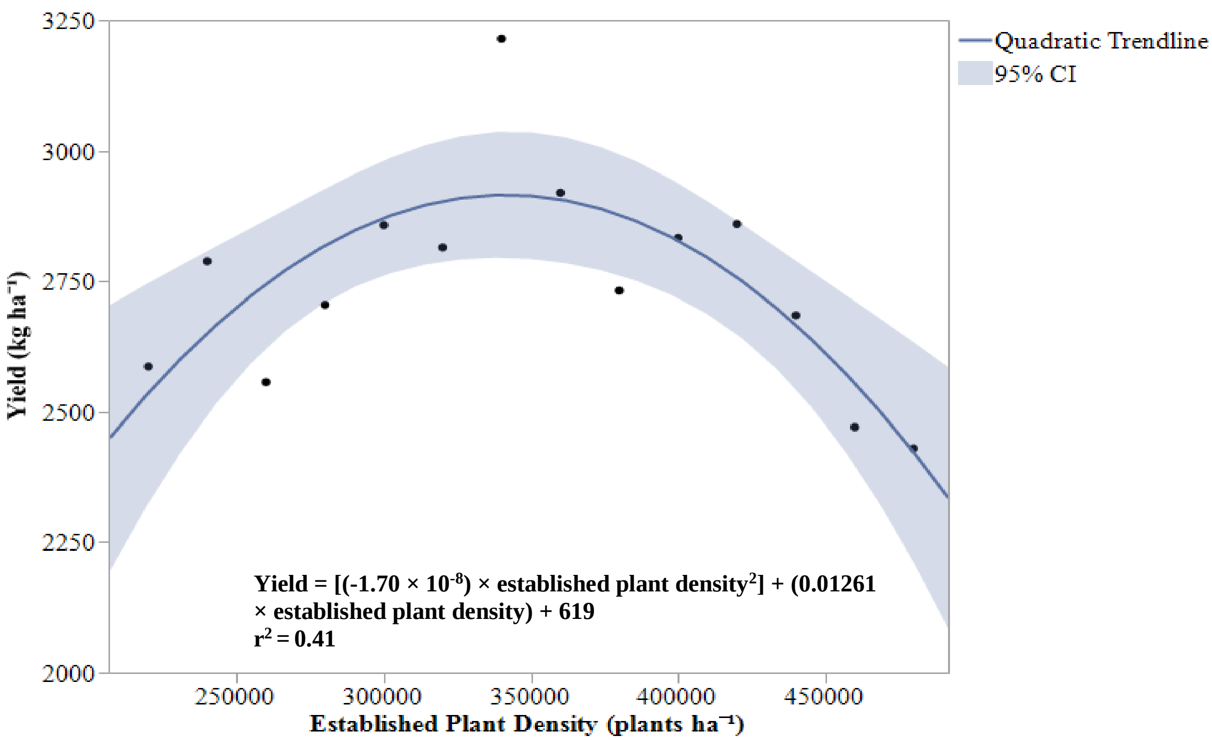

Figure 13. Established plant density effect on yield, 2016-2017.
Regression summary of yield and established soybean plant density in North Dakota producer fields, 2016-2017.

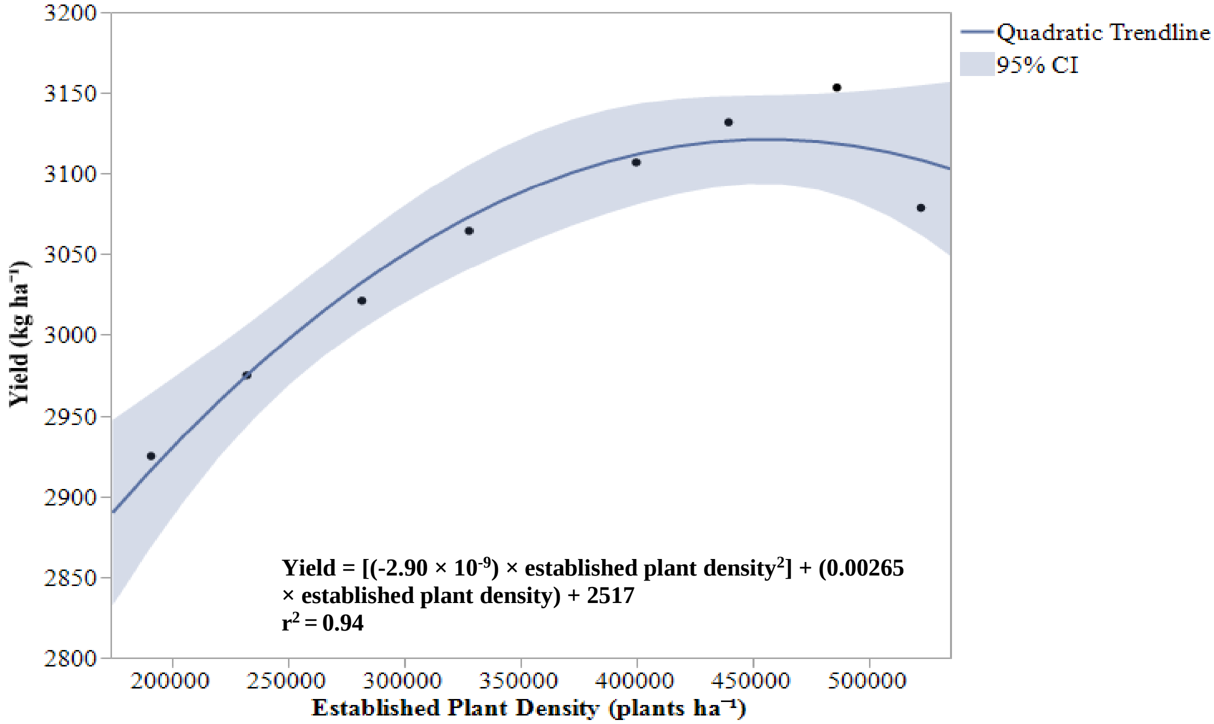

Figure 14. Established plant density effect on yield, 2017-2018.
Regression summary of yield and established soybean plant densities in experimental research, 2017-2018.

The established plant density quadratic regression analysis found that established pant density and yield are closely related (Table 14). Yields increased with established plant density until approximately 520 000 plants ha^{-1} and yield decreased thereafter (Figure 14). The quadratic equation explains 63% of yield variation more than that of the field data. Although the experimental yield data is more precise, the suggested maximum yield calculated from the research data is 86 000 plants ha^{-1} more than the field data calculation. Data from experimental research likely experienced less variation within each tested environment than the soybean producer fields.

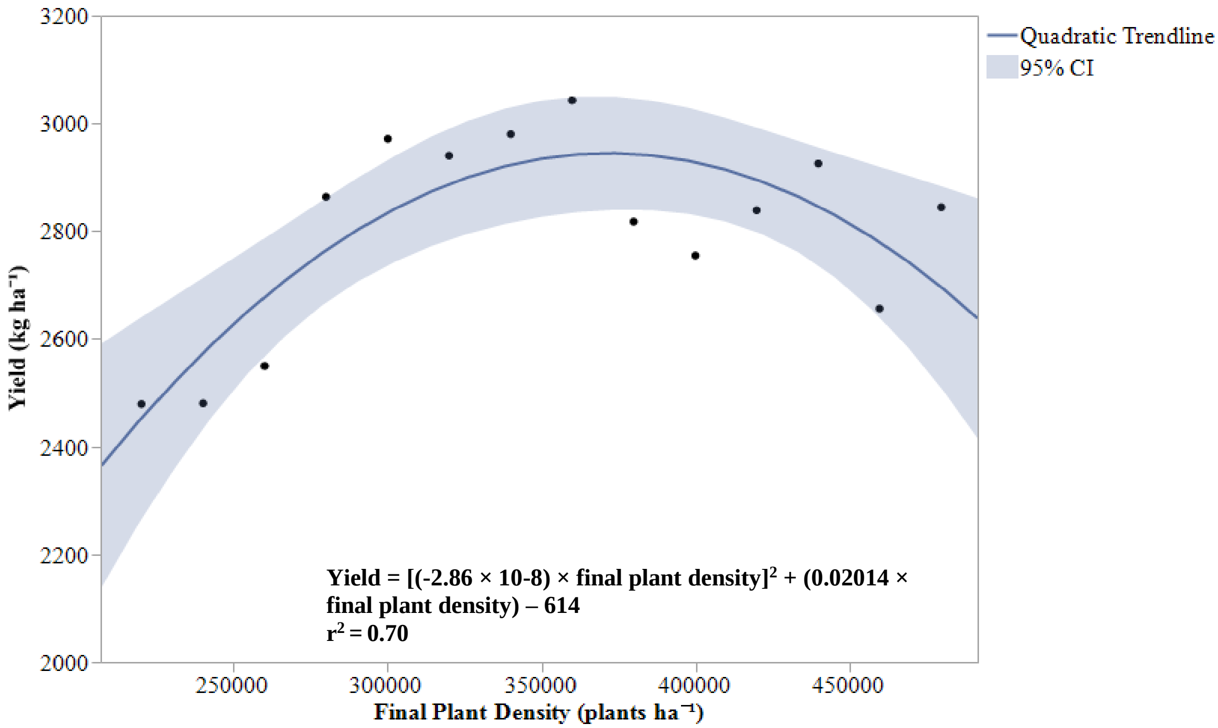

Figure 15. Final plant density effect on yield, 2016-2017.
Regression summary of yield and final soybean plant density in North Dakota Producer fields, 2016-2017.

Field final plant density was also analyzed with quadratic regression and found yield was significantly influenced by late season plant density (Table 13). Yields were found to have a parabolic relationship with final plant densities with 70% of variance observed in yield (Figure 15). At 352 031 plants ha^{-1}, the function maximum yield is 2931 kg ha^{-1}. There is an approximate 20 000 plant ha^{-1} and a 22 kg ha^{-1} difference between function maximum points when comparing established and final plant density. Plant density differences are likely attributed to plant loss between the soybean growing seasons.

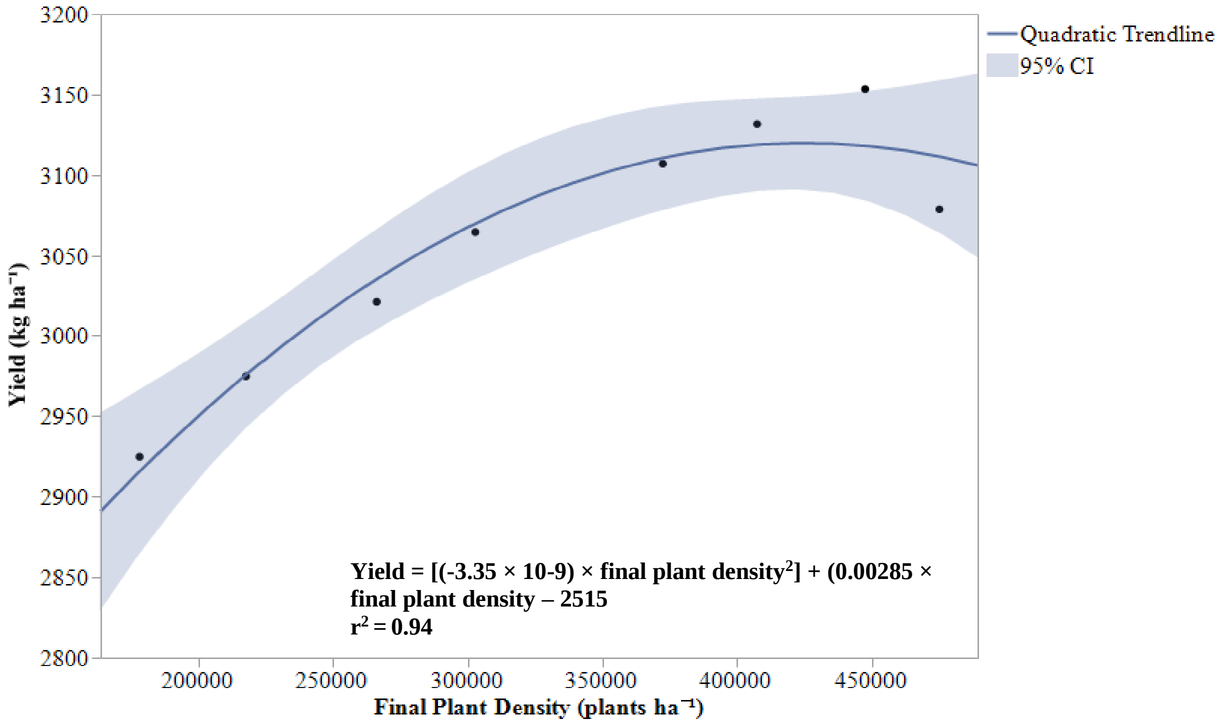

Figure 16. Final plant density effect on yield, 2017-2018.
Regression summary of yield and final soybean plant densities in experimental research, 2017-2018.

Quadratic regression analysis was also performed on experimental research and observed that yield was highly dependent on final plant density (Figure 16). The relationship between final plant density and yield were closely associated ($r^2 = 0.91$). The quadratic equation calculated the maximum yield (3121 kg ha^{-1}) to occur at 425 612 plants ha^{-1}, which is 73 581 plants ha^{-1} more than the field data equation predicts.

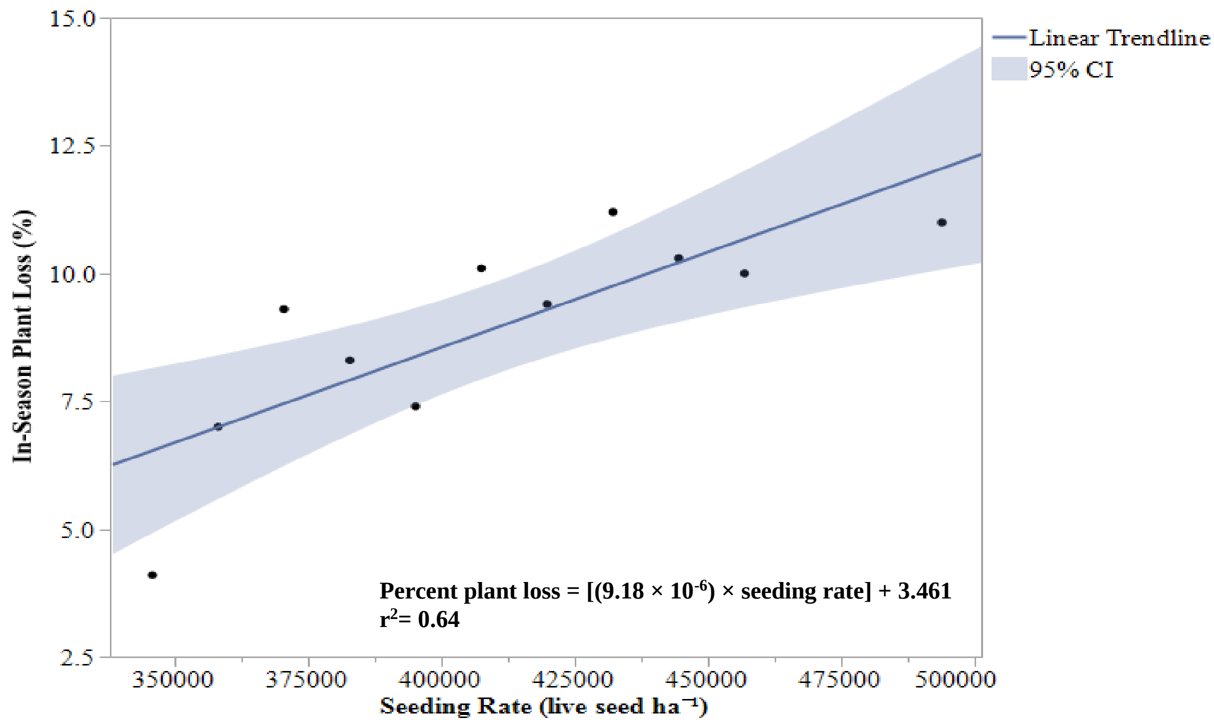

Figure 17. Seeding rate effect on in-season plant loss, 2016-2017.
Regression summary of soybean plant loss and seeding rates in field visit data, 2016-2017.

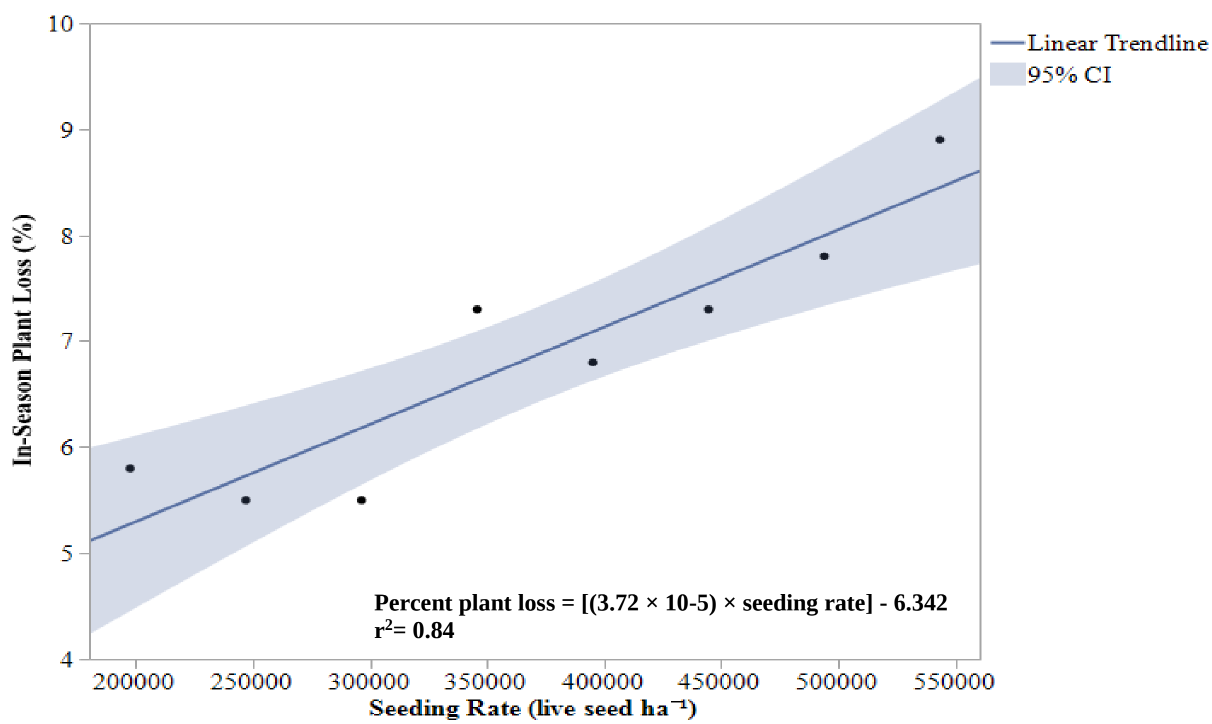

Figure 18. Seeding rate effect on in-season plant loss, 2017-2018.
Regression summary of soybean plant loss and seeding rates in experimental research, 2017-2018.

Plant density reductions expressed as percent were observed during soybean field visits in 2016 and 2017 between established and final plant density observations (Figure 17). Linear regression analysis for seeding rate significantly influenced in-season plant loss (Table 15). The general positive trend found plant loss increases as seeding rates increases. Seeding rates of 345 000 and 430 000 live seed ha^{-1} experienced the lowest and highest plant loss of 4.1% and 11.2%, respectively.

Table 15. Summary of linear regression models for in-season plant loss.

		Linear Equation†	$r^{2‡}$	CV
Field Visit	x = Seeding Rate	Y= (9.18×10^{-6})x + 3.461§	0.64	14.8
Experimental Research	x = Seeding Rate	Y= (3.72×10^{-5})x - 6.342	0.84	7.6

†Equations from PROC REG. All models significant at $P \leq 0.01$.
‡r^2 = regression coefficient, CV = coefficient of variation.
§Y = % plant loss.

Experimental research observed seeding rate also significantly influenced plant loss (Table 15). The linear regression for the experimental research (Figure 18) explains 20% more variation in yield than field visit data. Mean in-season plant losses were 8.9% and 6.9%, for field visit and experimental research, respectively. Survey plant loss was expected to be larger due to increased variability between surveyed field environments. Using the quadratic function maximum values for established (370 094 plants ha^{-1}) and final plant density (352 031 plants ha^{-1}) to calculate plant loss, a 4.8% plant loss is expected if optimal plant densities are achieved.

During soybean field visits and research observations, reasons for soybean plant loss were disputable and not straightforward. Differences between plants during early-season observations were not easily visible. However, plant loss became more apparent later in the growing season during reproductive phases. Most notably, plant loss was observed due to competition between plants. Under the soybean canopy, stunted plants were considerably less vigorous and shorter than other plants. Limited sunlight access presumably resulted in less vigorous plants with reduced or no pod production. In addition, fields experiencing IDC had visibly reduced vigor and additional minor plant loss.

Field and experimental data presented are only a sample representation of soybean yields and management conditions in North Dakota. Although experimental data predicted yield based on counted plants with greater accuracy than field visit data, the field data represents conditions more likely to be found in a North Dakota soybean producer's field. In addition, the field data suggests the NDSU recommended established plant density observation to be modified to a late-season (or final) plant density of 370 500 plants ha^{-1} instead.

Economic Analysis

An economic analysis determined soybean net revenue gained for main effects row spacing and seeding rate. Estimated market prices and seed costs found net revenue ha^{-1} for each treatment analyzed. Soybean market prices can vary based on transportation and global demand creating challenging decisions for soybean producers.

Table 16. Estimated soybean net revenue per hectare based on row spacing and seeding rate yields averaged across 15 environments.

	Market Price (\$ kg^{-1})									
Row spacing	0.29		0.31		0.33		0.35		0.37	
cm	-----------		-----------		\$ ha^{-1}		-----------		-----------	
30[‡]	882	a[†]	940	a	999	a	1057	a	1115	a
61	810	b	864	b	918	b	972	b	1025	b
Seeding rate										
live seed ha^{-1}										
197 600	824	c	878	c	931	c	985	c	1038	c
247 000	833	bc	888	bc	942	bc	997	bc	1051	bc
296 400	843	abc	899	abc	954	abc	1010	abc	1065	abc
345 800	853	ab	910	ab	966	ab	1023	ab	1080	ab
395 200	848	abc	904	abc	961	abc	1018	ab	1074	ab
444 600	862	a	920	a	978	a	1036	a	1094	a
494 000	857	ab	915	ab	974	a	1032	a	1090	a
LSD (0.05)	26		28		30		31		33	

[†]Means in a column, for row spacing or seeding rate, followed by the same letter are not significantly different at ($P \leq 0.05$).
[‡]Soybean seed prices were estimated as \$52 for 140 000 seeds (Duffy, 2018).

Row spacing net revenue was consistent with yield response as 31 cm row spacing was more profitable. Profit margins increased as estimated market prices increased (Table 16). At the lowest estimated market price, 30 cm row spacing profited \$72 ha^{-1} more than 61 cm row spacing. Profit differences between row spacing increased as estimated market prices increased with a \$90 ha^{-1} difference observed at \$0.37 kg^{-1}.

Net revenue from varying seeding rates peaked at 444 600 live seed ha^{-1}. Increasing seeding rates above 444 600 live seed ha^{-1} do not show signs of increasing profit Table 16). Differences between the least and most profitable seeding rates diverged as market price increased with a low and high of \$38 and \$56 ha^{-1}, respectively. Although the 444 600 live seed ha^{-1} provided the most profit, a rate of 296 400 live seed ha^{-1} provided similar net revenue. However, planting 444 600 live seed ha^{-1} more closely aligns with the current NDSU recommendation of established plant density of 370 500 plants ha^{-1}.

CONCLUSION

Seeding rate and row spacing influence North Dakota soybean yield and other factors. Greater emergence rates occur in 61 cm row spacing and as seeding rates increase. More GDD are required for soybean establishment in years observing less than normal rainfall. Seeding rate does not influence percent of established plant density during emergence.

Soybean producers are likely to improve yields by increasing seeding rates and using 30 cm row spacing compared with 61 cm. Narrow row spacing increased yield by 183 kg ha^{-1}, but reduced plant height by 2 cm compared to wide row spacing. Canopeo is not an effective tool to predict yield. Based on North Dakota field data, maximum soybean yields are obtained at a seeding rate of 414 000 live seed ha^{-1}. Experimental plot data found the highest yield at 494 000 live seed ha^{-1}. Quadratic regression analysis found soybean producers should have the highest yields with an established plant density of 370 000 plants ha^{-1}. Field data found having a final plant density of 352 000 plants ha^{-1} should maximize yields. Based on field data, final plant density (r^2 = 0.70) predicts yield more precisely than established plant density (r^2 = 0.41). North Dakota soybean producers can expect more in-season plant loss as seeding rates increase beginning at 346 000 live seed ha^{-1}. Small plot research found 2% more plant loss occurring in 61 cm row spacing than 30 cm. Net Revenue was the highest in 30 cm row spacing and with a 444 600 live seed ha^{-1} seeding rate

North Dakota soybean producers should consider current crop management practices and other input costs before making row spacing or seeding rate adjustments. This research can be improved upon by implementing additional soybean row spacing and seeding rates commonly used in North Dakota. Further research on the causes of in-season plant loss would also benefit North Dakota soybean producers.

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APPENDIX

Table A1. Soil test results at all environments in 2017 and 2018.

Year	Location	Depth	NO_3-N	P	K	pH	OM†
		cm	kg ha^{-1}	mg kg^{-1}			%
2017	Casselton	0-30	22	31	335	7.6	3.8
		30-61	96	20	252	7.7	3.1
	Ransom	0-30	21	10	216	7.2	4.5
		30-61	72	10	151	7.6	3.1
	Sargent	0-30	29	29	212	6.7	4.2
		30-61	75	9	180	7.4	3.4
	Steele	0-30	24	7	148	7.5	4.1
		30-61	54	2	95	7.6	2.7
	NW22NAD†	0-30	8	15	440	7.9	5.5
		30-61	7	6	330	8.0	3.7
	NW22CTD†	0-30	5	16	432	7.9	5.5
		30-61	5	6	290	8.2	3.5
2018	Prosper	0-30	9	22	318	8.0	5.0
		30-61	105	4	131	8.3	2.8
	Sargent	0-30	28	33	375	7.2	5.7
		30-61	48	5	265	7.7	3.0
	Steele	0-30	15	19	172	5.7	4.0
		30-61	30	4	112	6.1	2.4
	NW22NAD†	0-30	16	13	333	7.8	5.5
		30-61	48	6	300	8.0	3.6
	NW22CTD†	0-30	14	15	382	7.8	5.5
		30-61	49	7	338	8.0	3.8

†OM = Organic matter. NAD = naturally drained, CTD = controlled tile drained.

Table A2. Total number of observations from North Dakota soybean field visits, 2016-2017.

Regression Model	Number of Total Observations
Seeding Rate x Canopeo	1550
Established Plant Density x Canopeo	145
Canopeo x Yield	156
Seeding Rate x Yield	195
Established Plant Density x Yield	197
Final Plant Density x Yield	205
Seeding Rate x In-Season Plant Loss	191

Table A3. Mean plant densities at NW22 in 2017 averaged across row spacing and seeding rate with corresponding growing degree days for the naturally drained (NAD) environments.

	NAD 1																			
Treatment	Growing Degree Days																			
	170		181		192		203		227		239		264		277		318		361	
cm																				
30	0	a†	0	a	33874	a	107102	a	143363	a	153304	a	178436	a	207020	a	323331	a	346518	a
61	608	a	3032	b	39862	a	104327	a	137134	a	139508	a	172666	a	216884	a	319034	a	338601	a
live seed ha^{-1}																				
197 600	0		0	b	20195		58424	c	79064	c	82120	c	109293	b	129513	b	176756	c	183588	c
247 000	0		0	b	16182		50114	c	76019	c	80158	c	100101	b	125471	b	230250	c	240596	bc
296 400	0		1046	b	29580		97830	bc	125424	bc	132530	bc	151035	b	167660	b	248651	c	262864	bc
345 800	0		0	b	39884		97309	bc	125016	bc	117450	c	143519	b	159817	b	256637	c	286449	b
395 200	1060		5301	a	56496		159360	a	203944	a	213234	a	235972	a	288811	a	400717	b	433889	a
444 600	0		3195	ab	50593		128122	ab	186709	ab	194089	ab	235322	a	286528	a	442128	ab	479563	a
494 000	1069		1069	b	45142		148841	ab	185567	ab	205261	a	253608	a	325856	a	493143	a	510974	a
LSD (0.05)	ns		3935		ns		60862		69867		64774		78204		82903		81329		84440	
	NAD 2																			
cm																				
30	0	a	1705	a	23279	a	91727	a	139985	a	153230	a	183089	a	212224	a	309464	a	322103	a
61	0	a	295	a	21117	a	104472	a	153800	a	152481	a	186518	a	227872	a	314586	a	336177	a
live seed ha^{-1}																				
197 600	0		1875		18048	ab	49286	c	74435	d	87010	c	92085	c	118802	d	165352	d	185493	d
247 000	0		1032		17924	ab	73116	c	98389	cd	104450	c	124178	c	167376	d	209026	d	214959	d
296 400	0		0		6259	b	58730	c	108517	cd	110492	c	152975	c	170378	cd	280381	c	284443	c
345 800	0		0		27324	ab	95567	bc	138762	bcd	141821	bc	167724	bc	193333	cd	285844	c	306195	c
395 200	0		2029		28760	ab	139274	ab	190791	ab	195908	b	250687	ab	284025	ab	406108	ab	418458	b
444 600	0		0		15948	ab	91638	bc	160635	bc	138310	bc	173988	bc	247475	bc	370786	b	402212	b
494 000	0		2063		41127	a	179088	a	256714	a	292004	a	331989	a	358957	a	466679	a	492224	a
543 400	0		0		4282	b	24560	d	122496	bcd	187766	b	187700		237106		292061	c	462565	a
LSD (0.05)	ns		ns		34339		61151		72614		79671		85979		79258		61067		59130	

†Means in column, for row spacing or seeding rate, followed by same letter are not significantly different at $P \leq 0.05$.

Table A4. Mean plant densities at NW22 in 2017 averaged across row spacing and seeding rate with corresponding growing degree days for the controlled tile drainage (CTD) environments.

	CTD 1									
	Growing Degree Days									
Treatment	170	181	192	203	227	239	264	277	318	361
cm										
30	0 a†	1720 a	35624 b	111747 b	155789 a	163188 a	193294 a	231324 a	337781 a	362444 a
61	607 a	5439 a	67423 a	147087 a	178928 a	187097 a	204134 a	232019 a	321732 a	341725 a
live seed ha^{-1}										
197 600	0	0	20642 c	80677 cd	91880 cd	98562 ce	116296 e	142901 c	204228 c	214685 c
247 000	0	1945	16056 c	50613 d	84670 d	90754 e	101762 e	142150 c	216224 c	230210 c
296 400	0	6276	48807 bc	106088 bcd	136501 cd	139531 de	155836 de	172651 bc	248732 bc	261794 bc
345 800	0	1055	43610 bc	122980 bc	152889 bc	159024 cd	188347 cd	216242 b	300413 b	328984 b
395 200	1060	6195	89585 a	220321 a	280304 a	289511 a	328545 a	329187 a	436402 a	459306 a
444 600	1065	8520	70828 ab	156200 ab	212355 b	218671 bc	246447 bc	296889 a	448614 a	471441 a
494 000	0	1070	71137 ab	169041 ab	212908 b	229941 ab	253773 b	321678 a	453689 a	498171 a
LSD (0.05)	ns	ns	35476	66027	64784	63847	64673	65095	78468	80949
cm	CTD 2									
30	0 a	0 a	9234 a	75836 a	129219 a	138382 a	178683 a	217791	313118 a	335023 a
61	915 a	4265 a	21759 a	97489 a	145896 a	140339 a	171623 a	229360	319822 a	334596 a
live seed ha^{-1}										
197 600	0	0	6088 b	46150 c	69118 d	74897 c	93407 c	122244 c	177284 d	183924 e
247 000	0	0	2063 b	36234 c	71053 d	72985 c	88073 c	127139 c	210961 cd	218955 e
296 400	0	0	8236 b	71362 bc	108139 cd	114178 bc	145406 bc	166427 c	259960 c	277363 d
345 800	0	1053	24460 ab	129395 ab	187218 ab	198495 a	230124 a	254470 b	334668 b	350909 c
395 200	0	0	12350 b	81769 bc	152681 bc	156741 ab	194052 ab	262214 b	368001 b	380262 bc
444 600	0	0	2048 b	68762 bc	151705 bc	157927 ab	224485 ab	266249 b	387919 b	418048 b
494 000	3202	13874	53222 a	172970 a	222990 a	200289 a	250524 a	323788 ab	476499 a	514211 a
543 400	0	0	11646 b	135565 ab	208394 ab	217834 a	280284 a	366286 a	507950 a	539481 a
LSD (0.05)	ns	ns	28826	62800	67188	72029	79975	72380	56402	56027

†Means in column, for row spacing or seeding rate, followed by same letter are not significantly different at $P \leq 0.05$.

Table A5. Mean plant densities at NW22 in 2018 averaged across row spacing and seeding rate with corresponding growing degree days for the naturally drained (NAD) environments.

	NAD 1															
Treatment	Growing Degree Days															
	104		115		126		137		148		172		196		277	
cm																
30	0	a†	48 863	a	141 307	b	211 836	b	268 399	b	298 065	b	312 172	b	314 996	b
61	1 191	a	56 985	a	185 545	a	263 553	a	306 212	a	325 767	a	341 732	a	348 569	a
live seed ha^{-1}																
197 600	0		52 849	b	95 629	d	139 054	d	162 204	e	177 035	d	187 677	d	191 562	d
247 000	1 026		31 930	b	97 203	d	147 087	d	192 612	de	218 389	cd	253 652	c	262 755	c
296 400	1 037		34 057	b	124 883	d	186 069	cd	226 679	d	250 096	c	265 216	c	267 292	c
345 800	1 045		40 571	b	145 394	cd	245 743	bc	305 701	c	338 003	b	350 163	b	355 295	b
395 200	0		34 823	b	193 286	bc	258 703	b	294 836	c	325 364	b	335 626	b	336 679	b
444 600	0		116 602	a	226 271	ab	332 664	a	385 565	b	419 671	a	431 065	a	435 293	a
494 000	1 061		59 634	b	261 310	a	354 547	a	443 538	a	454 858	a	465 256	a	473 603	a
LSD (0.05)	ns		42 024		58 579		64 080		51 757		50 042		51 300		54 665	
	NAD 2															
cm																
30	0	a	36 546	a	127 937	a	220 222	b	288 493	b	315 414	b	327 393	b	330 855	b
61	0	a	49 244	a	176 039	a	270 652	a	321 705	a	341 446	a	352 928	a	362 048	a
live seed ha^{-1}																
197 600	0		20 885		70 670	d	108 041	e	155 046	g	161 100	e	181 987	f	196 113	f
247 000	0		31 421		111 312	cd	171 969	d	210 440	f	228 137	d	234 038	e	235 063	f
296 400	0		38 866		131 389	bc	221 777	c	257 200	e	267 134	d	280 178	d	286 291	e
345 800	0		54 164		153 277	bc	244 119	c	304 653	d	328 125	c	337 341	c	348 651	d
395 200	0		54 897		178 730	b	298 184	b	390 373	c	435 372	b	440 546	b	441 599	bc
444 600	0		40 682		167 620	b	307 401	b	375 149	c	426 761	b	432 945	b	432 945	c
494 000	0		59 350		250 912	a	366 573	a	442 829	b	452 380	b	474 097	b	484 497	b
543 400	0		51 378		219 123		402 799	a	488 136	a	543 512	a	552 833	a	554 897	ab
LSD (0.05)	ns		ns		51 391		49 061		39 125		41 848		43 380		50 072	

†Means in column, for row spacing or seeding rate, followed by same letter are not significantly different at $P \leq 0.05$.

Table A6. Mean plant densities at NW22 in 2018 averaged across row spacing and seeding rate with corresponding growing degree days for the controlled tile drainage (CTD) environments.

cm	CTD 1							
30	0 a[†]	47 786 a	144 754 b	230 558 a	286 261 a	301 497 a	312 409 a	314 685 a
61	302 a	51 707 a	192 879 a	255 019 a	282 105 a	313 277 a	321 033 a	324 613 a
live seed ha^{-1}								
197 600	0	20 731	95 686 d	123 425 f	155 599 c	165 384 e	167 403 e	167 403 e
247 000	0	46 425	104 643 d	159 914 ef	237 630 b	212 619 d	218 520 d	221 468 d
296 400	0	40 170	130 620 cd	200 432 de	235 308 b	269 585 c	279 738 c	286 889 c
345 800	0	49 790	183 776 bc	250 200 cd	267 494 b	292 204 c	301 421 c	303 511 c
395 200	0	66 835	201 725 ab	286 355 bc	341 959 a	376 074 b	387 304 b	388 354 b
444 600	1 057	85 436	213 509 ab	321 114 ab	349 985 a	395 127 ab	413 610 ab	418 740 ab
494 000	0	38 836	251 759 a	358 085 a	401 305 a	440 709 a	449 056 a	451 176 a
LSD (0.05)	ns	ns	63 746	64 569	65 802	46 649	46 143	47 060
cm	CTD 2							
30	0 a	44 139 a	133 751 b	212 829 b	326 617 a	312 419 a	323 328 a	325 634 a
61	1 486 a	54 569 a	192 155 a	280 798 a	281 683 a	327 808 a	333 459 a	340 650 a
live seed ha^{-1}								
197 600	0	32 231 b	99 266 d	151 621 f	165 290 d	178 653 f	182 538 e	183 548 f
247 000	2 052	42 137 ab	104 000 d	171 710 ef	222 241 d	221 468 ef	226 469 de	226 469 ef
296 400	0	46 051 ab	131 547 cd	217 186 de	249 437 cd	269 256 de	273 294 d	276 296 e
345 800	2 091	46 946 ab	188 441 bc	245 276 cd	345 676 bc	317 670 cd	337 055 c	345 322 d
395 200	0	52 963 ab	182 145 bc	293 096 bc	344 065 bc	375 367 cd	375 280 c	391 060 cd
444 600	1 057	55 883 ab	235 088 b	296 963 bc	396 570 bc	439 367 b	449 550 b	449 550 bc
494 000	0	69 271 ab	200 190 b	351 846 b	405 770 ab	439 012 b	454 576 b	459 741 bc
543 400	0	81 597 a	304 107 a	441 339 a	515 968 a	505 166 a	520 743 a	529 064 a
LSD (0.05)	ns	43 341	62 315	65 187	113 445	61 021	62 110	63 244

[†]Means in column, for row spacing or seeding rate, followed by same letter are not significantly different at $P \leq 0.05$.

Table A7. Mean plant density for Casselton, ND, 2017 and Prosper, ND, 2018 averaged across row spacing and seeding rate with corresponding growing degree days.

	Casselton, ND															
	Growing Degree Days															
	173		185		221		245		257		296		337		458	
cm																
30	2 859	b[†]	119 264	b	314 013	a	338 740	a	354 724	a	146 095	a	362 845	a	362 987	a
61	11 698	a	158 169	a	307 704	a	336 373	a	348 567	a	144 108	a	358 343	a	358 483	a
live seed ha^{-1}																
197 600	3 044	a	66 998	d	157 052	f	168 461	d	185 248	e	76 139	f	180 411	f	205 169	f
247 000	9 026	a	105 481	bcd	221 920	e	234 171	c	246 291	d	103 275	e	246 324	e	258 283	e
296 400	4 173	a	94 801	dc	307 660	d	321 710	b	341 908	c	140 858	d	328 439	d	341 908	d
345 800	10 516	a	152 923	bc	312 874	cd	339 731	b	350 909	c	144 953	d	344 757	d	355 115	d
395 200	8 379	a	160 801	b	360 766	bc	411 747	a	417 662	b	169 884	c	401 269	c	421 011	c
444 600	12 681	a	242 515	a	436 437	a	439 392	a	451 759	b	186 206	bc	445 283	bc	459 123	bc
494 000	3 131	a	147 497	bc	379 306	b	447 682	a	467 746	b	194 394	b	458 033	b	484 539	b
543 400	12 898	a	209 852	a	443 257	a	456 096	a	548 181	a	220 983	a	513 719	a	552 464	a
LSD (0.05)	14 236		62 150		49 241		54 907		51 591		20 523		47 594		47 613	
	Prosper, ND															
	Growing Degree Days															
	131		142		153		164		176		200		224		314	
cm																
30	49 979	b	167 040	b	199 056	b	229 035	a	193 207	a	173 290	a	180 759	a	212 053	a
61	76 824	a	227 148	a	270 461	a	276 366	a	296 508	a	299 610	a	311 741	a	333 210	a
live seed ha^{-1}																
197 600	24 759		105 982	c	145 356	f	158 868	e	178 736	e	187 205	f	189 222	f	189 222	f
247 000	20 895		113 833	c	169 977	ef	182 924	e	197 539	e	211 383	f	213 434	f	213 434	f
296 400	49 598		174 715	bc	221 909	de	253 989	d	271 774	d	278 702	e	280 666	e	280 666	e
345 800	32 113		170 229	bc	253 913	d	293 519	cd	326 662	c	334 075	d	336 165	d	336 165	d
395 200	67 580		224 673	ab	273 603	cd	345 668	bc	381 529	b	393 633	c	393 633	c	393 633	c
444 600	76 124		270 814	a	357 555	ab	397 988	b	410 202	b	423 783	bc	426 953	bc	426 953	bc
494 000	63 073		264 673	a	345 354	bc	398 389	b	425 049	b	465 920	b	465 920	b	465 920	ab
543 400	63 073		291 519	a	421 320	a	463 878	a	472 389	a	514 947	a	514 947	a	514 947	a
LSD (0.05)	ns		74 747		71 828		54 471		46 581		46 582		47 851		54 599	

[†]Means in column, for row spacing or seeding rate, followed by same letter are not significantly different at $P \leq 0.05$.

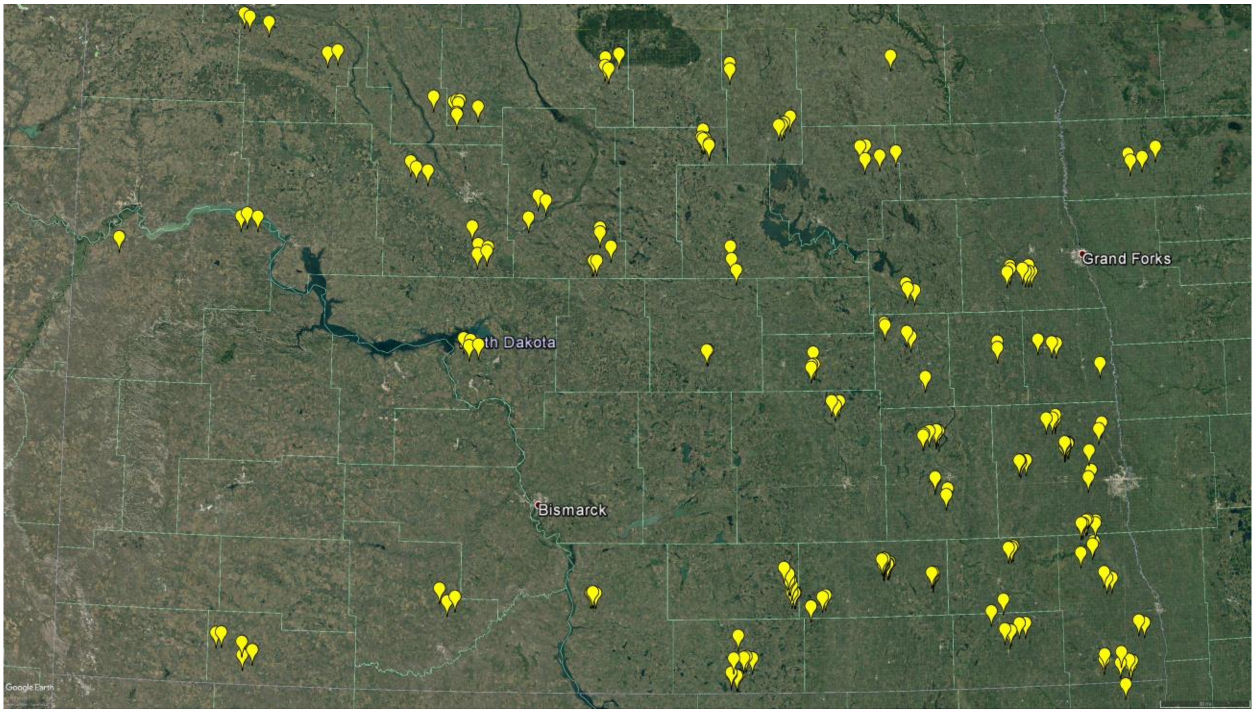

Figure A1. North Dakota field visit locations in 2016 and 2017.

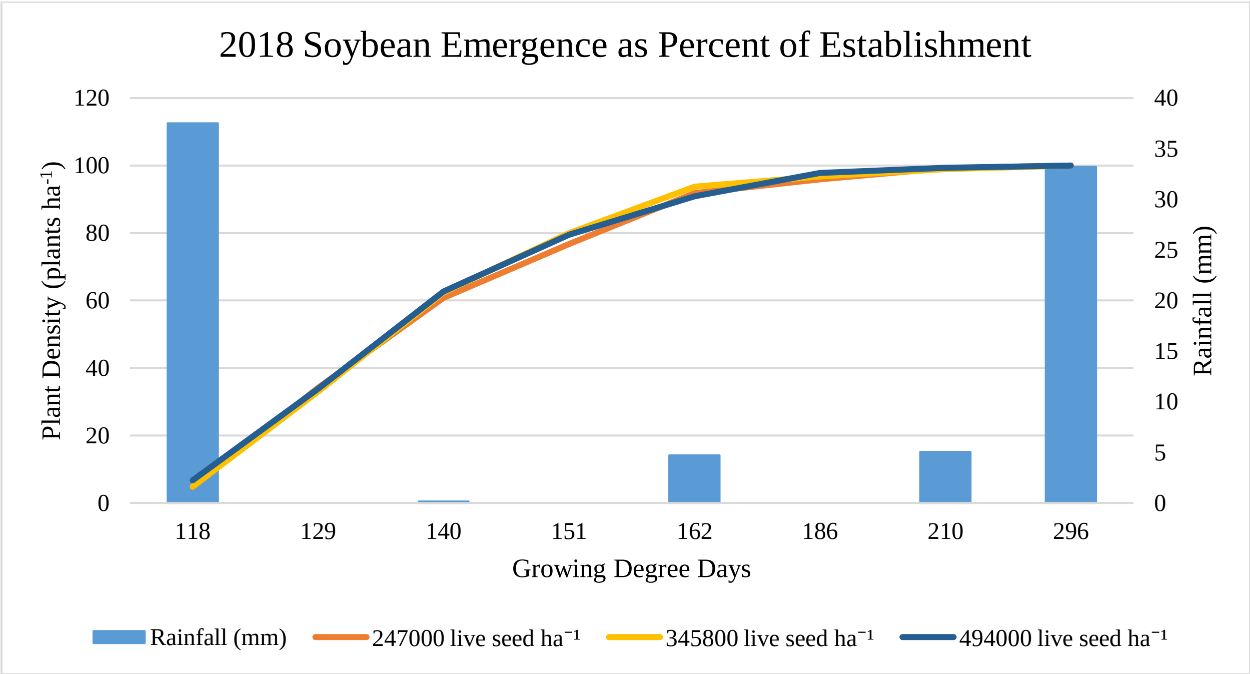

Figure A2. Soybean emergence as percent of establishment in 2018.
Soybean plant densities as a percentage of established plant density observed with corresponding growing degree days (GDD) and recorded rainfall events in 2018.

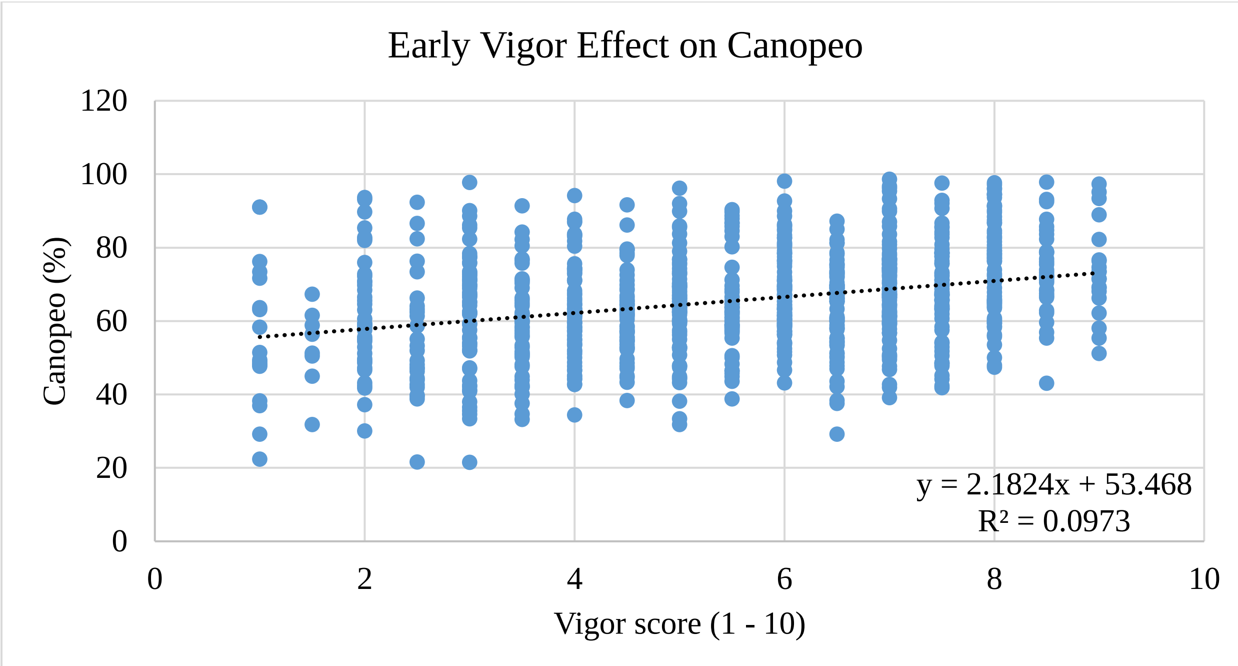

Figure A3. Early vigor effect on soybean Canopeo readings.

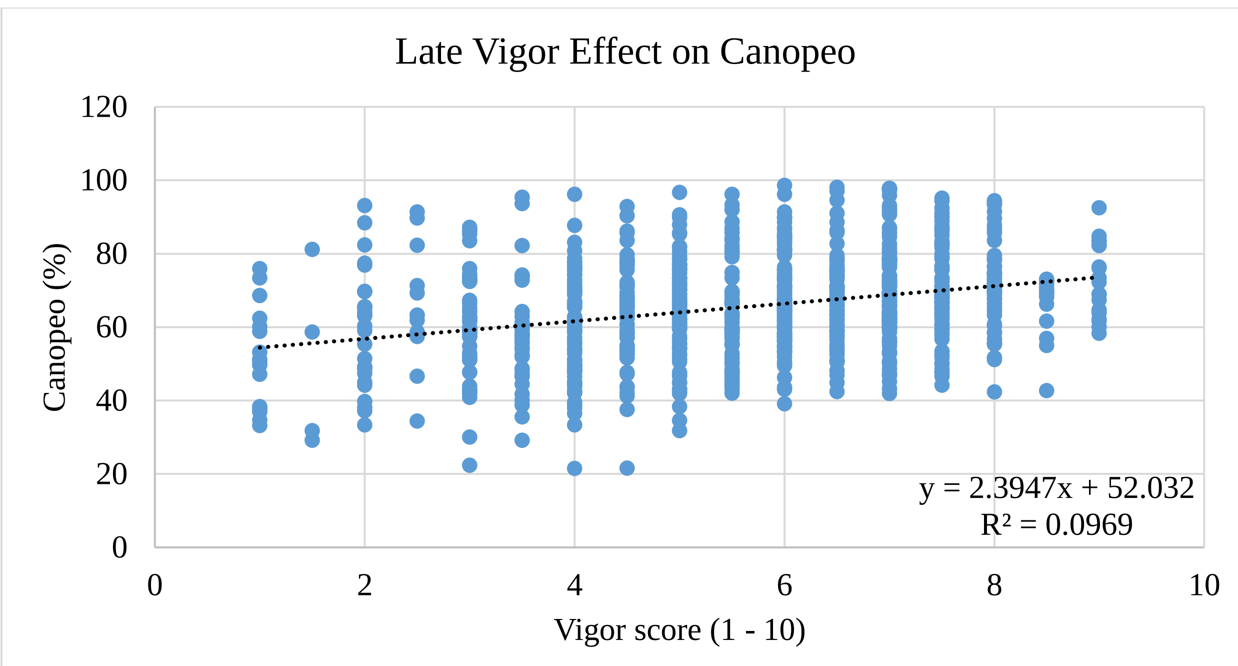

Figure A4. Late vigor effect on soybean Canopeo reading.

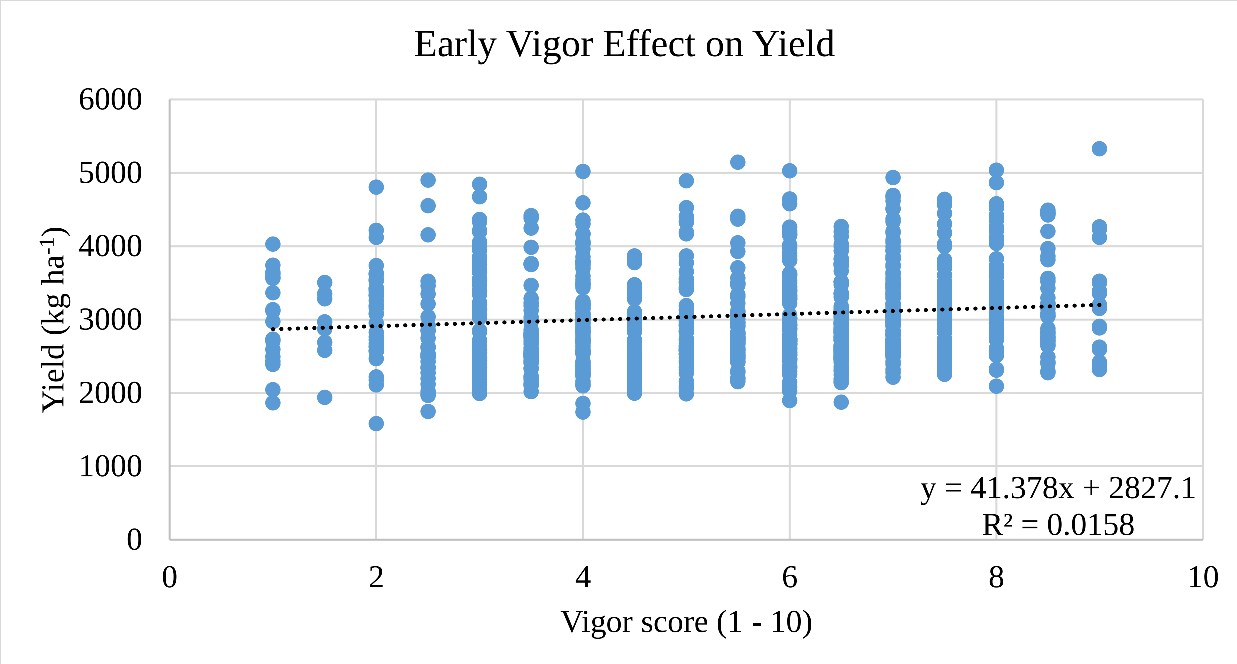

Figure A5. Early vigor effect on soybean yield.

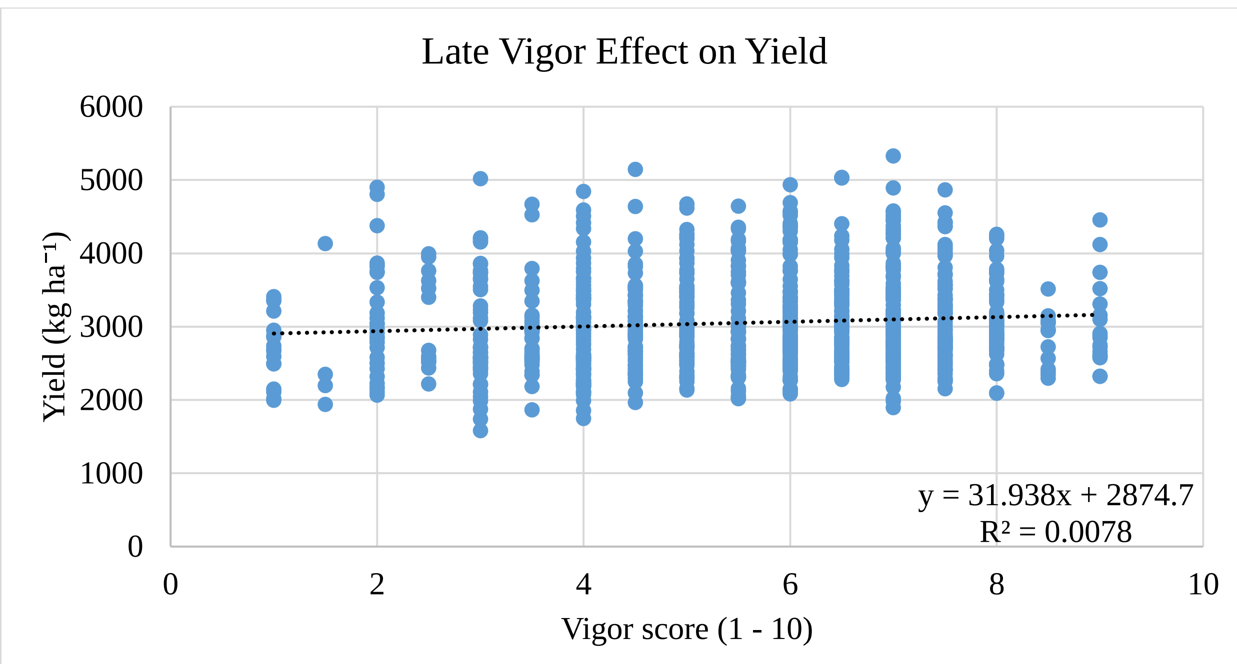

Figure A6. Late vigor effect on soybean yield.

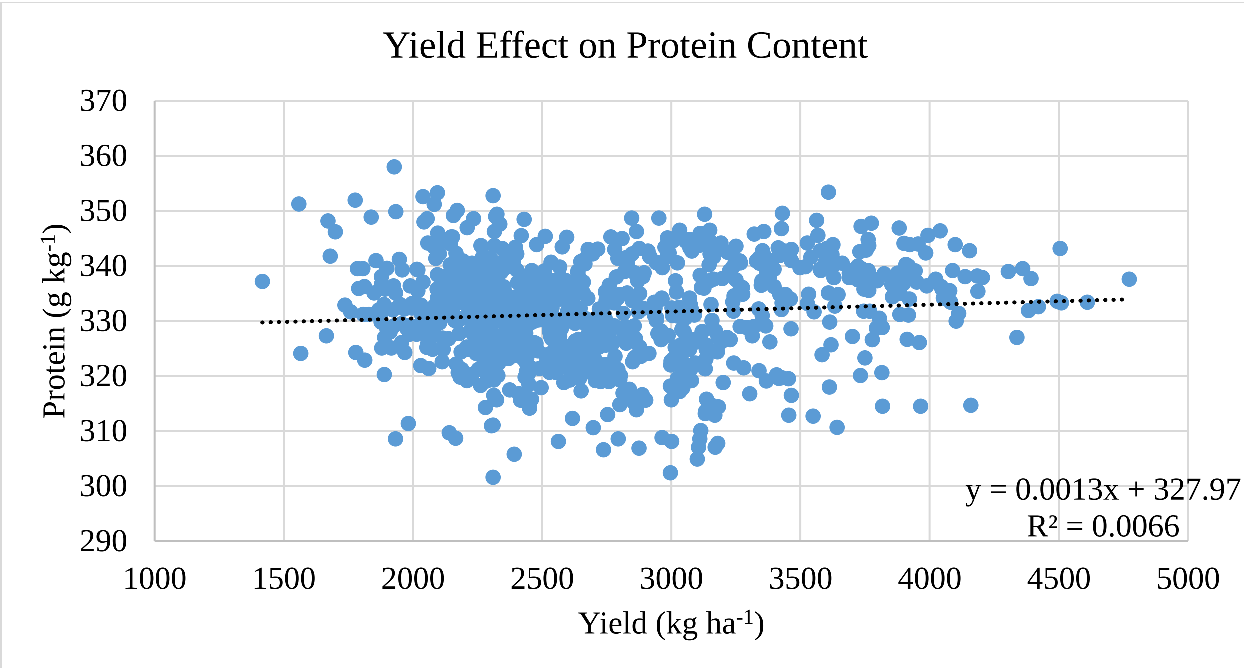

Figure A7. Soybean yield effect on protein content.

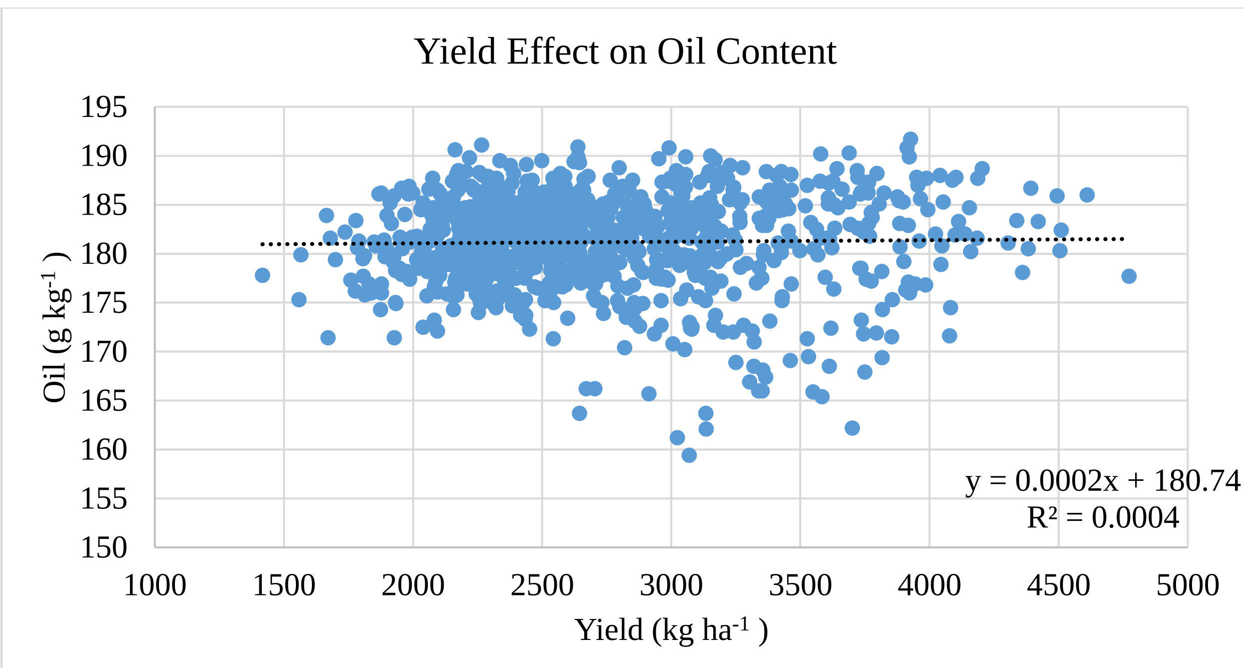

Figure A8. Soybean yield effect on oil content.

ND Soybean Producer Survey, 2017

ALL INFORMATION PROVIDED WILL BE KEPT CONFIDENTIAL

Producer name:_________________________ **Mailing address:**________________________________ **Phone** (for questions):___________________

Email (to send reports/findings):__________________________________

Any questions, please contact survey coordinator: **Peder Schmitz, 701-231-8063 or peder.schmitz@ndsu.edu**

Please provide four **soybean** fields on your farm in **2017** (please exclude flooded out/heavy hail fields)

		EXAMPLE	2017 Soybean	2017 Soybean	2017 Soybean	2017 Soybean
Pre-season & Planting Information	**Specify field location by Section: Township: Range** →	S22:T140N:R49W	___:___:___	___:___:___	___:___:___	___:___:___
	Please sketch in the boundaries of this field within the section, whether or not section number is given above →	NW 1/4, NE 1/4 (shaded), SW 1/4, SE 1/4	NW1/4, NE1/4, SW1/4, SE1/4	NW1/4, NE1/4, SW1/4, SE1/4	NW1/4, NE1/4, SW1/4, SE1/4	NW1/4, NE1/4, SW1/4, SE1/4
	If field location is not specified above, provide GPS coordinates of approx. center of the field OR County & approx. field location by road number	46.93235, -96.84264 Cass 40 ave E of I29				
	Field size in **acres**	40 acres				
	Planting Date in this field **(Month/Day/Year):**	5/10/17				
	Seeding Rate **(seeds/ac)** and estimate **established stand:**	150,000 | 138,000				
	Row spacing **(inches)**: / Inoculation with bacteria **(Y/N)**:	14 | Y				
	Variety Name **(PLEASE BE SPECIFIC - Brand & Number):**	Pioneer | P07T50R				
	Seed Treatment? (Y/N) If so, give product **Brand Name**	Y | CruiserMaxx				
	Starter/planting-time fertilizer? What nutrient(s)?	Yes | N,P Liquid				
	Crop in this field in 2016 & Yield; Residue baled or grazed?	Wheat | 55 | N				
	Tillage after 2016 crop? No-Till **(NT)**; Ridge **(RT)**; Strip **(ST)**; Disk **(D)**; Chisel **(C)**; Vertical **(V)**; Field Cultivator **(FC)**; Land Rolling **(LR)** – Indicate timing (month/year)	D 11/16 FC 5/17 LR 5/17				
	Type of drainage: none, **surface** drainage, some newer tile, newer systematic tile, old clay tile, other	Some newer tile/ limited surface				
	Fertilizer after 2016 crop? (non-starter) -Specify rate (lbs. NUTRIENT/acre) and timing (month/year)	P_2O_5: 50 | K_2O: 10; Other: S (11); Time: 5/16	P_2O_5: | K_2O:; Other:; Time:	P_2O_5: | K_2O:; Other:; Time:	P_2O_5: | K_2O:; Other:; Time:	P_2O_5: | K_2O:; Other:; Time:
	Any Lime (L) or Manure (M)? If yes, specify timing (mo/yr)	No				
In-season & Harvest	**Soybean YIELD (bu/a) in this field in 2017:**	34.4 bu/ac				
	Avg. Yield of your **Lowest** & **Highest** Yielding field (bu/a): ***across ALL soybean fields you harvested in 2017***	Low: 25 | High: 49	Low: | High:	**Total** number of soybean fields **in 2017**: ______		
	PRE- or POST-emergence herbicide program or BOTH?	Post only				
	Any in-season foliar fungicide (F) / insecticide (I)?	F and I				
	Soybean Cyst Nematodes (Yes-level/No/I don't know)?	Yes-low				
	Iron Deficiency Chlorosis - IDC (Yes-level/No)?	Yes				
	Any significant yield loss due to insects, diseases, weeds, frost, hail, flood, lodging, poor stand? Specify problem and extent	Aphids (low) Hail (8/17)-minor				

NCSRP North Central Soybean Research Program — NDSU Extension Service North Dakota State University

Please include any other pertinent information on the back of this sheet
Return completed form to: Hans Kandel - NDSU Plant Sciences - Dept 7670 PO Box 6050 Fargo, ND 58108-6050

Figure A9. Example of a North Dakota Soybean Survey form.