YIELD-LIMITING FACTORS IN NORTH DAKOTA SOYBEAN FIELDS

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

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In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Plant Sciences

November 2017

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Yield-limiting Factors in North Dakota Soybean Fields

By

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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

Average soybean [*Glycine max* (L.) Merrill] yields in North Dakota remain below north central USA averages, and crop yield potentials. The effect of planting date (PD), cultivar relative maturity (RM), and seeding rate (SR), on yield, were evaluated in 821 producer fields in 2014-2016 seasons. Crop management varied by location. State average PD was 19 May, and planting after 1 May reduced yield average 0.4% d^{-1}. Planting a cultivar with 0.1 RM earlier than recommended reduced yield by 1.3%. Producers estimated seedling mortality at 10%; when observed, it was 12.3%. An additional 7.9% reduction of established population occurred in-season. In-season plant reductions of 4.5% were also observed in research trials. North Dakota producers should plant closer to 1 May if conditions are favorable, select latest-maturing cultivars adapted for area, maximize established plant population relative to seeding rate, and determine causes of in-season plant reductions to adapt management practices if necessary.

ACKNOWLEDGMENTS

I feel so blessed for the opportunity that Dr. Hans Kandel has so generously provided to allow me to further my education and professional development. I cannot fully express my gratitude for all the time, knowledge, and experiences that he has so freely offered to ensure my success in this program and beyond. Dr. Kandel has been a positive influence on me and my family, and I will forever treasure the mentorship he has provided. Thank you Dr. Kandel.

I also am very grateful for the guidance, feedback, and encouragement that Dr. Joel Ransom, Dr. Tom DeSutter, and Dr. Burton Johnson have provided as committee members. They have each sacrificed many hours of personal time to not only broaden my agricultural knowledgebase, but inquire on the general welfare of my family.

I would like to thank the 130+ soybean producers who provided field data for this research; including many North Dakota Soybean Council and Growers' Association members. This would not have been possible without the assistance of many extension service representatives statewide. I would especially like to recognize Lindy Berg, Rachel Wald, Tim Becker, Sheldon Gerhardt, and Chandra Langseth, as they are each an outstanding example and exceptional resource for producers in their area. Thank you to Peder Schmitz, Chad Deplazes, Darin Eisinger, and Grant Mehring, for their continued support and assistance with various components of this project.

I am so grateful for this opportunity that I have had to learn and experience so many new things. I credit it all to the continued strength and support that I have received from my Heavenly Father, and my wonderful wife Courtney. Thank you so much Courtney for being my best friend, for your unfailing encouragement, for your endless patience, and for being an amazing mother to our children. I truly would have never finished this without your support.

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LIST OF ABBREVIATIONS

CMF ....Producer crop management factor.

EF ....Environmental factor.

GR ....Soybean growing region.

IR...Incremental seeding rate.

LSD ....Least significant difference.

NASS ....National Agricultural Statistical Survey.

NC-USA...North Central USA.

NDSU..North Dakota State University.

NRCS ....Natural Resources Conservation Service.

NDAWN ....North Dakota Agricultural Weather Network.

PD ....Planting date.

RM ....Cultivar relative maturity.

SAS ....Statistical Analysis System.

SR..Seeding rate.

USDA...United States Department of Agriculture.

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INTRODUCTION

Increases in soybean [*Glycine max* (L.) Merrill] production in the North Central region of the USA (NC-USA) are needed to satisfy increasing global demand for food, biofuel, and livestock feed. Therefore, producers should seek to maximize yields on soybean hectares planted. Average soybean yield in the NC-USA (comprising Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota and Wisconsin) during 2010-2014 was 2892 kg ha^{-1}, yet some producers can consistently attain soybean yields near or greater than 5380 kg ha^{-1} (Specht et al., 1999; Grassini et al., 2014; Van Roekel and Purcell, 2014). An estimated 2.43 million hectares of soybean were harvested in North Dakota in 2016 with an average yield of 2791 kg ha^{-1} (USDA, 2017).

As represented in Figure 1, environmental factors (i.e. sunlight, rainfall, and soil) and genotype primarily determine the yield potential of a crop. Yield at harvest will differ from the crop yield potential, as management practices applied by producers have varying levels of influence on overall yield. The difference in crop productivity between yield potential and actual yield when harvested, is referred to as the yield gap (Cassman et al., 2003).

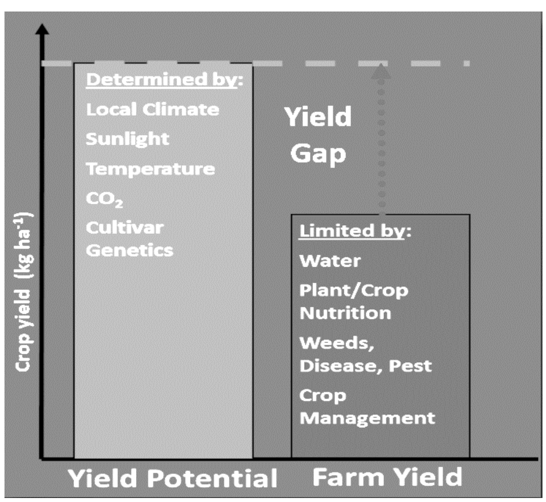

Figure 1. Factors influencing soybean yield potential and actual farm yield attained. Adapted from Cassman et al. (2003).

A common approach for identifying yield-limiting factors in producer fields is for researchers to selectively apply differing levels of management practices in research trials conducted in multiple producer fields (Villamil et al., 2012). Research results are evaluated to determine whether the tested management practice is statistically higher- or lower-yielding than the prior practice used. Additionally, it is necessary to determine if the improvement in yield justifies any additional time or costs associated with the change in crop management. An alternative method is the use of producer-reported yield data, coupled with information regarding applied crop management practices (Grassini et al., 2011b). This approach can be used to (1) evaluate current on-farm management relative to recommended optimal practices, and (2) discern the yield impact of individual factors in the context of large-scale fields. This can be contrasted to findings in small experimental plots, and ensure that proposed practices are within the range of cost-effective management actually being used by producers. Factors including producer-reported data, and regional weather and soil information, provide the framework for larger spatial representation of current soybean management and productivity across the varying growing areas of North Dakota.

To identify factors limiting soybean yields in North Dakota, management and yield data from 889 producer fields were collected for 2014, 2015, and 2016 growing seasons. Field data were analyzed to identify yield-limiting producer crop management factors (CMF). Identifying soybean yield-limiting factors allows NDSU research and extension specialists to adjust current agronomic recommendations (if necessary) and to promote maximum attainable yield in North Dakota producers' fields. Although there were many CMF reported by producers on the survey, this thesis will focus on differences in soybean yield response at varying seeding rates, timing of planting, established plant populations, and cultivar relative maturity rating.

REVIEW OF LITERATURE

Timing of Planting

In Minnesota and Wisconsin, an early planting date (1 May compared to 15 May) has resulted in significant yield increases (Grau et al., 1994; De Bruin and Pedersen, 2008b). Environmental factors encountered during germination, emergence, and early vegetative growth stages, have a direct influence on crop yield. Dependent on genotype, soybean plants can adapt development to survive and produce in varying environmental conditions (Pierozan et al., 2015). Planting date determines duration of vegetative growth. Environmental conditions may differ with earlier seeding, compared to normal planting date.

Soybean seedlings emerge as elongation of the hypocotyl moves the cotyledons towards the surface of the soil. Days to seedling emergence, and the rate of hypocotyl elongation, are influenced by temperature (Hatfield and Egli, 1974). Hypocotyl elongation was observed at temperatures ranging from 10°C to 40°C. Although seedling emergence occurred throughout this range, it was most rapid between 25°C to 35°C (Hatfield and Egli, 1974). Seedling emergence is expected 5-15 d after planting in North Dakota (Kandel and Endres, 2015). As the seedling emerges through the soil surface, the growing point of the seedling is exposed above ground and susceptible to variant weather and fluctuations in ambient temperature. Of primary concern, a late spring frost may damage the apical terminal shoot, resulting in a significant reduction in the established plant population (Hume and Jackson, 1981). For the region in which the crop is grown, determining the appropriate timing of seedling emergence is critical for establishing a healthy, viable soybean plant population.

Relative Maturity

To maximize yield, it is important to select a soybean cultivar with a relative maturity (RM) appropriate for planting timing, and adapted for the region in which it is grown. Length and timing of soybean vegetative growth and flowering period, and soybean end-use traits (i.e. quality and oil composition) are influenced by photoperiod and temperature (Garner and Allard, 1930; Howell and Cartter, 1953; Zhang et al., 2001, Han et al., 2006). Soybean maturity groups of North America were originally delineated based on geospatial differences in photoperiodic factors and in-season temperatures (Morse et al., 1949; Scott and Aldrich, 1970). Genetic improvements of modern cultivars and climate change have prompted researchers to modify and expand these maturity groups to include 13 zones ranging from 000 to X (Zhang et al., 2007; Mourtzinis and Conley, 2017 [Figure 2]). Adapted North Dakota maturity groups range from 00 to 1 (Kandel and Endres, 2015).

Scott and Aldrich (1970) indicated the date of maturity of cultivars within the same maturity group can vary from 10 to 18 d. To account for these differences in RM, maturity group zones are subdivided by 10 units (.0 to .9) and assigned to cultivars based on the number of d delay in physiological maturity a cultivar exhibits compared to the earliest expected timing of maturity within a group. This unit number is appended to the respective maturity group and represents the RM of a cultivar (i.e. RM of 0.5 within North Dakota in Figure 2).

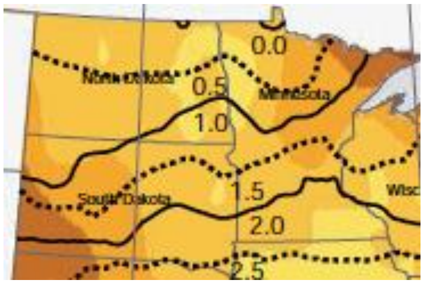

Figure 2. Observed soybean maturity groups in the northern United States.
†Lines indicate maturity group boundaries. Source: Mourtzinis and Conley, 2017.

Seeding Rate and Plant Population

Soybean yield is influenced by initial seeding rate, and the number of established plants ha^{-1} (Egli and Zhen-wen, 1991; Van Roekel et al., 2015). The seeding rate that promotes maximum attainable yield varies dependent on growing conditions (Shibles et al., 1975). Soybean producers primarily select a seeding rate based on field productivity in previous years and cost of seed ha^{-1}. Selecting an optimal seeding rate supported by regional university studies helps producers maximize crop productivity and economic efficiency. A proper seeding rate ensures that producers avoid reduced yields due to plant overcrowding (De Bruin and Pedersen, 2009) and light-use inefficiencies (Purcell et al., 2002; Edwards et al., 2005).

Weber et al. (1966) evaluated soybean growth at varying plant densities by adjusting both row spacing and seeding rate. Increased plant competition was observed when the distance between two plants was <6 cm. The increased competition resulted in decreased branching, and a reduced number of pods and seeds per plant. Determining the optimal plant density and seeds per plant is necessary to avoid yield losses in soybean (Van Roekel et al., 2015).

To maximize yield in North Dakota production fields, NDSU recommends an established soybean plant density of 370 600 plants ha^{-1} (Kandel and Endres, 2015). The seeding rates that will provide this recommended plant population will vary by factors such as management practices, seed germination percent, and planting conditions. Though yield response at varying seeding rates has been researched in areas of the NC-USA (Cooper, 1977; De Bruin and Pedersen, 2008a), there is limited information on expected plant population establishment at varying seeding rates. Additionally, plant losses that occur after the population has been established, at differing plant population densities, have yet to be published.

At a fixed seeding rate, row spacing influences the plant spacing of seeds within each row. Weber et al. (1966) indicated that soybean plants grown at high densities have fewer branches, pods, and seeds per plant. Narrowing row spacing while applying a consistent seeding rate will result in greater distance between each plant. Numerous studies in the northern soybean growing region of the US have reported yield increases at reduced row spacing of 25 cm, compared to 76 cm spacing (Ablett et al., 1991; Lueschen et al., 1992; Lee, 2006). These findings were supported by other studies including varying seeding rate densities, planting dates, and tillage practices (Shibles and Weber, 1965; Lueschen et al., 1992).

Increased yields at narrow row spacing are primarily attributed to reduced days it takes from seedling emergence to canopy closure, at which point interception of solar radiation is maximized (Campillo et al., 2012). Achieving canopy closure at late vegetative, or early reproductive stages, provided for additional pod formation, and increased soybean yield (Board et al., 1992). Maximizing solar radiation interception at early developmental stages increases the amount of accumulated photosynthates required for seed fill (Shibles and Weber, 1966) and provides for significant yield increases (Board and Harville, 1994; Andrade et al., 2002; Board, 2004).

OBJECTIVES

The primary goal of this research was to identify producer crop management practices that are yield-limiting in North Dakota soybean fields. Producer management of seeding rate and date, cultivar RM, and established plant population, were the main factors evaluated. The second objective was to validate field data reported on the paper survey by producers, and identify any unreported yield-limiting factors in producers' fields, with a focus on established plant population, percent crop canopy cover, and seasonal plant loss.

The third objective was to evaluate early and late-season soybean plant population in small research plots to quantify seasonal plant losses at varying established populations and to relate late-season plant population to yield. The fourth objective was to estimate yield reductions resulting from manageable soybean yield-limiting factors in North Dakota, and provide possible management recommendations to producers.

MATERIALS AND METHODS

Producer Survey

A paper survey was distributed to soybean producers throughout North Dakota. Data were collected from soybean producers statewide to provide representation of current soybean production systems. Collecting data from multiple producers, with differing management practices, provided for a diversified sampling of producer crop management factors (CMF) and corresponding yield data. A network of county extension agents, industry representatives, and Soybean Council/Growers Association representatives, assisted in collecting surveys. Survey forms were completed by at least four producers for most participating counties each year. Field data were collected from three growing seasons. In the first-year survey, producers were asked for field information for the prior two crop seasons (2014 and 2015). A second survey was conducted in the spring of 2017 for the 2016 growing season. Surveys were collected for at least 280 soybean fields for each of the three growing seasons. Fields with unreported yields, incomplete agronomic information, or with adverse in-season factors (i.e. hail, flooding) were excluded from the analyses.

Upon receipt of a completed survey, each field was assigned a unique identifier, and data were input into an Excel database (Microsoft Office 2013, Redmond, Washington). Field locations were converted from US legal land description (Public Land Survey System, US Bureau of Land Management) to global positioning system (GPS) coordinates utilizing Earth Point software (Earth Point, Boise, Idaho) and geospatially referenced on Google Earth (Google Inc., San Francisco, California). Field boundaries were manually outlined by referencing Google Earth imagery to match field boundaries as recorded by producers on the paper survey form. Field area was converted into hectares.

Information regarding various CMF were requested. Factors of primary interest in this project are identified in Table 1.

Table 1. Summary of crop management factors recorded by the North Dakota soybean producer survey 2014-2016.

Crop management factor (CMF)	Reported as
Planting date (PD)	month/date
Cultivar relative maturity (RM)	cultivar name and number
Seeding rate (SR)	seeds ha^{-1}

Using a similar method to Akyüz et al. (2017), RM of cultivars were transformed prior to statistical analyses to prevent computational errors. Each RM was associated with a respective RM code (Table 2) to maintain a consistent unit of scale (incremental whole number) when performing statistical analyses.

Table 2. Cultivar relative maturity and corresponding relative maturity code.

RM†	RM code‡	RM	RM code
00.4	4	0.5	15
00.5	5	0.6	16
00.6	6	0.7	17
00.7	7	0.8	18
00.8	8	0.9	19
00.9	9	1.0	20
0.0	10	1.1	21
0.1	11	1.2	22
0.2	12	1.3	23
0.3	13	1.4	24
0.4	14	1.5	25

†RM, cultivar relative maturity,
‡Scale adapted from Akyüz et al., 2017.

Yield at harvest was converted to kg ha^{-1}. As yields were compared for multiple growing seasons from varying locations, yields were normalized for each growing season by transforming individual yields into a percentile value, relative to the statewide mean yield (i.e. Yield_{2014})

reported by producers for the respective season. Transformed yields (percentile values) were multiplied by a combined-year weighted average yield, allowing comparison of yields in kg ha^{-1} instead of a percentile value. Combined-year weighted average was calculated as: (Yield$_{2014}$*[n] fields$_{2014}$ + Yield$_{2015}$*[n] fields$_{2015}$ + Yield$_{2016}$*[n] fields$_{2016}$)/ total [n] fields$_{2014\text{-}2016}$. Incidence and severity (low/moderate/high) of any diseases, pests, or adverse growing conditions (i.e. iron deficiency chlorosis, aphids, soybean cyst nematode, or hail) were reported. Fields with factors moderate or high in magnitude were excluded from the final dataset.

Statistical analysis was completed utilizing Statistical Analysis System (SAS) 9.3 software (SAS Institute, Cary, NC). Multiple regression and covariate analysis techniques were applied as have been used in prior studies that led to peer-reviewed publications (Lobell et al., 2005; Tittonell et al., 2008; Grassini et al., 2011a; Villamil et al., 2012). These techniques were necessary as survey data does not follow a traditional experimental field trial approach wherein random environmental differences can be experimentally minimized by applying replicate blocking, factorial treatment designs, and well-known statistical analyses (Grassini et al., 2015).

Of the 889 fields collected for the 2014-2016 growing seasons, some fields were excluded due to discrepancies, incomplete data, or adverse in-season factors as previously described. The final statewide dataset was comprised of 821 soybean fields (Figure 3). Additional fields were excluded from certain analyses dependent on CMF being modeled. These fields were automatically selected for exclusion by SAS if missing data were detected for any of the factors being evaluated; this was done to avoid misrepresentation in regression results.

The coefficient of determination for single factor analysis is represented as r^2. For multiple factor regression models, the adjusted multiple coefficient of determination is represented as R^2_{adj} and was calculated using SAS to quantify the amount of variability in yield response (independent variable) explained by dependent variables. The R^2_{adj} is recommended when evaluating the fit of regression models with multiple variables as terms (Steel and Torrie, 1980). This limits inflated R^2 values, and errors due to overfitting models (where fit begins to model random error in data). The R^2_{adj} is used when comparing regression models with differing number of predictive variables and/or observations, to account for any inflation in R^2 induced by covariates (Piper and Boote, 1999).

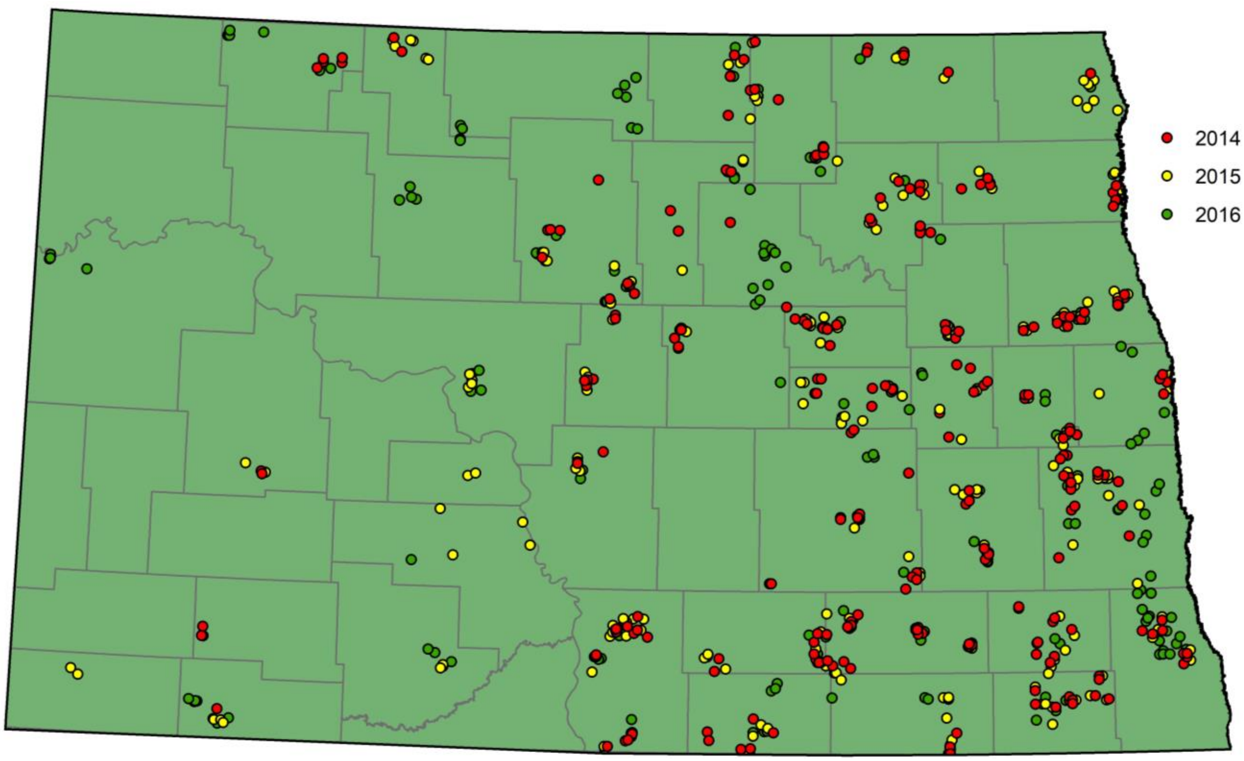

Figure 3. Producer soybean fields from 2014-2016 survey.

For multiple regression models, violations of assumptions were tested to avoid misrepresentation of data. Variable residuals were plotted to ensure standard errors were random across the dataset. The Box-Cox method (Box and Cox, 1964; 1982) is commonly applied in agriculture to evaluate fit and accuracy of values predicted from a regression model, based on the distribution and variance of the input variables (Piepho, 2009; Scudiero et al., 2014; Zuber et al., 2015). The Box-Cox method was applied in this study to evaluate the fit of residuals of yield values predicted by CMF variables in the linear regression model. Box-Cox analysis in SAS (PROC TRANSREG) manipulates model variables into various transformations, and regresses the modified variables to validate that linear regression is the best-fit model.

Blalock (1963) noted that multicollinearity is a concern when developing multiple regression models as highly-correlated independent variables can drastically influence the significance and fit of variables and the overall model. As recommended by Hair et al. (1995), multicollinearity was screened for by evaluating the variance inflation factor. The inflation factor was calculated in SAS for each variable, as it was added as a term in stepwise regression models (Olivoto et al., 2017). An acceptable variance inflation factor value for any variable added to a stepwise multiple variable regression model was <10.

Mallows' C_p statistic (Mallows, 1973) was reported in SAS output for each sequential variable added to a model. This aided in regression model selection by detecting variables that were likely inducing bias or abnormal variance in predicted responses (Ruffo and Bollero, 2003; Culman et al., 2013). Models were selected to maximize the R^2 value, while including only significant variables that improved the precision of the model, as indicated by the calculated coefficient of variance (CV= s / mean). Pearson correlation coefficient (r) was included in SAS output for pairings of independent variables and evaluated to ensure autonomy (Snedecor and Cochran, 1981).

Soybean Growing Regions

As geospatial differences in statewide yield were revealed in this study, it was hypothesized that some variability was likely influenced by location-dependent environmental influences (i.e. differing soil type, precipitation, climate, and growing season length). Additionally, crop management is likely to differ dependent on regional environmental influences. To account for this, differences in environmental factors (EF) were compared statewide to define distinct soybean growing regions (GR) throughout North Dakota. Within each region we identified the producer crop management practices (i.e. seeding rate, timing of planting, row spacing) that provided for the highest average yields.

An extensive literature review was performed to select and evaluate EF of primary influence on yield, represented by relevant, readily-available data. Selected EF included geological and ecological features, soil properties, water availability, and climatic influences. Data identifying varying levels within individual EF (i.e. increasing scale of soil crop-productivity ratings) have been previously quantified and recorded, and provide a geospatial framework for identifying areas with similar soybean growing conditions. Utilizing Esri ArcGIS 10.5 software (Environmental Systems Research Institute, Redlands, CA), geospatially-referenced metadata comprising each EF was retrieved from the ArcOnline Image Service interfaced with the program. Metadata were rendered and projected as graphic representations (imagery layers) onto a topographical map of North Dakota providing geospatial representation for each EF. Each EF imagery layer was evaluated subjectively to identify and outline general areas of differences within the EF (based on hue or color intensity and representative of varying environmental conditions). North Dakota soybean GR were delineated after compiling and overlaying all EF-relevant imagery layers.

The most relevant EF influencing growth and development of crops (soil, water availability, and temperature) were applied as layers for defining GR. Level III and IV Omernik Ecoregions (North Dakota Game and Fish Department, NDGISHub, 2014) provided the base layer as these ecoregions are scaled and grouped based on similarities in spatial biophysical and soil properties influenced by geological, pedological, and edaphological relationships (Omernik, 1988). Differences among soil crop productivity ratings were outlined by evaluating the USA Soils Crop Production layer as represented in Figure 4 (USDA, NRCS, Esri, 2017a).

Statewide differences in water availability and crop-use levels were determined by evaluating three different representations related to these EF. As portrayed in Figure 5, soil properties influencing level of water retention and plant-available water were evaluated utilizing the USA Soils Available Water Storage (USDA, Esri, 2016b). Differences in average depth of subsurface saturation zones (water table) were outlined referencing the USA Soils Water Table Depth representation (USDA, NRCS, Esri, 2017b). Water use and other EF influencing crop development were depicted by the USA Evapotranspiration imagery (University of Montana, Esri, 2016). The USA Cropland metadata with the most recent available representation (2013) of concentration and geospatial extent of soybean hectares was used (USDA, Esri, 2016a).

To form an aggregated representation of all EF evaluated, beginning with the lowest level of definition (broadest scale metadata), individual EFs were overlaid one upon another, forming a combined geospatial framework for defining GR (Figure 6). This geospatial framework allowed for similarities in proximal location and extent of coverage to be compared and aggregated for multiple EF. Small areas lying within the defined GR, depicting differences among <4 EF properties, were identified as areas likely to have slightly-reduced yield potential and productivity compared to the rest of the GR. Outlined areas for individual EF with limited representation in the geospatial framework (only associated with one EF), were excluded when defining GR boundaries.

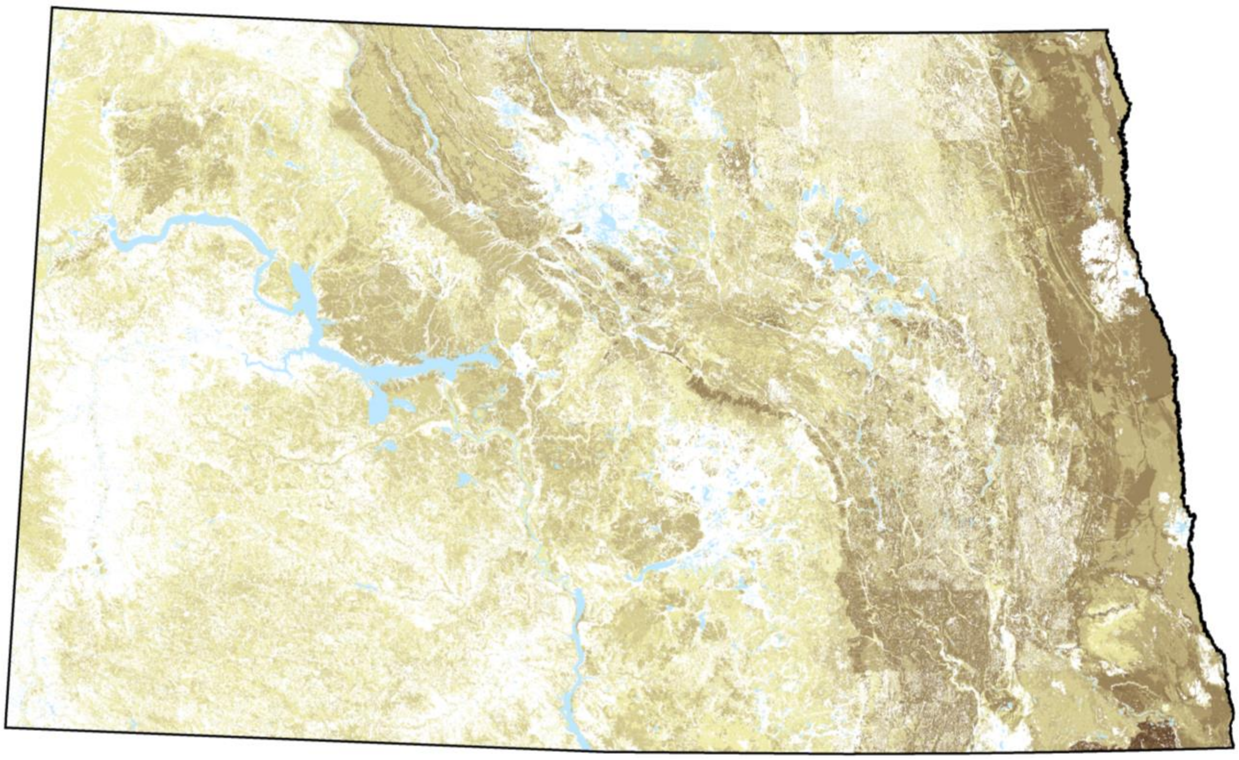

Figure 4. USA Soils Crop Production representation for soil productivity index in North Dakota.
Source: USDA, NRCS, Esri, 2017a.

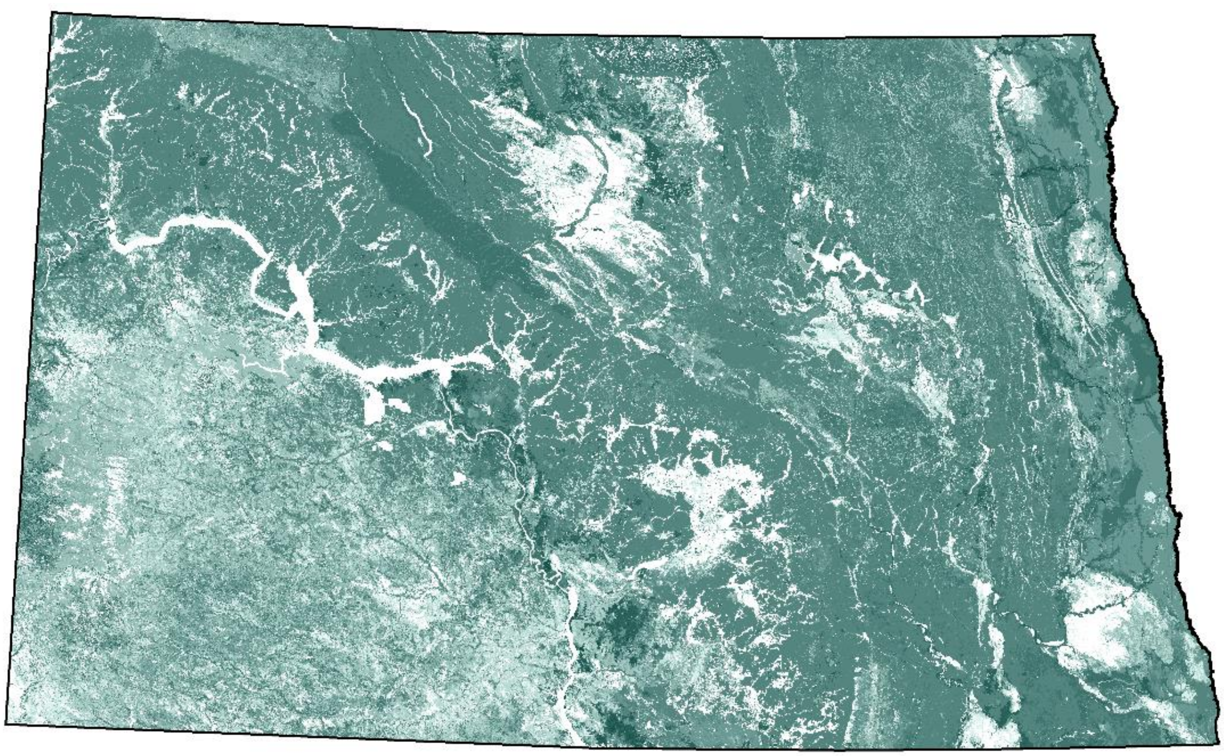

Figure 5. USA Soils Available Water Storage representation in North Dakota.
Source: USDA, Esri, 2016b.

Climate zones retrieved from the Global Yield Gap Atlas (www.yieldgap.org) were utilized to divide areas that had similar soil and water properties, but differing annual mean temperature, growing season length, and climatic influences. Additionally, some aggregated areas in Western North Dakota were later combined with neighboring areas to provide adequate representation of surveyed fields when performing GR data analyses. After completion of individual, cross-comparison, and compiled evaluation of all EF, 10 distinct soybean GR were identified within North Dakota (Figure 6). These GR were numbered incrementally, beginning with GR 1 as the highest-yielding region, based on 2014-2016 producer survey yield averages.

A finalized representation of North Dakota soybean GR (Figure 7) provided a practical resource for geospatial reference of GR locations. For all fields located within the same GR, influence of EF on yield was considered uniform, and thereby excluded from any GR-specific analyses. The elimination of EF as a possible yield-influencing factor allowed for all fields within the same GR to be considered to have the same yield potential. This was necessary to accurately evaluate the direct influence of varying CMF on yield, by excluding any possible confounding effects induced by EF. This yield gap analysis method to identify CMF influencing yield, is similar to the approach described by the Food and Agricultural Organization of the United Nations and Daugherty Water for Food Institute at the University of Nebraska (FAO and DWFI, 2015). Within any GR, varying CMF are compared with resultant yields to identify those that are yield-limiting.

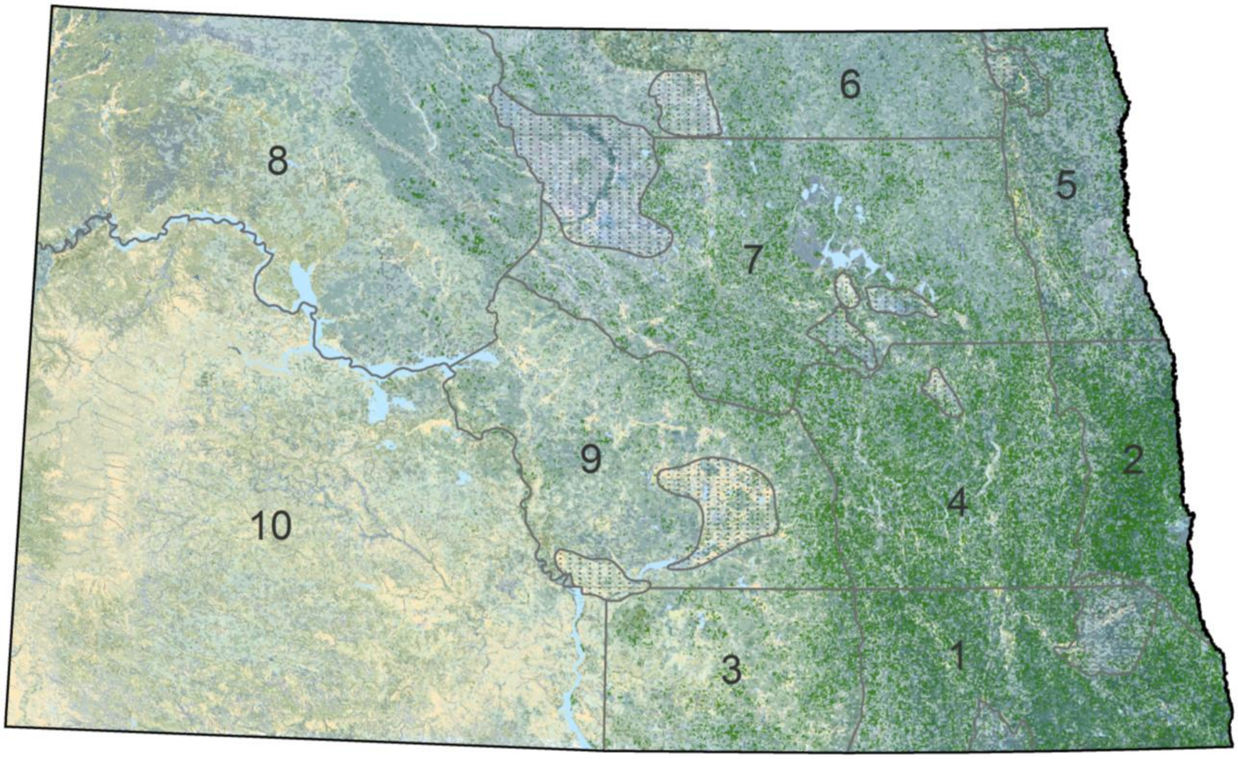

Figure 6. Compiled representation of factors defining soybean growing regions in North Dakota. Sources: USDA, NRCS, ND Fish and Game Management, University of Montana, Esri, 2017.

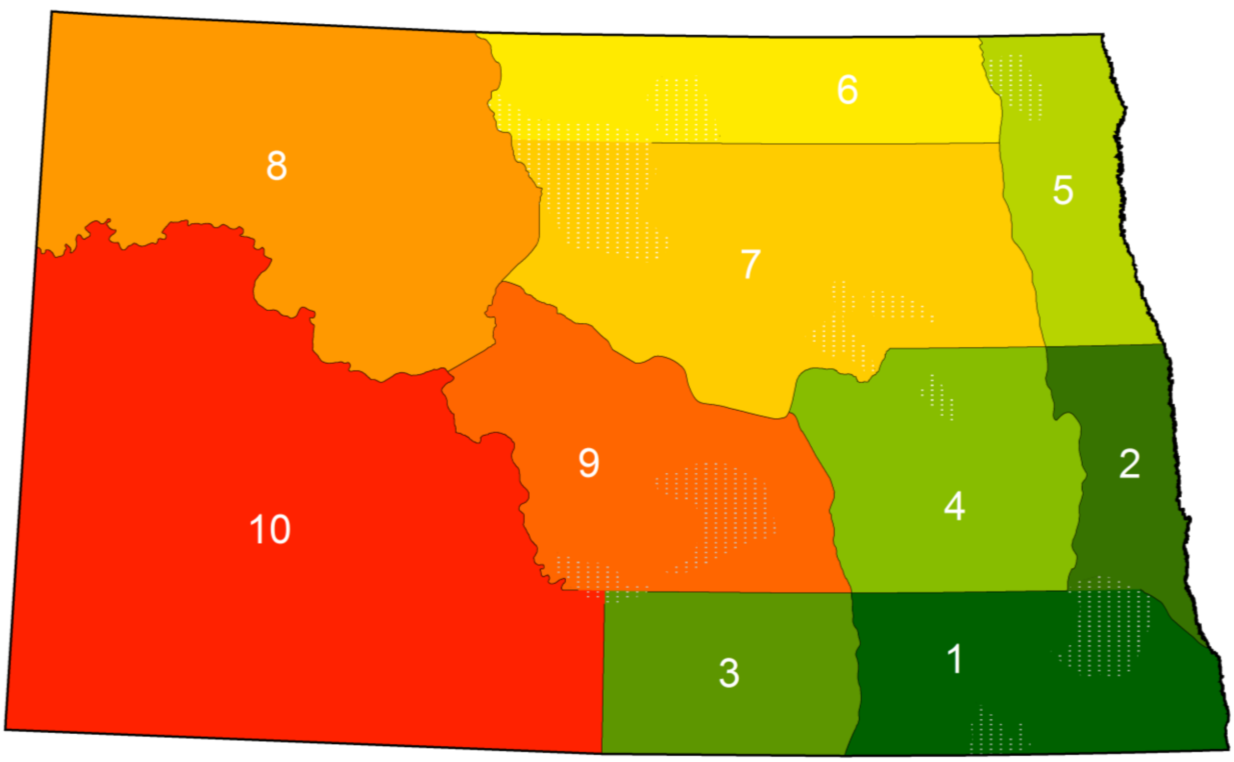

Figure 7. Outlined representation of soybean growing regions in North Dakota.

Producer Field Visits

Producer fields were visited during 2016 and 2017 growing seasons to verify established plant populations, observe crop management practices, and quantify any yield-limiting production issues. Field visit data were compared with information reported by the producer on the paper survey. In-season observations were performed in 100+ fields yr^{-1} to ensure proper spatial representation of soybean production throughout the state, and to be able to perform data analysis likely to lead to statistically-significant results. Most fields were selected with the assistance of county extension agents to ensure representation of actual soybean production in their respective county and that varying management practices could be evaluated.

Exact field locations were provided by producers following planting and geospatially-referenced with the same technique utilized for survey fields. Observations were performed twice during the growing season with an early (prior to flowering, R1 [Fehr et al., 1971]) and the mid-reproductive stage (R4). Observed producer management practices and growing environment factors were recorded as well as identification of any yield-limiting factors. Date of observation and plant growth stage (according to Fehr et al., 1971) was recorded at each visit.

To estimate plant population, all established, living soybean plants within a 2.74 m row length were counted in three locations within each field, and row spacing was measured in cm, to calculate the established population of the field in plants ha^{-1}. Locations sampled within each field were >36 m from any field border or other sample site, and headland rows were avoided. Determining both an early and late-season population estimate is important as these values were not always indicated by producers on the 2014-2016 paper surveys.

Three photographs were captured at each plant count location to evaluate canopy closure. Images were processed utilizing the Canopeo App (Oklahoma State University, Stillwater, OK) interfaced with MatLab R2015b software (MathWorks Inc., Natik, MA) to determine the canopy coverage. This value represents the percent live, green tissue within the photo area captured and as suggested by Patrignani and Ochsner (2015), can be used to evaluate crop progression towards maximum canopy closure (Figure 8).

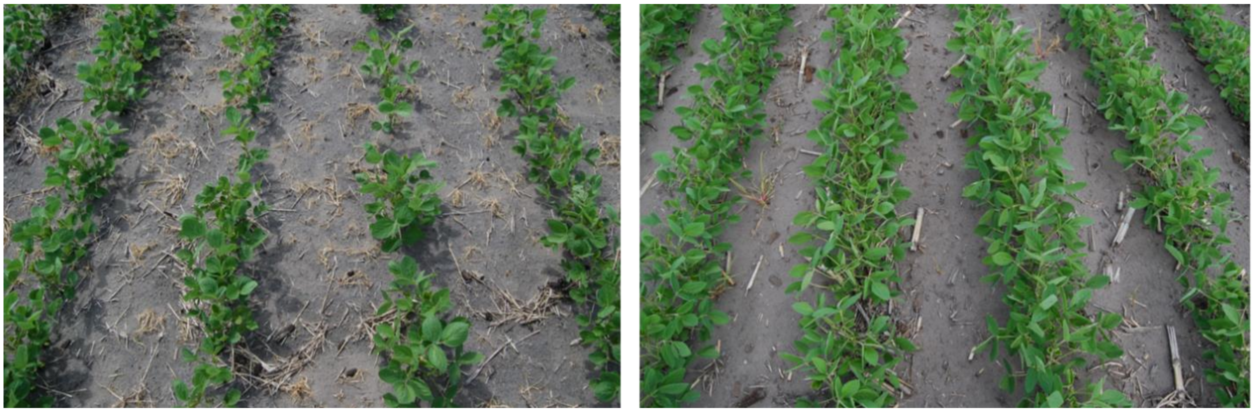

Figure 8. Imagery of soybean plant populations with corresponding Canopeo value. Populations had observed Canopeo values of 25 (left) and 50 (right). Captured at V4 growth stage, in fields managed by the same producer, on June 28, 2016 in Grand Forks County, ND.

Any probable yield-limiting factors observed were rated on a three-level scale (low, medium, high) to represent the overall influence of the factor on the whole field. These factors included weeds, diseases, and water (excess or limited). Presence was indicated, and magnitude of influence was rated subjectively as low, medium, or high. These observations were compared to information provided by producer on the survey. Fields with factors considered to have a medium or high influence on overall yield of the field, were excluded from data analyses. Data from summer field visits were analyzed by regression analysis methods in SAS (PROC REG). Fields observed in 2016 had harvest yield data provided by the producer in the fall paper survey. Data from 2016 in-season observations of agronomic practices and crop management were compared to the producer-reported yield for the respective field.

Experimental Research Trials

Small plot research trials were performed to evaluate plant losses during the growing season using replicated experimental designs. Experiments were conducted at three environments in 2016, and five environments in 2017. The experiment was a randomized complete block design with four replicates.

In 2016 and 2017, the experiment was conducted at the NDSU NW22 agricultural research station near Fargo, ND (46.9321° -96.8589°), with soil a complex of Fargo (fine, smectitic, frigid Typic Epiaquerts) and Ryan (fine, smectitic, frigid Typic Natraquerts) silty clay that are poorly-drained. Two annual environments were represented at this station. The first environment includes tile drainage (installed in 2008) with perforated pipes at 7.62 m intervals, and an applied water management strategy. The second environment includes a portion of the research site with the water control structures closed, to simulate a non-tile, naturally-drained condition. The third environment for the 2016 growing season was in Ransom County, ND (46.4413° -97.8024°) with soil compromised of a loam mixture of Barnes (fine-loamy, mixed, superactive, frigid Calcic Hapludolls) and Svea (fine-loamy, mixed, superactive, frigid Pachic Hapludolls). All environments in 2016 had a previous crop of corn (*Zea mays* L.).

For the 2017 growing season, research environments were located in similar environments as described previously at NW22 (two environments) and Ransom County, ND. Two additional environments in 2017 included: Sargent County, ND (46.2117° -97.6546°), with a soil complex of Hamerly (fine-loamy, mixed, superactive, frigid Aeric Calciaquolls) and Tonka (fine, smectitic, frigid Argiaquic Argialbolls); and Casselton, ND (46.8841° -97.2374°) on silty clay loams of Kindred (fine-silty, mixed, superactive, frigid Typic Endoaquolls) and Bearden (fine-silty, mixed, superactive, frigid Aeric Calciaquolls) poorly-drained soils. Previous crop at

NW22 and Casselton was spring wheat (*Triticum aestivum* L. emend. Thell). Ransom and Sargent had a previous crop of soybean and corn, respectively.

Soybean cultivars ranged in RM from 0.5 to 0.9. Cultivars were selected to include cultivars adapted for growth in this agricultural region, including field tolerance to iron deficiency chlorosis and soybean cyst nematodes. Cultivars seeded in 2016 were PS 30-80 and PFS 15R07. In 2017, cultivars included AG0934 at Sargent, AG0835 at Casselton and Ransom, and AG0835 and AG0536 at NW22. Germination percentage was determined on all cultivars utilizing the ragdoll method and SR were based on live seed.

Independent of row spacing, NDSU recommends an established plant density of at least 370 600 ha^{-1} (Kandel and Endres, 2015). Seeding rates were selected to ensure diversity in growing conditions in high- and low-density plant populations. Seven different soybean SR were used and treatments were identified by increasing numbers corresponding with incremental seeding rates (IR 1 to IR 7). The control treatment (IR 4) was targeting an established plant population of 390 000 plants ha^{-1}, and rates of remaining treatments were assigned in increments of 49 400 seeds ha^{-1} equally above and below the IR 4 control (Table 3).

Prophylactic treatment for seedling and root diseases with fungicide mefenoxam [(R)-2-[(2,6-dimethylphenyl) methoxyacetylamino] propionic acid methyl ester] and fluidoxonil [4-(2,2-Difluoro-1,3-benzodioxol-4-yl)-1H-pyrrole-3-carbonitrile] as ApronMaxx RTA (Syngenta Crop Protection, Basel, Switzerland) was applied at a slurry rate of 3.6 ml kg^{-1} seed to all seed prior to planting in 2016. Seeds in 2017 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). Vault SP (BASF, Ludwigshafen, Germany) was applied at planting at a rate of 1.8 g kg^{-1} seed to promote root nodulation by mutualistic *Bradyrhizobium japonicum*.

Table 3. Seeding rates of experimental treatments for 2016-2017 soybean research trials.

Treatment	Incremental seeding rate (IR)†
	seeds ha^{-1}
IR 1	-148 200
IR 2	-98 800
IR 3	-49 400
IR 4	Control
IR 5	+49 400
IR 6	+98 800
IR 7	+148 200

†Seeding rate amount in seeds ha^{-1} relative to control.

Row spacing was fixed at 30.5 cm for all environments. Soybean was planted with a Hege 1000 no-till planter (Hege Company, Waldenburg, Germany), in 4-row, 11.6 m^2 plots. A 0.91 m section within the two inner rows was marked at planting, and the number of live soybean plants within the staked area was counted after the plot was completely emerged and established early in growing season (growth stage V3). The late-season count was performed at harvest within the same staked area, and included only pod-bearing plants with seed-filled pods contributing to yield. Plant populations in plants ha^{-1} were calculated for both observation timings and percent plant loss within each experimental unit was determined.

Plot lengths were measured at harvest maturity to account for variance in planting length or in-season damage. Approximately 9.3 m^2 were harvested with a Wintersteiger Classic plot combine (Wintersteiger Ag Company, Austria). A Clipper multi-sieve seed cleaner (Ferrell-

Ross, Bluffton, IN) was utilized to remove any excess plant material or soil from grain prior to weighing whole plot yields with a Mettler Toledo XS6001S scale (Mettler-Toledo LLC, Columbus, OH). Moisture and test weight was determined for each observation with a GAC 2100 moisture tester (DICKEY-John Corp., Minneapolis, MN). Seed yield for each plot was calculated at a corrected moisture content of 130 g kg^{-1}.

Variate analysis of experimental data was performed utilizing in SAS 9.3 (PROC GLM). Environment was considered a random effect and SR a fixed effect. Data were analyzed for each environment. A test for homogeneity across environments was performed in SAS (PROC GLM) for SR influence on each dependent variable (early plant population, late plant population, plant loss, and yield), prior to compiling data from each 2016 and 2017 environment for combined analysis. Variable means from individual and combined analyses were compiled and mean separations using LSD was performed at $P \leq 0.05$ level. Values for LSD were established based on a protected F-test.

RESULTS AND DISCUSSION

Producer Survey

Regression models represented by linear equations were developed by evaluating yield response (dependent variable) at varying producer-reported (independent variables) namely: planting date (PD), relative maturity (RM), and seeding rate (SR). Linear equations were used to identify producer crop management factors (CMF) influencing yield statewide, and yield within each soybean growing region (GR). Yields of 2014-2016 producer-reported data had a normal distribution (Figure 9) and mean yield of 2739 kg ha^{-1}. Yields ranged from 1169 kg ha^{-1} to 4523 kg ha^{-1}; 95% of these yields where between 1609 and 3856 kg ha^{-1}.

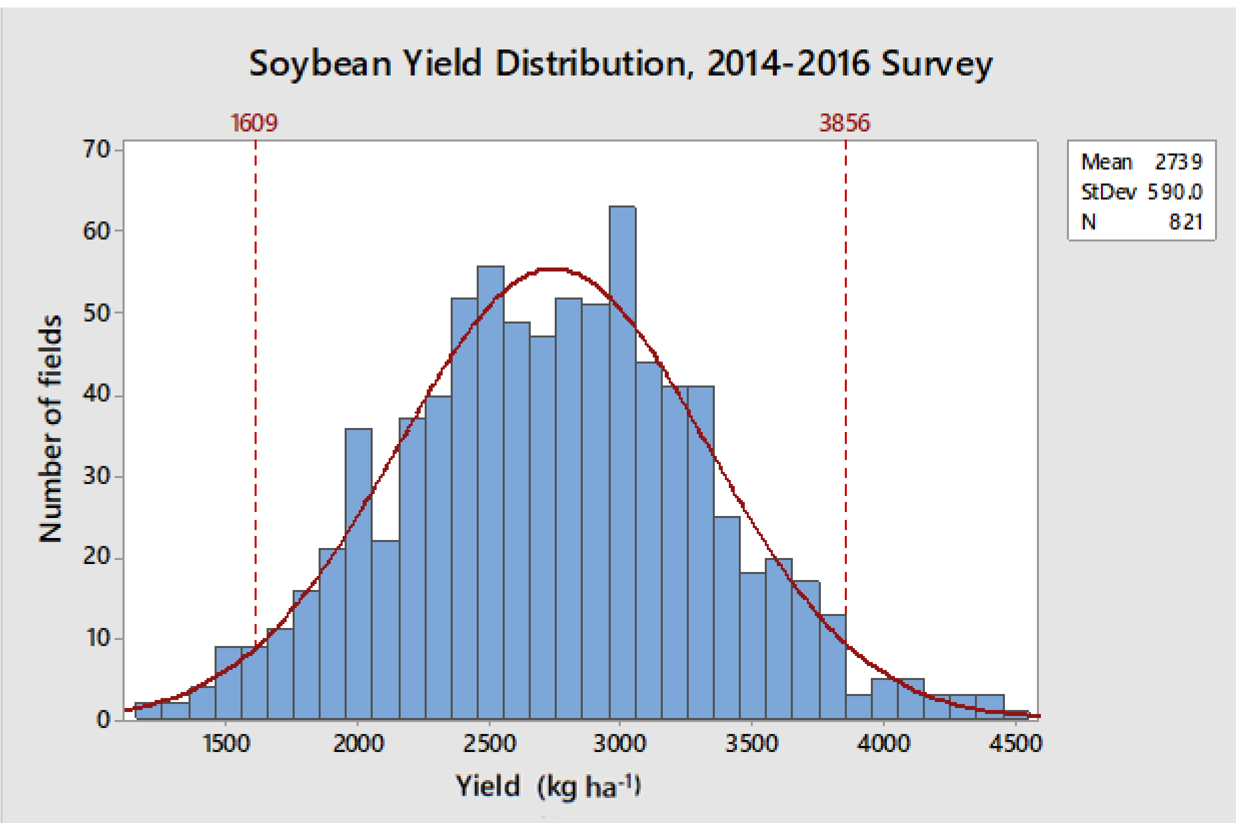

Figure 9. Normal distribution of producer-reported soybean yield, 2014-2016 survey.

Statewide: Single Factor Analysis

Planting Date

As a limited number of producers statewide applied the same management for all three CMF evaluated (PD, RM, and SR), linear regression analysis was performed in SAS (PROC REG) to evaluate the yield response at varying levels of individual CMF. Individual year results indicated a significant (P<0.05), and increasing association, between PD and yield over the three surveyed years (Table 4). In 2016, 17% of variation in yield was associated with producer differences in planting date, compared to only 12% in 2014 (Table 4).

Table 4. Summary of linear regression models of soybean planting date influence on yield statewide in North Dakota.

Year	Linear equation†	r^2	r§	CV §	PD⁋	Predicted Yield#	Observed Yield#
						----------kg ha^{-1}---------	
2014 (n=252)	Y= 6243 - 24.2x_1‡	0.12	-0.34	20.6	5/25	2734	2737
2015 (n=278)	Y= 5850 - 22.3x_1	0.15	-0.40	20.8	5/20	2728	2731
2016 (n=279)	Y= 7213 - 33.2x_1	0.17	-0.41	18.2	5/14	2764	2765
Combined	Y= 5616 - 20.6x_1	0.12	-0.34	20.1	5/19	2753	2744

†Equations from PROC REG. All models and variables significant at P<0.05.
‡Y, yield in kg ha^{-1}; x_1, day of the year of planting (i.e. May 15th is 135th day of the year).
§r, Pearson correlation coefficient; CV, coefficient of variation.
⁋Statewide average producer-reported PD (planting date).
#Predicted yield calculated with mean PD reported for year. Observed is mean producer-reported yield.

These yield results are supported by other research findings that noted greater yields from fields planted prior to 15 May (Kandel and Endres, 2015). Statewide producer-reported average PD was 11 d closer to 1 May in 2016, compared to 2014 (Table 5). Overall yield increased from 2737 kg ha^{-1} to 2765 kg ha^{-1} (1.0%) over the three survey years (calculations based on Table 5 results). Regression analysis of combined 2014-2016 data resulted in an r^2 value of 0.12, indicating that a portion of yield response is explained by changes in PD (Table 4). Pearson's correlation coefficient value (r= -0.34) indicate a negative correlation between PD and yield.

Table 5. Means and range of producer-reported planting dates and yields statewide in North Dakota.

Year	Planting date (PD)		Yield	
			----------kg ha^{-1}---------	
	mean	range	mean	range
2014 (n=252)	5/25	[5/01-6/12]	2737	[1376-4416]
2015 (n=278)	5/20	[5/01-6/12]	2731	[1223-4523]
2016 (n=279)	5/14	[5/01-6/04]	2765	[1286-4127]
Combined	5/19	[5/01-6/12]	2744	[1223-4523]

These findings, and the association identified by the linear regression model, are relevant findings as delaying PD past 1 May will have a negative influence on overall yield. These results will benefit producers as they can easily adapt their PD (assuming favorable growing conditions) to directly influence their overall yield potential.

Relative Maturity

Similar findings for variability across years was observed for yield response associated with different selections of soybean cultivar RM. Results for individual year linear regression analysis evaluating soybean RM influence on yield revealed r^2 values of 0.15 and 0.10, in 2014 and 2015 respectively (Table 6). In 2016, 27% of variation in yield response was associated with cultivar RM selected by a producer. However, though a significant relationship is observed in all three years, year-to-year variability in yield is observed even though RM selected by producers was relatively unchanged (Table 7). These findings indicate that there are other factors influencing yield. Lower r^2 values observed in 2014 and 2015 may represent the reduced influence of RM on yield when soybean is grown in a water-limited environment.

Table 6. Summary of linear regression models of soybean cultivar relative maturity influence on yield statewide in North Dakota.

Year	Linear equation†	r^2	r§	CV §	RM¶	Predicted Yield#	Observed Yield#
						----------kg ha^{-1}---------	
2014 (n=254)	Y= 2036 + 49.5x_2	0.15	0.39	20.2	0.4	2729	2733
2015 (n=284)	Y= 2122 + 42.6x_2	0.10	0.30	21.4	0.5	2718	2731
2016 (n=283)	Y= 1835 + 59.7x_2	0.27	0.52	17.4	0.5	2731	2752
Combined	Y= 1999 + 50.7x_2	0.16	0.41	19.7	0.5	2760	2739

†Equations from PROC REG. All models and variables significant at P<0.05.
‡Y, yield in kg ha^{-1}; x_2, cultivar relative maturity code.
§r, Pearson correlation coefficient; CV, coefficient of variation.
¶Statewide average producer-reported RM (relative maturity).
#Predicted is calculated with mean reported RM. Observed is mean producer-reported yield.

Table 7. Means and range of producer-reported cultivar relative maturity planted and yields statewide in North Dakota.

Year	Relative maturity (RM)		Yield	
			----------kg ha^{-1}---------	
	mean	range	mean	range
2014 (n=254)	0.4	[00.4-1.4]	2733	[1376-4416]
2015 (n=284)	0.4	[00.5-1.4]	2731	[1223-4523]
2016 (n=283)	0.5	[00.5-1.5]	2752	[1169-4127]
Combined	0.5	[00.4-1.5]	2739	[1169-4523]

Monthly total rainfall data at the Fargo, ND, weather station for the 2014 to 2017 growing seasons (Table 8) were retrieved from the North Dakota Agricultural Weather Network (NDAWN, NDSU, Fargo, ND). The Fargo station was selected as greater than 40% of the fields included in this study are located within 160 km of Fargo, ND. Summation of monthly rainfall deficit/surplus provides a cumulative rainfall amount for comparison across growing seasons. A cumulative deficit of -38 mm and -70 mm was determined for 2014 and 2015 growing seasons respectively. Conversely, a cumulative rainfall surplus of +28 mm was observed in 2016.

Table 8. Summary of recorded monthly total rainfall surplus or deficit as reported by NDAWN as departure from normal total rainfall for 2014 to 2017 growing seasons.

	2014	2015	2016	2017
Month	Total rainfall (as deviation from normal)†			
	------------------------------------mm------------------------------------			
June	+41	-35	-30	-42
July	-37	0	+61	-48
August	-28	-11	-17	-7
September	-14	-24	+14	+5
Cumulative	-38	-70	+28	-92

†Data retrieved from the North Dakota Agricultural Weather Network (NDAWN, Fargo, ND, 2017).

This difference in cumulative rainfall amounts may explain the variability in association between yield and RM between years (Table 7). Desclaux and Roumet (1996) noted that soybean under drought stress, especially during reproductive stages, exhibited an earlier timing for seed-filling and a significant decrease in duration of seed-maturing period, leading to an earlier timing of plant senescence and reduced seed yield. Drought stress may explain the reduced influence of RM on yield in 2014 and 2015.

Seeding Rate

Individual year linear regression analysis results indicated SR was not significant when comparing variation in yield response (Table 9). It is expected that other CMF not included in this study are confounding factors in these results. Though not requested on the paper survey, some producers reported that SR was adapted at planting dependent on soil moisture, tillage practices, residue amount from previous year crop, and type of equipment available at planting (i.e. a higher SR is commonly used when planting with an air seeder as seedling emergence may be reduced compared to row planter).

Table 9. Summary of linear regression models of soybean seeding rate influence on yield statewide in North Dakota.

Year	Model†	r^2	r‡	CV‡	SR§		Yield¶	
					seeds ha^{-1}/1000		--------kg ha^{-1}--------	
					mean	range	mean	range
2014 (*n*=250)	ns	0.01	-0.03	21.7	418	[334-494]	2742	[1376-4416]
2015 (*n*=281)	ns	0.01	0.04	22.4	413	[334-494]	2737	[1223-4523]
2016 (*n*=279)	ns	0.01	0.07	20.4	415	[340-494]	2744	[1169-4127]
Combined	ns	0.01	0.03	21.5	415	[334-494]	2741	[1169-4523]

†All models and variables nonsignificant at $P<0.15$.
‡r, Pearson correlation coefficient; CV, coefficient of variation.
§Statewide average of producer-reported SR (seeding rate).
¶Yield is mean producer-reported yield in kg ha^{-1}.

Instead of comparing SR to yield, it would be better to evaluate the number of plants established early in the growing season (after all viable seedlings have emerged and survived) or plant population at harvest. This is further discussed in the soybean field visit results. Producers can perform early-season plant population counts, and compare this value to initial seeding rate to determine percent of seeds that survived. Individual producers comparing multiple years of field-specific and/or cultivar-specific data can apply this information when targeting a desired established soybean plant population.

Statewide: Multiple Factor Analysis

Stepwise linear regression analysis in SAS (PROC REG) for individual growing seasons (2014, 2015, and 2016) identified PD and RM as significant variables ($P<0.05$) of influence on yield (Table 10). The SR variable was eliminated from all individual year regression equations when p>0.10. Comparing R^2_{adj} values for individual year equations, it is apparent that the strength of association between yield, and PD and RM, differed by year. Planting date and RM explained 21% of the observed variation in yield in 2015, and 33% in 2016 (Table 10). Utilizing the linear equations in Table 10, an expected yield loss was calculated for each year for producers selecting a cultivar with a RM earlier-maturing than recommended. When comparing two fields planted the same day in 2016 (PD is fixed in the model equation) with RM differing by one unit (i.e. RM= 0.3 compared to RM= 0.4), a yield reduction of 48.4 kg ha^{-1} (0.9%) was observed when selecting the earlier RM cultivar.

Table 10. Summary of multiple variable regression models of significant crop management factors influencing soybean yield statewide in North Dakota.

Year	Linear equation†	R^2_{adj}§	C_p§	CV §
2014 (n = 248)	$Y= 5040 - 20.2x_1 + 44.6x_2$‡	0.24	2.8	19.0
2015 (n = 275)	$Y= 4947 - 19.7x_1 + 38.1x_2$	0.21	4.6	19.9
2016 (n = 275)	$Y= 5141 - 23.3x_1 + 48.4x_2$	0.33	3.7	16.3
Combined	$Y= 3636 - 15.3x_1 + 46.0x_2 + 1.38x_3$	0.24	-	18.7

†Equations from PROC REG. All models and variables significant at P<0.05.
‡Y, yield in kg ha^{-1}; x_1, day of the year of planting (i.e. May 15th is 135th day of the year); x_2, relative maturity code; x_3, seeding rate in seeds ha^{-1} divided by 1000.
§R^2_{adj}, adjusted R^2; C_p, Mallows' C_p statistic; CV, coefficient of variation.

For producers to maximize yield potential, they should plant cultivars with the highest RM rating adapted for their region. Based on statewide linear equations for individual years, the greatest hypothetical yields are expected in fields planted closest to 1 May, with cultivars having a RM near 1.5. However, due to varying growing season lengths and EF throughout North Dakota, these findings are only applicable to producers in the most southern and eastern portion of the state (Figure 10). It is recommended that farmers only plant when conditions are favorable for plant establishment, and not solely based on calendar date. Additionally, RM 1.5 is considered extremely late for soybean growth in the state.

For combined 2014-2016 survey data, PD, RM, and SR were all significant predictors of yield (Table 10), and explained 24% of the observed variation in yield. Utilizing the combined statewide linear equation (Table 10), delaying planting past 1 May (assuming RM and SR selected by the producer was unchanged) resulted in an average daily yield reduction of 0.4% (15.3 kg ha^{-1}). Producers that delayed planting until the statewide average planting date of 19 May (Table 11), are expected to have an average total yield reduction of 9.4% (275 kg ha^{-1}) compared to 1 May planting. Producers seeking to improve yield, can directly influence their overall yield by adapting timing of planting to be closer to 1 May (while ensuring that conditions are favorable for plant establishment). Selecting the proper maturity group is important, as RM had a significant influence on yield. For each unit change in RM, yield differed by 46.0 kg ha^{-1}. However, geospatial location of field within the state will limit the range of RM that can be planted to reach physiological maturity prior to a frost event in the fall.

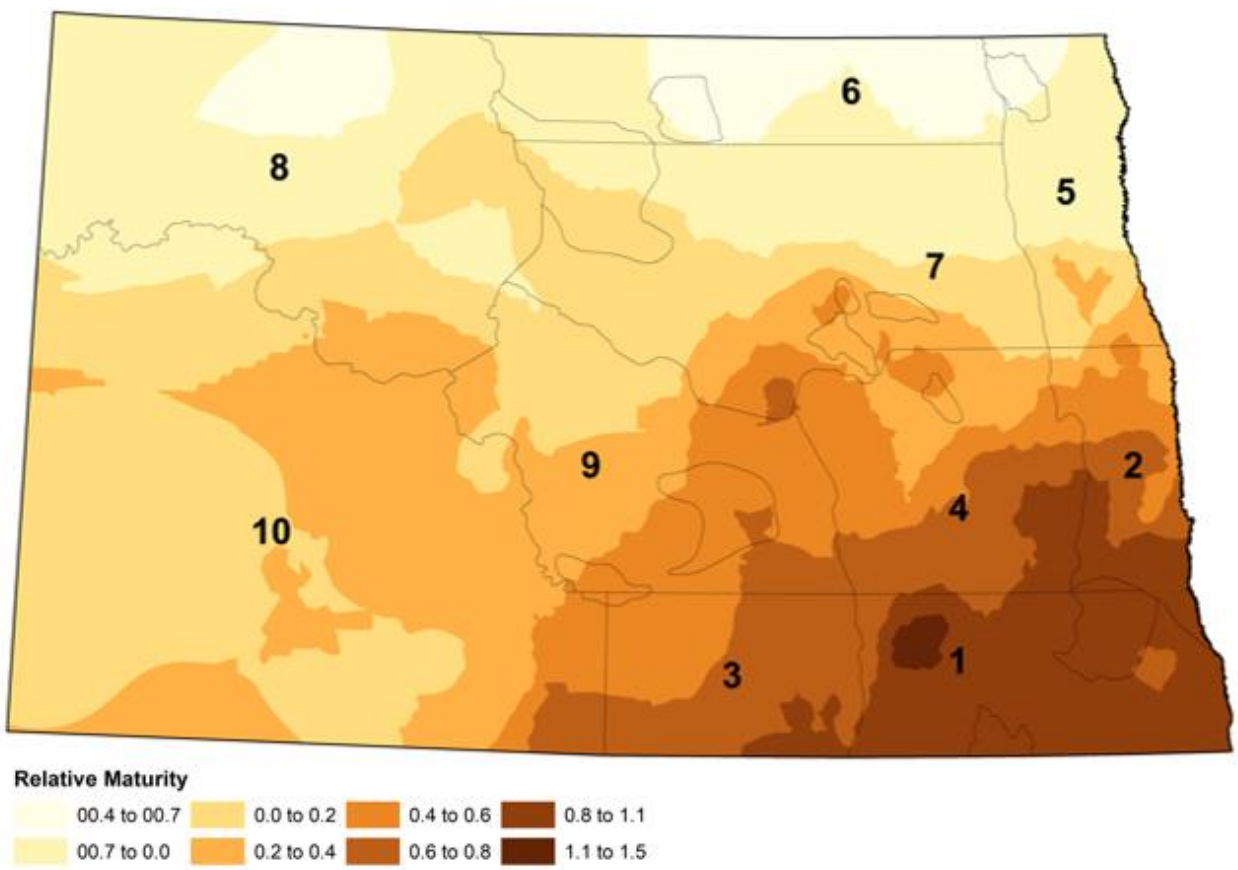

Figure 10. Distribution of soybean cultivar relative maturities planted in 2014-2017 producer fields and overlaying soybean growing regions in North Dakota.

Seeding rate had significant influence on yield when coupled with PD and RM. However, the expected yield increase is only 13.8 kg ha^{-1} for every 10 000 seeds ha^{-1} increase for SR ranging from 334 000 seeds ha^{-1} and 494 000 seeds ha^{-1} (Table 11). Selecting a cultivar one unit later in RM (1.3% yield increase) and adjusting PD from 19 May to 15 May (1.6% yield increase), had a comparatively greater influence on overall yield compared with increasing SR by 10 000 seeds ha^{-1} (0.4% yield increase).

Table 11. Means and range of producer-reported soybean management practices and yields statewide in North Dakota.

Year	Crop management factor						Yield	
	PD†		RM		SR			
					seeds ha^{-1}/1000		--------kg ha^{-1}--------	
	mean	range	mean	range	mean	range	mean	range
2014 (n = 248)	5/25	[5/01-6/12]	0.4	[00.4-1.4]	418	[334-494]	2747	[1376-4416]
2015 (n = 275)	5/20	[5/01-6/12]	0.4	[00.6-1.4]	412	[334-494]	2737	[1223-4523]
2016 (n = 275)	5/14	[5/02-6/05]	0.5	[00.5-1.5]	416	[340-494]	2757	[1286-4127]
Combined	5/19	[5/01-6/12]	0.5	[00.4-1.5]	415	[334-494]	2747	[1223-4523]

†PD, planting date; RM, cultivar relative maturity; SR, seeding rate in seeds ha^{-1} divided by 1000.

As GR were defined based on geospatial differences in environmental influences, GR was also included as a potential dependent variable (representative of EF) in the combined year stepwise regression analysis performed in SAS (PROC REG). The resultant linear model for 2014-2016 statewide data indicated that GR had a significant influence on yield in combination with PD and RM (Table 12).

Table 12. Summary of multiple variable linear regression model of significant crop management factors influencing soybean yield statewide in North Dakota.

Years	Linear equation†	R^2_{adj}§	CV§
2014-2016 (n = 798)	$Y = 5064 - 14.9x_1 + 11.0x_2 - 92.2x_4$‡	0.31	17.7

†Equations from PROC REG. All models and variables significant at P<0.05.

‡Y, yield in kg ha^{-1}; x_1, day of the year of planting (i.e. May 15th is 135th day of the year); x_2, cultivar relative maturity code; x_4, North Dakota soybean growing region.

§R^2_{adj}, adjusted R^2; CV, coefficient of variation.

Overall model fit improved with an R^2_{adj}= 0.31 (Table 12) compared to R^2_{adj}= 0.24 (Table 10) when GR was omitted as a potential yield-influencing variable. These results indicate that an additional 7% of variation in yield across the three growing seasons was associated with differences in EF (as represented by GR as a variable). However, a high correlation was observed (r= -0.68) between RM and GR (as reported on SAS output). This is understandable as cultivar RM are defined by similar properties defining GR in North Dakota including geospatial location, growing season length (photoperiodic factors), and climatic influences. This strong correlation, coupled with increased model fit (due to confounding factor), is indicative of multicollinearity. For this reasoning, GR was excluded from all other regression model analyses.

Growing Region: Single Factor Analysis

Planting Date

Simple linear regression analysis was performed utilizing SAS (PROC REG) to evaluate the influence of PD on yields within each GR throughout North Dakota. Growing regions 3, 4, 5, and 10 were all observed to have a negatively-associated linear relationship between PD and yield. The greatest association was observed in GR 3 as differences in PD were able to explain 42% of the variation in yields observed within the GR (Table 13).

Predicted yields were calculated from respective linear equation using mean reported PD for each GR (Table 14). Predicted yield values were compared to producer-reported yields within each GR. All linear equations (excluding GR 10) were predictive of the observed average yield, with precision of less than one d deviation (based on comparison of PD linear coefficient and yield difference between predicted and observed yield relative to individual GR).

Table 13. Summary of linear regression models of soybean planting date influence on yield in North Dakota soybean growing regions, combined 2014 to 2016 growing seasons.

GR‡	Linear equation†	r^2	r§	CV §	PD⁋	Predicted# Yield	Observed# Yield
						----------kg ha^{-1}---------	
3 (*n*=104)	Y= 8514 - 40.5x_1‡	0.42	-0.65	17.5	5/20	2844	2849
4 (*n*=148)	Y= 4879 - 15.5x_1	0.11	-0.33	16.7	5/18	2740	2753
5 (*n*=61)	Y= 4933 - 15.8x_1	0.12	-0.35	19.5	5/22	2689	2695
10 (*n*=38)	Y= 8005 - 41.3x_1	0.25	-0.50	27.2	5/24	2058	2339

†Equations from PROC REG. All models and variables significant at P<0.05.
‡GR, soybean growing region; Y, yield in kg ha^{-1}; x_1, day of the year of planting (i.e. May 15th is 135th day of the year).
§r, Pearson correlation coefficient; CV, coefficient of variation.
⁋Mean PD (planting date) reported by surveyed producers within GR.
#Predicted yields calculated using mean producer-reported planting date. Observed is mean producer-reported yield in kg ha^{-1}.

Table 14. Means and range of producer-reported planting dates and yields statewide in North Dakota soybean growing regions, combined 2014 to 2016 growing seasons.

Growing Region	Planting date (PD)		Yield	
			----------kg ha^{-1}---------	
	mean	range	mean	range
3 (*n*=104)	5/20	[5/01-6/10]	2849	[1707-4523]
4 (*n*=148)	5/18	[5/01-6/12]	2753	[1376-4004]
5 (*n*=61)	5/22	[5/01-6/12]	2695	[1286-4078]
10 (*n*=38)	5/24	[5/01-6/06]	2080	[1223-3548]

Relative Maturity

Findings from linear regression analysis of RM influence on yield within each GR were all observed to be not significant, or in violation of fit/normality assumptions acceptable for proper representation of regression models. These results are not surprising however as GR were classified with growing season length as a defining environmental factor.

Seeding Rate

Seeding rate was also evaluated for a possible association with yield response within each GR for combined 2014-2016 growing seasons. Yields in GR 9 were observed to have a significant positive relationship with increasing SR, explaining 20% of variance observed in yield. Based on incremental increases in SR of 10 000 seeds ha^{1}, a calculated average yield increase of 2.2% (50 kg ha^{-1}) was observed (Table 15). As these results are represented by less than 30 fields, additional data is needed prior to making conclusions for the whole population of soybean producers in GR 9.

Table 15. Summary of linear regression models of soybean seeding rate influence on yield in North Dakota soybean growing region 9, combined 2014 to 2016 growing seasons.

GR‡	Linear equation†	r^2	r§	CV §	SR⁋	Predicted Yield#	Observed Yield#
					seeds ha^{-1} / 1000	----------kg ha^{-1}---------	
9 (n=27)	$Y = 231 + 5.0x_3$‡	0.20	0.44	15.8	424	2351	2339

†Equations from PROC REG. Model and variable significant at P<0.05.
‡GR, soybean growing region; Y, yield in kg ha^{-1}; x_3, seeding rate in seeds ha^{-1} divided by 1000.
§r, Pearson correlation coefficient; CV, coefficient of variation.
⁋Mean SR (seeding rate) reported by surveyed producers within GR 9.
#Predicted yield calculated with reported mean SR. Observed is producer-reported mean yield.

Growing Region: Multiple Factor Analysis

Statewide data was separated by soybean growing region (GR) in North Dakota (Figure 7) to eliminate environmental factors as a variable, thereby providing a fair comparison for CMF influence on yield. Mean and range values for producer-reported CMF and yields differed by GR (Table 16).

Stepwise regression analysis for each of the 10 GR was performed to evaluate yield response as determined by PD, RM, and SR. Two out of the 10 GR evaluated had significant linear regression models, indicating that multiple CMF had an influence on yield within the GR

(Table 17). Analysis results for remaining GR were excluded due to at least one of the following findings: unfit linear model, multicollinearity among model variables, single variable regression equations (as these were analyzed as single variable models to improve precision), or lack of diversity among CMF data (i.e. geospatial groupings of field data, fields representing whole GR were farmed by ≤3 producers, or similar management practice(s) adopted broad scale throughout GR).

Table 16. Means and range of producer-reported soybean management practices and yields in soybean growing regions in North Dakota, combined 2014-2016 survey data.

GR[†]	Crop management factor[‡]						Yield	
	PD		RM		SR			
					seeds ha^{-1}/1000		--------kg ha^{-1}--------	
	mean	range	mean	range	mean	range	mean	range
1 (*n*=141)	5/18	[5/02-6/12]	1.0	[0.3-1.5]	417	[346-494]	3200	[1854-4198]
2 (*n*=53)	5/12	[5/01-5/31]	0.7	[00.9-1.3]	410	[371-457]	3062	[1592-4152]
3 (*n*=103)	5/20	[5/01-6/10]	0.7	[0.2-1.4]	410	[334-474]	2853	[1707-4523]
4 (*n*=148)	5/18	[5/01-6/12]	0.6	[00.9-1.4]	408	[346-482]	2753	[1376-4004]
5 (*n*=61)	5/22	[5/01-6/12]	0.0	[00.5-0.9]	415	[340-494]	2695	[1286-4078]
6 (*n*=43)	5/23	[5/05-6/04]	00.7	[00.4-00.9]	425	[346-445]	2423	[1753-3258]
7 (*n*=158)	5/21	[5/02-6/10]	0.1	[00.5-0.8]	427	[348-494]	2545	[1521-3837]
8 (*n*=28)	5/17	[5/05-5/25]	00.8	[00.5-0.4]	439	[408-482]	2424	[1636-3336]
9 (*n*=27)	5/24	[5/15-6/04]	0.3	[00.8-0.6]	424	[371-457]	2339	[1666-3262]
10 (*n*=36)	5/23	[5/01-6/06]	0.3	[0.2-0.9]	373	[334-445]	2093	[1223-3548]

[†]GR, North Dakota soybean growing region.
[‡]PD, planting date; RM, relative maturity; SR, seeding rate in seeds ha^{-1} divided by 1000.

Multiple variable regression analysis of producer fields in GR 3 revealed yield was significantly influenced by PD (P<0.05) and RM (P<0.10) as these CMF together were associated (R^2_{adj}= 0.44) with variance observed in reported yields (Table 17). These findings support statewide survey results discussed previously, and confirms that some producers within GR 3 experienced significant yield losses from delayed planting, resulting in incomplete maturation of cultivar, or by selecting a cultivar with a RM too late for their growing area.

Table 17. Summary of regression models of significant crop management factors influencing yield in defined soybean growing regions in North Dakota, producer survey data 2014-2016.

Growing Region	Linear equation†	R^2_{adj}§	C_p§	CV§
3 (n=103)	$Y = 9359 - 41.6x_1 - 39.9x_2$‡¶	0.44	4.3	17.3
4 (n=148)	$Y = 2672 - 12.7x_1 + 39.1x_2 + 2.9x_3$	0.17	-	16.1

†Equations from PROC REG.
‡Y, yield in kg ha^{-1}; x_1, day of the year of planting (i.e. May 15th is 135th day of the year); x_2, cultivar relative maturity code; x_3, seeding rate in seeds ha^{-1} divided by 1000.
§R^2_{adj}, adjusted R^2; C_p, Mallows' C_p statistic; CV, coefficient of variation.
¶Indicates $P<0.10$. All other models and variables significant at $P<0.05$.

Variation in soybean yields in GR 4 were significantly associated (R^2_{adj}= 0.17) with PD, RM, and SR (Table 17). Converse to negative association between RM and yield in GR 3, RM in GR 4 was positively associated with changes in yield, indicating that producers have the potential to increase their yield by 39.1 kg ha^{-1} simply by selecting a cultivar with an RM one unit later than previously selected (Table 17). Producers within GR 4 are likely to see a positive yield response by selecting an earlier PD, later-maturing RM, or higher SR compared to the GR 4 mean values for these CMF as outlined in Table 18.

Table 18. Summary of predicted yield response as determined by selection of crop management factor for fields located within soybean growing region 4 in North Dakota.

	CMF†			Yield	
Management	PD	RM	SR	Predicted§	Difference⁋
			seeds ha^{-1}/1000	----------------kg ha^{-1}----------------	
Observed‡	5/18	0.6	409	2731	-
Alternate 1	5/14	0.7	415	2838	+107.3
Alternate 2	5/10	0.9	415	2967	+236.3

†CMF, producer crop management factor; PD, soybean planting date; RM, relative maturity; SR, seeding rate in seeds ha^{-1}/1000.
‡Observed, CMF input values based on producer-reported survey data; Alternate, proposed CMF selections to reduce effect of yield-limiting factors.
§Calculations based on growing region 4 linear equation (Table 14) and respective CMF inputs.
⁋Yield difference in kg ha^{-1} compared to previous level of CMF input.

Applying the linear equation representing CMF influence on yield in GR 4, predicted yields were calculated based on varying producer-reported CMF (Table 18). Predicted yields represent producer fields where yield-promoting CMF practices are applied. Producers selecting PD four days earlier, cultivar with RM one unit later-maturing, and an additional 6 000 seeds ha^{-1} (all compared to producer-reported mean values for GR 4), are expected to see an average increase in yield of 107.3 kg ha^{-1} (Table 18).

Soybean Field Visits

Data compiled from 2016-2017 observations in producer soybean fields were compared to field data reported by producer on paper survey. Linear regression analysis was performed in SAS (PROC REG) evaluating soybean plant establishment and survivability in varying crop management settings. All surveyed producers (2014-2016) reported an average seedling loss of 10% when comparing seeds ha^{-1} at planting, to the plant population (in plants ha^{-1}) established during the growing season. To verify this reported seedling loss, early-season plant populations observed in producer fields in 2016 were compared to the seeding rate reported by the producer on the survey. An average seedling loss of 12.3% was observed in the 88 producer fields.

Plant population at early-season vegetative growth stages (VC to V3), was compared to late-season (reproductive stage R2-R5) population within the same field (Figure 11). As expected, a significant linear relationship (P<0.001) was observed between early and late-season plant populations (r^2= 0.81) in producer soybean fields in 2016. Variability in late-season populations between fields is apparent in Figure 11.

A significant linear relationship (P<0.001) was observed in 2017 fields also (Figure 12). Early-season plant population in 2017 explained 64% over the variation observed in late-season populations.

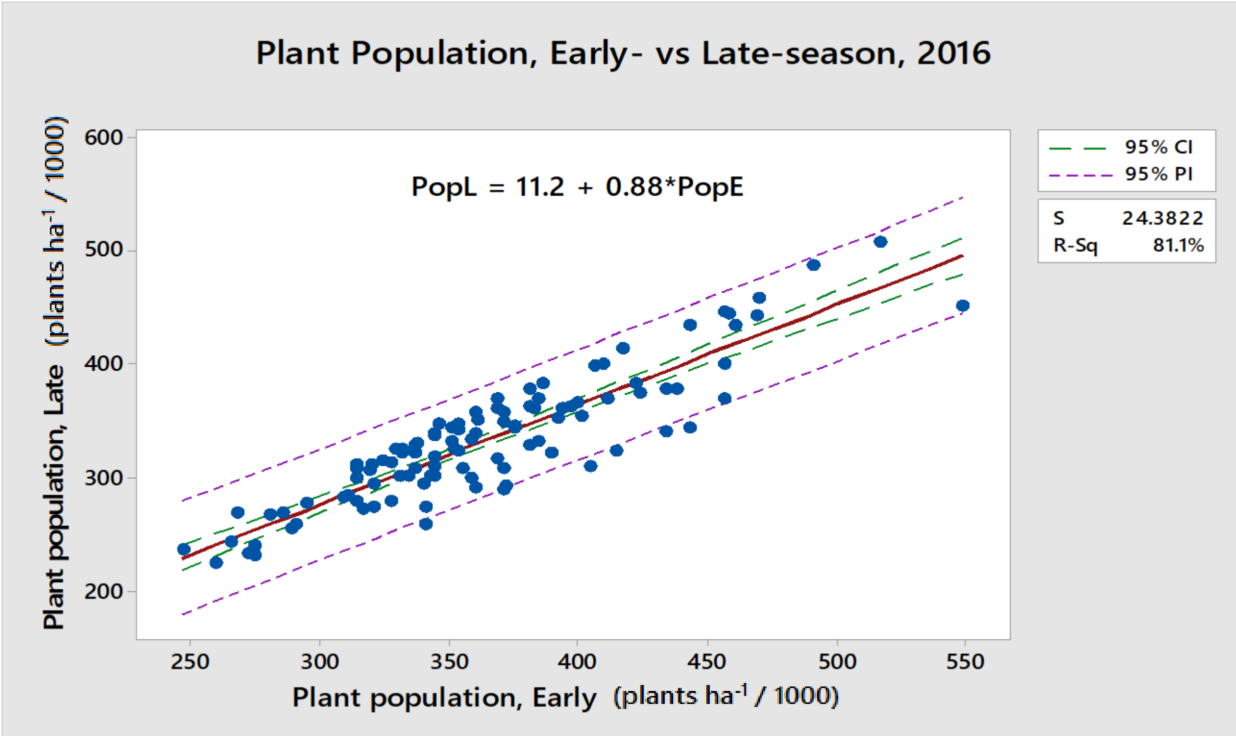

Figure 11. Regression summary of soybean plant populations in North Dakota producer fields at early vegetative (V2-V4) and late reproductive stages (R4-R5), 2016.

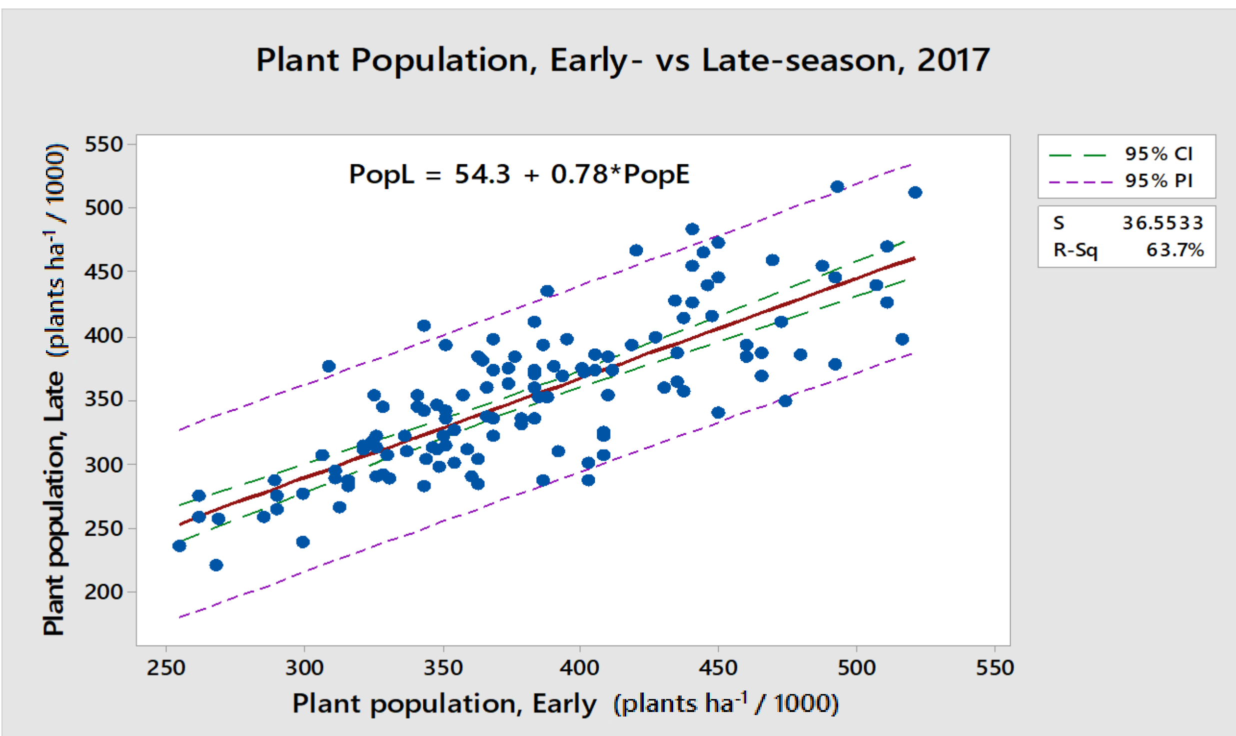

Figure 12. Regression summary of soybean plant populations in North Dakota producer fields at early vegetative (V2-V4) and late reproductive stages (R4-R5), 2017.

Linear equations for individual year field visit data reveal an average plant population reduction throughout the growing season of 8.7% in 2016, and 7.3% in 2017 (Table 19). The observed difference in plant loss between 2016 and 2017 was likely influenced by differences in weather and growing conditions for each season. On average, the 2016 growing season had timely rainfall events and growing conditions favorable for greater yields than the 2017 growing season (Table 8).

While completing soybean producer field observations in 2016, differences in vigor among seedlings and plants were apparent. Soybean plants with increased vigor had greater vegetative growth, allowing interception of sunlight earlier in the season compared to less-vigorous plants. It was observed that plants growing under the shade of these vigorous plants lacked, or had a reduced number of seed-bearing pods. Differences in vigor among seedlings or plants was not readily-apparent in the 2017 growing season. This can likely be attributed to dry growing conditions (Table 8) and fluctuations in ambient temperatures from May through July 2017.

Table 19. Summary of linear regression equations of observed and predicted soybean plant populations and mean in-season plant loss in North Dakota producer fields, combined 2016-2017 field data.

Year	Linear equation†	Obs. PopE§	Pred. PopL¶	Calc. Loss#	Obs. PopE	Pred. PopL	Calc. Loss	Obs. Plant loss††
		plants ha^{-1} /1000		%	plants ha^{-1} /1000		%	%
2016 (*n*=105)	y= 11.2 + 0.88x‡	247	229	7.3	549	494	10.0	8.7
2017 (*n*=129)	y= 54.3 + 0.78x	255	253	0.8	521	461	11.5	7.3
Combined	y= 33.3 + 0.83x	247	238	3.6	549	489	10.9	7.9

†Equations from PROC REG. All models significant at $P<0.001$.
‡y, late-season plant population in plants ha^{-1} divided by 1000; x, early-season plant population.
§PopE, observed early plant population; values are lower/upper boundaries of input for independent variable (x).
¶PopL, predicted late-season plant population; dependent (y) variable in linear equation.
#Loss, calculated in-season plant loss; calculated as difference between PopE and PopL, divided by (PopE/100).
††Mean observed plant loss from 2016-2017 observations in producer fields.

Multiple flushes of seedling emergence and a general reduction in soybean plant vegetative growth were observed in 2017 compared to 2016. The increased variability in 2017 between early and late-season plant populations is possibly a result of adverse environmental conditions observed throughout the growing season.

To account for variability of in-season plant populations observed over 2016-2017, data were combined for linear regression analysis as summarized in Figure 13. A significant linear relationship (*P*<0.001) was observed between early and late-season soybean plant populations. Plant populations that had more plants ha^{-1} early in the growing season, had increased variability in population size late-season (Figure 13). Producers can benefit from these findings as they suggest that multiple plant population counts may need to be performed at different timings in a growing season.

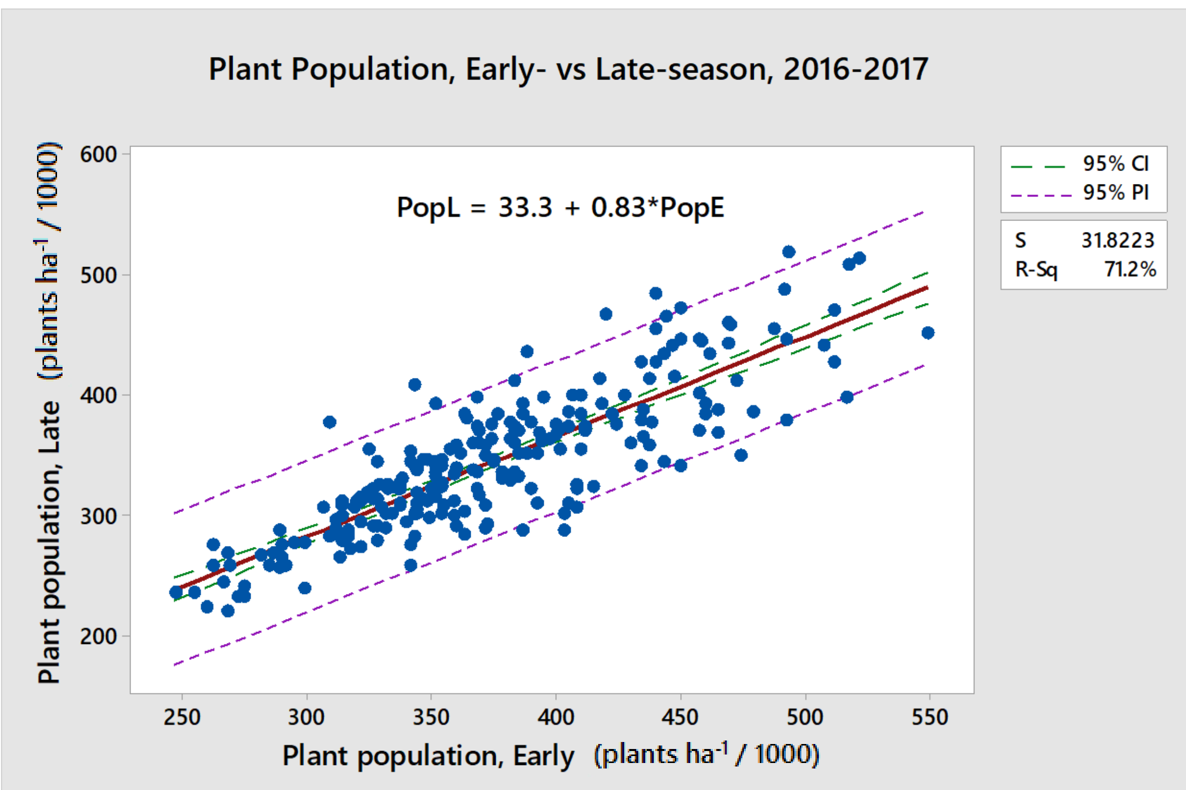

Figure 13. Regression summary of soybean plant population in North Dakota producer fields at early vegetative (V2-V4) and late reproductive stages (R4-R5), 2016-2017.

Plant populations are important for producers to determine as NDSU recommends an established population of 370 600 plants ha^{-1} to maximize yield, however this research indicates that there is a reduction in population between plant establishment and reproductive growth stage R5. The results also indicate that level of plant loss varies year to year and farm to farm.

Plant loss also varied with increasing early-season plant population densities (Figure 14). In-season losses were 10.9% in early plant populations of 549 000 plants ha^{-1}, compared to 3.6% loss in populations of 247 000 plants ha^{-1} (Table 19). The nonlinear relationship in Figure 14, shows that increases in percent plant loss were associated with increasing plant population densities (r^2= 0.087).

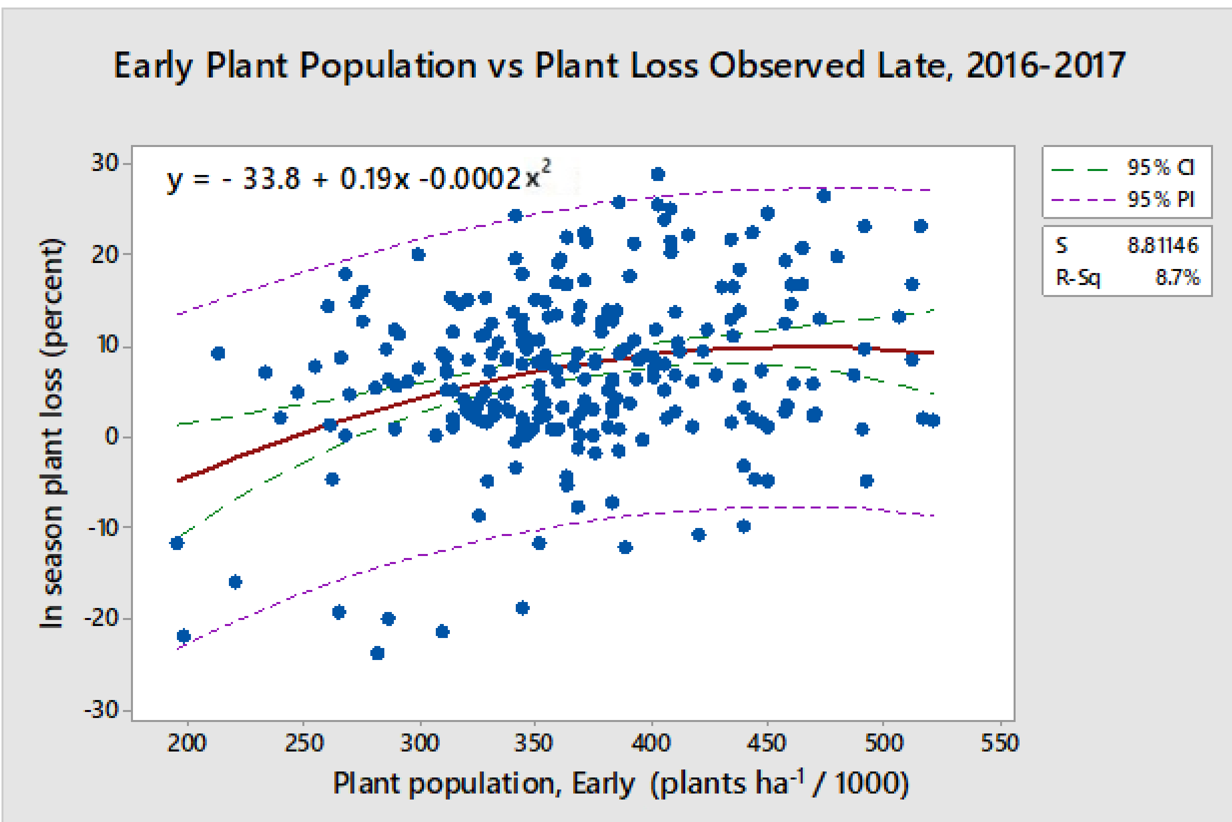

Figure 14. Regression summary of soybean plant population at early vegetative growth (V2-V4) and plant loss between reproductive stages (R4-R5) in North Dakota producer fields, 2016-2017.

These results are presented with caution as there was a considerable number of fields in 2017 that had increased plant populations at the late-season visit, compared to the early-season visit. Increased plant populations observed late-season could be attributed to random error at sampling, or represent variability induced by CMF or EF. Another possible explanation why more plants were counted later in the season could be due to early-season dry conditions and more plants germinating after additional rainfall. Although additional plants emerged after the early-season visit in June, it is unlikely that these plants contributed to yield due to the reduced growth period. Aside from averaging these results with the results reported from experimental trials, further research is suggested with exact locations marked in producer fields to improve precision in findings.

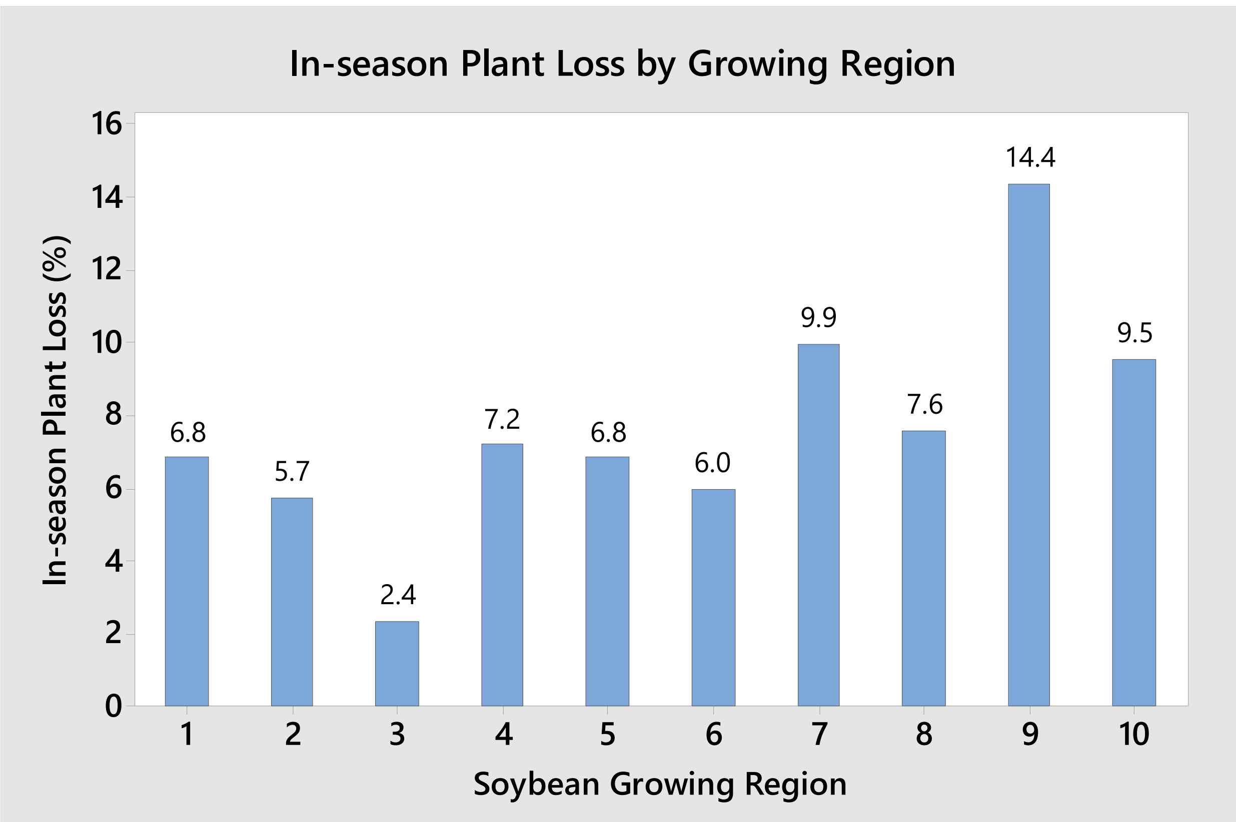

Figure 15. Graphical summary of soybean plant population losses observed in-season in producer fields in North Dakota soybean growing regions, 2016-2017.

There were apparent differences in observed plant loss percent in the varying soybean GR in North Dakota providing evidence of varying EF influences across the state (Figure 15). Increased plant losses were observed in lower-yielding GR (GR 8 to 10) compared to higher-yielding GR (GR 1 to 3). This difference is likely explained by varying types and levels of environmental factors (i.e. water availability, soil type, and climatic factors) that were defining characteristics for individual GR (Figure 6).

As Hoyos-Villegas et al. (2014) reported an association between yield and increasing percent ground canopy cover, early-season plant populations were compared to Canopeo values from producer field visits in 2016. As reflected in Figure 16, on average, fields with larger early plant populations were weakly associated (r^2= 0.093) with higher Canopeo readings (P<0.05).

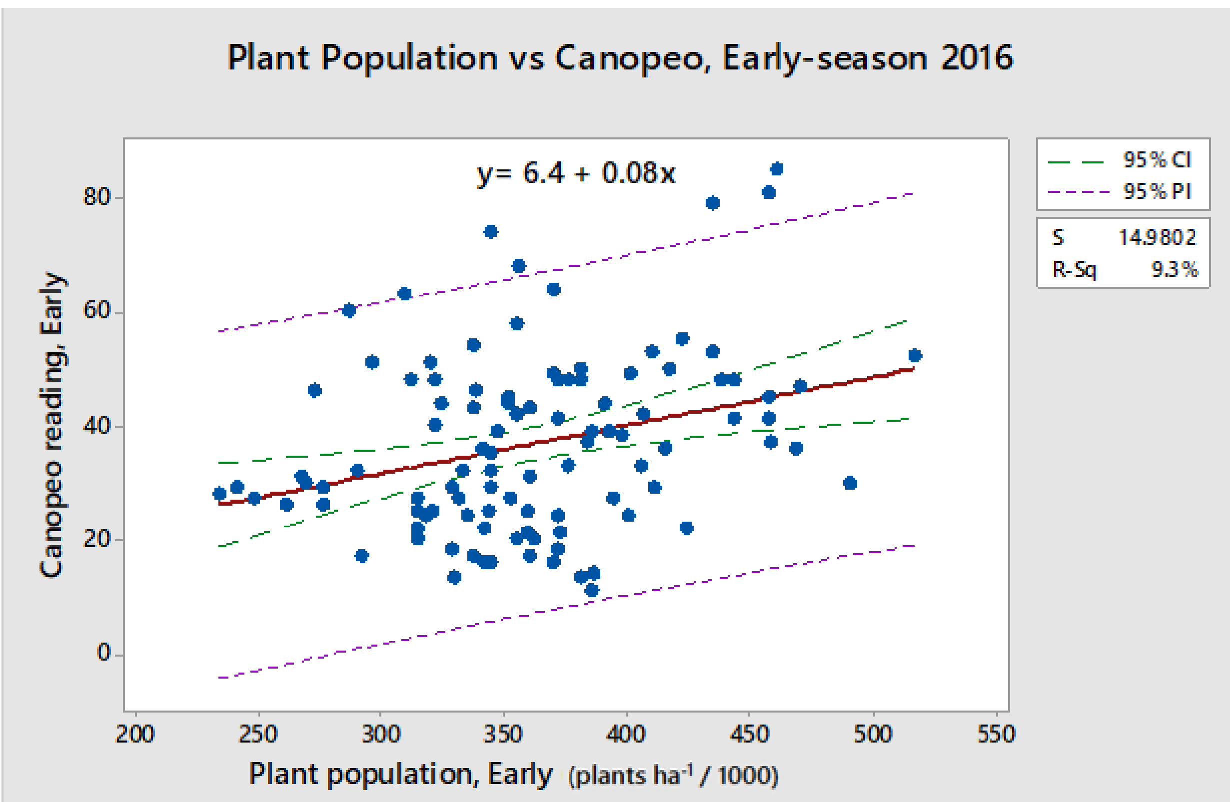

Figure 16. Regression summary of early-season soybean plant population and Canopeo readings in North Dakota producer fields, 2016.

Variability in ground canopy cover between fields is represented by variability in Canopeo output values. These differing values are likely influenced by plant growth stage, level of natural lighting at image capture, and inherent error (10%) of Canopeo processing system (Patrignani and Ochsner, 2015). Costa et al. (1980) reported that row spacing had a greater influence on canopy coverage than plant population. Additionally, genetic improvements in modern soybean cultivars have allowed for increased branching of some cultivars, maximizing canopy closure and yield in wide (97 cm) row spacing (Norsworthy and Shipe, 2005).

Experimental Research Trials

Soybean yield, plant populations, and in-season plant losses, at varying treatments of incremental seeding rates (IR) and cultivar were analyzed for each environment. At NW22 and Ransom 2016 where two cultivars were included at all SR treatments, there were no interactions between SR and cultivar. Therefore, cultivars were considered a random sample of possible cultivars used, and cultivars were combined as the primary variable of focus was SR.

Results for ANOVA and significance at individual environments are compiled in Table 20. Least squares mean values and associated LSD values were calculated in SAS and are compiled in Table 21 for individual 2016 and 2017 environments. Seeding rate had a significant influence on early and late plant populations in all eight environments. Yield varied significantly at varying IR in 4 out of 8 environments (Table 21).

Table 20. Summary of significance from ANOVA results evaluating seeding rate influence on plant population and yield at individual 2016-2017 research environments.

Source	df	NW22 Natural drainage, 2016				NW22 Natural drainage, 2017			
		PopE[‡]	PopL[‡]	Loss[‡]	Yield	PopE	PopL	Loss	Yield
Seeding rate	6	***	***	ns	**	***	***	ns	ns
Residual error	39								
		NW22 Control drainage, 2016				NW22 Control drainage, 2017			
Seeding rate	6	***	***	**	ns	***	***	ns	**
Residual error	39								
		Ransom County, 2016				Ransom County, 2017			
Seeding rate	6	***	***	ns	***	***	***	ns	ns
Residual error	18								
		Casselton, 2017				Sargent County, 2017			
Seeding rate	6	***	***	ns	**	***	***	ns	ns
Residual error	18								

[†]*, **, and ***, indicate significance at $P<0.05$, $P<0.01$, and $P<0.001$ respectively.
[‡]PopE, early-season plant population; PopL; late-season plant population. Loss, observed in-season plant loss.
[§]ns, nonsignificant.

Table 21. Summary of least squares means and LSD values for 2016 and 2017 research environments.

	NW22, Natural drainage								Ransom County, ND							
	2016				2017				2016				2017			
Treatment	PopE[§]	PopL[§]	Loss[§]	Yield	PopE	PopL	Loss	Yield	PopE	PopL	Loss	Yield	PopE	PopL	Loss	Yield
	plants ha^{-1}/1000		%	kg ha^{-1}	plants ha^{-1}/1000		%	kg ha^{-1}	plants ha^{-1}/1000		%	kg ha^{-1}	plants ha^{-1}/1000		%	kg ha^{-1}
IR 1[‡]	198a	183a	6.4	2333a	260a	256a	1.6	2546	251a	212a	15.5	4050a	229a	229a	0	3490
IR 2	304b	277b	8.5	2253a	307ab	298ab	3.3	2607	263a	255a	2.6	4282ab	260a	260a	0	3604
IR 3	331bc	308bc	7.0	2319a	343bc	325bc	4.8	2563	298ab	269a	9.6	4422bc	305a	305ab	0	4177
IR 4	379cd	358cd	5.1	2455ab	406c	393cd	3.4	2655	360bc	267a	21.3	4590cd	399b	386b	2.5	3766
IR 5	415d	375d	9.4	2696b	489d	502e	3.6	2659	386c	373b	2.9	4624cd	502cd	498cd	1.0	4105
IR 6	432d	402d	7.0	2667b	520d	460de	5.0	2802	458d	421bc	8.0	4781d	484bc	471c	3.3	3980
IR 7	515e	467e	9.9	2641b	554d	527e	4.8	2843	529e	473c	10.4	4710d	592d	561d	5.3	4163
Mean	368	338	7.6	2480	411	394	3.8	2668	363	324	12.7	4494	396	387	1.7	3898
LSD (0.05)	69	64	ns	282	74	69	ns	ns	66	64	ns	235	91	82	ns	ns

	NW22, Controlled drainage								Casselton, ND				Sargent County			
	2016				2017				2017				2017			
IR 1	192a	183a	4.0ab	2333	269a	260a	3.3	2520a	247a	247a	0	3590a	224a	224a	0	3263
IR 2	269b	254b	5.9abc	2523	321ab	307ab	4.3	2673ab	287a	283a	1.3	4223b	296a	287a	3.0	3340
IR 3	317b	296bc	6.0abc	2497	379b	361b	4.3	2756bc	319a	310a	2.8	4012ab	314a	301a	4.0	3295
IR 4	327b	319c	2.1a	2490	451c	437c	3.0	2856abc	413b	404b	2.0	4517bc	413b	408b	1.0	3736
IR 5	452c	400d	11.5cd	2574	482c	473cd	1.8	2835abc	484bc	484bc	0	4486bc	426b	404b	5.0	3720
IR 6	465c	417d	12.5d	2533	507c	496d	2.3	2986d	534c	534c	0	4514bc	507bc	489bc	3.5	3506
IR 7	488c	429d	8.8bcd	2667	606d	583e	3.8	2955cd	543c	534c	1.8	4802c	597c	565c	5.5	3464
Mean	359	328	7.3	2517	431	417	3.3	2797	404	399	1.1	4306	397	383	3.1	3475
LSD (0.05)	69	65	6.0	ns	59	57	ns	216	87	86	ns	560	97	95	ns	ns

[†]Means in column, followed by same letter are not significantly different at $P<0.05$ according to LSD test.
[‡]IR, incremental seeding rate, differ in increments of 49 400 seeds ha^{-1} increasing from IR 1 to IR 7.
[§]PopE, early season plant population; PopL; late season plant population; Loss, observed in season plant loss. All values calculated by SAS (PROC GLM).
[¶]ns, nonsignificant.

Variance of environments was considered homogenous by Bartlett's Chi-square test for early and late-season plant populations. Error mean squares of yield and plant loss were homogenous as they differed across environments by less than a factor of 10. Results for ANOVA and levels of significance of combined analyses of 2016-2017 environments are provided in Table 22.

Table 22. Summary of significance of mean square values from ANOVA results evaluating seeding rate influence on plant population and yield for combined 2016-2017 environments.

SOV	df	PopE[†‡]	PopL[‡]	Loss[‡§]	Yield
Env [Environment]	7	-	-	-	-
Rep(Env)	24	-	-	-	-
SR [Seeding rate]	6	***	***	*	***
Env*SR	42	ns	ns	ns	ns
Residual error	284				

[†]*, **, and ***, indicate significance at P<0.05, P<0.01, and P<0.001 respectively.
[‡]PopE, early-season plant population; PopL; late-season plant population. Loss, observed in-season plant loss.
[§]Ransom County, 2016 excluded from combined analysis for Loss variable due to plot damage.
[¶]ns, nonsignificant.

Table 23 summarizes responses in yield, early and late-season plant populations, and plant loss, at increasing seeding rates for combined 2016-2017 environments. Seeding rate had a significant influence on yield, early and late-season plant population, and in-season plant loss over combined years. Yields differed significantly (P<0.05) more among low SR treatments (IR 1 to IR 3) compared to high SR treatments (IR 5 to IR 7). There appears to be an association between SR and amount of seedling loss. Further research is recommended to investigate seedling losses at increasing SR. Mean plant loss was significantly lower (Table 23) at IR 1 and IR 4 (calculated average 2.9%), compared to IR 5, IR 6, and IR 7 (calculated average 5.6%).

For combined 2016-2017 environments, average yield was 3199 kg ha^{-1} and increased with increasing SR. Average yield observed at the highest SR (IR 7) was 3389 kg ha^{-1}, while the treatment with lowest SR (IR 1) yielded 2916 kg ha^{-1} (Table 23). These results mirror findings of numerous studies reporting yield increases with increasing SR (Shibles et al., 1975; Ablett et al., 1991; Egli and Zhen-wen, 1991; Van Roekel et al., 2015).

Table 23. Summary of mean and LSD values for soybean plant populations, plant loss, and yield, at increasing seeding rates and relative yield response and efficiency, combined 2016-2017 research environments.

Treatment	PopE	PopL	Loss[§]	Yield	Response[¶]	Efficiency[#]
	----plant ha^{-1}/1000----		%	kg ha^{-1}	%	kg /1000 plants
IR 1[†]	234a[‡]	222a	2.8a	2916a	-	13.1
IR 2	290b	278b	4.4ab	3065b	+5.1	11.0
IR 3	329c	310c	4.6ab	3123bc	+1.9	10.1
IR 4	390d	365d	3.0a	3239cd	+3.7	8.9
IR 5	456e	433e	5.3b	3315de	+2.4	7.7
IR 6	482f	454e	5.5b	3349de	+1.0	7.4
IR 7	544g	507f	6.1b	3389e	+1.2	6.7
Mean	389	367	4.5	3199	+2.6	9.3
LSD (0.05)	27	27	2.0	132	-	-

[†]IR differ in increments of 49 400 seeds ha^{-1} increasing from IR 1 to IR 7.
[‡]Means in column, followed by same letter are not significantly different at P<0.05 by LSD test.
[§]Ransom County, 2016 data excluded from combined analysis of in-season plant loss.
[¶]Percent increase in total yield with increase in IR. Calculated as $(Yield_2 – Yield_1)/(Yield_1/100)$; $Yield_2$= Yield of current IR level; $Yield_1$= Yield one row above current.
[#]Efficiency of seed weight accumulation over growing season; calculated as yield divided by late plant population.

The lowest average early and late plant population (234 000 plants ha^{-1} and 222 000 plants ha^{-1}, respectively) for combined 2016-2017 environments was observed at the lowest SR treatment (IR 1). Early and late populations were greatest with IR 7 treatment (highest SR) at 544 000 plants ha^{-1} and 507 000 plants ha^{-1}, respectively (Table 23). Four out of the seven SR treatments (IR 1 to IR 4) provided late-season plant populations less than the recommended population of 370 600 plants ha^{-1} to maximize yield (Kandel and Endres, 2015).

Average yield from combined 2016-2017 data (Table 23) was used as the numerator to calculate an average seed accumulation ratio for each IR, using late-season plant population as the denominator. As outlined in Table 23, plants grown at low SR (< IR 4) were more efficient in accumulating seed weight, on a per plant basis, compared to plants grown at high SR (> IR 4). A positive yield response was observed with each unit increase in seeding rate (Table 23).

Yield increased 323 kg ha^{-1} (11.1%) as SR was increased between IR 1 and IR 4. Yield increased by 150 kg ha^{-1} (4.6%) as rates increased from IR 4 to IR 7. Decreasing rates of seed weight accumulation with increasing population was also apparent when yield was regressed for comparison to late-season plant populations (Figure 17). The significant nonlinear association between late population and yield (r^2= 0.99) is likely explained by increased competition at higher plant densities, as neighboring plants seek water and nutrient sources (Weber et al., 1966).

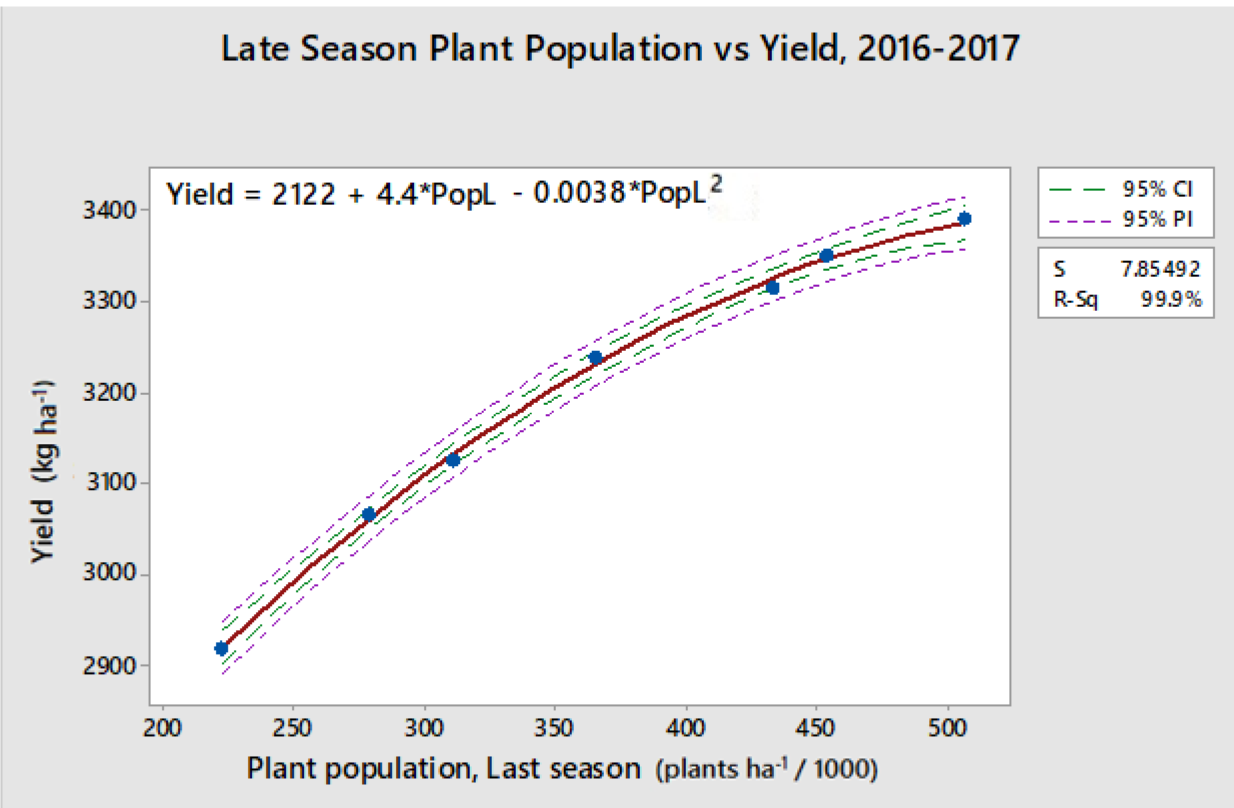

Figure 17. Regression summary of means of soybean plant populations observed at late reproductive stages and yields, combined 2016-2017 research environments.

SUMMARY

Results from the producer survey, producer field visits, and experimental research trials, all identified producer crop management practices that are yield-limiting in North Dakota soybean fields. Survey results for expected percent yield reduction relative to each yield-limiting factor were compiled for final comparison.

Seeding Rate

Producers should select a PD closest to 1 May, while ensuring local conditions are favorable for germination and seedling establishment. Based on individual factor analysis results (Table 24), producers statewide delaying planting later than 1 May, reduce total yield by 2.0% for every five d planting is delayed. Producers located in the south and western part of the state (GR 3 and GR 10), are expected to see yield losses at a higher rate of 2.0% for every four d delay in planting. This increased loss rate could possibly be driven by timing and amount of rainfall over the growing season. In years where water is deficient for an extended period, plants in the reproductive stage can mature earlier, resulting in a reduction of overall yield.

Table 24. Summary of individual crop management factor influence on soybean yield, statewide and soybean growing region, based on single factor linear regression analysis.

	Statewide				GR 3[¶]	GR 4	GR 5	GR 9	GR 10
CMF[†]	2014	2015	2016	Combined	Combined				
	---------------------%------------------------				----------------------%----------------------				
PD	-0.4[‡]	-0.4	-0.5	-0.4	-0.5	-0.3	-0.3	ns	-0.5
RM	-2.4	-2.0	-3.3	-2.5	ns	ns	ns	ns	ns
SR	ns	ns	ns	ns	ns	ns	ns	-2.2	ns
	-------------------kg ha^{-1}----------------------				--------------------kg ha^{-1}--------------------				
Yield[§]	2735	2731	2759	2742	2849	2753	2695	2339	2080

[†]CMF, crop management factor; PD, planting date; RM, relative maturity; SR, seeding rate.
[‡]Percent reduction of total yield per unit change in crop management factor. Units: PD, d delay in planting; RM, unit difference in cultivar RM; SR, 10 000 seeds ha^{-1}.
[§]Producer-reported mean yield; averaged for columns with >1 significant factor.
[¶]GR, North Dakota soybean growing region.
[#]ns, nonsignificant.

More than 60% of soybean fields in North Dakota are planted later than 15 May. Regional climatic factors limit many producers from planting the first week of May, however most producers should be able to adapt their planting day to be at least one d earlier than previously (assuming favorable growing conditions), to directly increase soybean yield potential. This is especially applicable to producers currently planting later than 15 May.

Relative Maturity

North Dakota soybean yields are also limited by producers' selecting cultivars that mature before the end of the growing season. The relative maturity that will provide for the greatest yield potential is primarily dependent on field location within the state. The range of relative maturities likely to grow full season is geospatially constrained. Producers statewide, on average, can increase soybean yield potential 2.5% by selecting a cultivar with a relative maturity one unit greater than currently used. For producers desiring to maximize plant growth to the full length of available growing season, it would be recommended to select from the latest-maturing cultivars adapted for their growing region.

However, although selecting a cultivar one unit later in RM resulted in a greater average yield increase than adjusting PD by 4 d (2.5% vs 2.0%), the range of cultivar RM adapted for growth within the same field is typically limited to four RM units (Table 16). Additionally, these expectations for yield reductions may not reflect actual reductions associated with the individual yield-limiting factor, as they are results from single factor analysis; thereby determined irrespective of each other.

As producers purchase seed months before planting, they are likely to select cultivar maturities dependent on expected timing of planting. Though the expected planting date may differ from the actual date (due to environmental conditions or planting order based on crop priorities), producers are not likely to plant a late-maturing cultivar later than recommended, to avoid losses from not reaching physiological maturity if an early frost event occurs. Percent yield reductions associated with RM selection are likely more precise when RM is considered in relation to PD, as represented by multiple factor analysis results (Table 25). Assuming planting date is fixed, producers can expect an average yield loss of 1.3% for each unit lower in RM that the selected cultivar is in comparison to the latest-maturity adapted for the growing area.

Table 25. Summary of multiple crop management factors influence on soybean yield statewide and soybean growing region, based on multiple factor linear regression analysis.

	Statewide				GR 3[¶]	GR 4	GR 5	GR 9	GR 10
CMF[†]	2014	2015	2016	Combined	Combined				
	---------------------%------------------------				-----------------------%----------------------				
PD	-0.4[‡]	-0.4	-0.5	-0.4	-0.4	-0.5	ns	ns	ns
RM	-0.9	-0.8	-0.9	-1.3	+0.4	-1.5	ns	ns	ns
SR	ns	ns	ns	-0.4	ns	-0.1	ns	ns	ns
	-------------------kg ha^{-1}----------------------				--------------------kg ha^{-1}--------------------				
Yield[§]	2747	2737	2757	2747	2853	2753	2695	2339	2093

[†]CMF, crop management factor; PD, planting date; RM, relative maturity; SR, seeding rate.
[‡]Percent reduction of total yield per unit change in crop management factor. Units: PD, d delay in planting; RM, unit difference in cultivar RM; SR, 10 000 seeds ha^{-1}.
[§]Producer-reported mean yield; averaged for columns with >1 significant factor.
[¶]GR, North Dakota soybean growing region.
[#]ns, nonsignificant.

Based on producer survey data, increasing SR will only provide a significant yield response when PD and RM are unchanged. This finding is most relevant to producers already planting as close to 1 May as local growing conditions allow, and have selected a late-maturing cultivar adapted for their growing region. Based on combined year survey data in Table 25, producers increasing seeding rate by 49 400 seeds ha^{-1}, should expect an average 2.0% increase in yield (at seeding rates between 334 000 seeds ha^{-1} and 494 000 seeds ha^{-1}). Findings from experimental trials observed an average yield response of 1.5% at similar increases in seeding rate of 49 400 seeds ha^{-1} (calculations based on Table 23). This finding is most beneficial for producers as expected yield response is a critical factor when determining if increasing seeding rate ha^{-1} is economical. Producers currently seeding at rates less than what will provide the recommended established population of 370 600 plants ha^{-1}, will likely see greater yield increases (calculated average 3.7%) by planting additional seeds per ha^{-1}. Any seeding rate increases above that may provide for an average yield increase of 1.9%; however economic feasibility of rate increases will depend on cost of seed.

Plant Population and In-season Plant Loss

Differences in harvest yield at varying seeding rates may be explained by losses incurred at various timings during the growing season. Though surveyed producers reported an estimated average seedling loss of 10% (between seeding and plant population establishment), field observations in producer fields discovered actual seedling losses averaged 12.3%. These findings are revealing as producers on average are underestimating the amount of seedling loss that occurs, and thereby not seeding at a sufficient rate to attain the recommended established population of 370 600 plants ha^{-1}. Producers may be able to estimate plant populations utilizing the Canopeo application to determine ground canopy cover; however, additional research is needed to eliminate possible confounding factors (i.e. row spacing, natural lighting at timing of image capture).

The most revealing result from this research was the finding that 7.9% of plants established early in the growing season, did not contribute to yield at harvest due to lack of pod formation, adequate seed fill, or plant mortality. Living soybean plants that are not contributing to yield are likely adversely affecting yield by consumption of water and nutrient resources that would otherwise be available to productive soybean plants during flowering and seed-fill. The in-season plant losses may also suggest that soybean fields were not adequately scouted for disease and pests, or that applied management was insufficient or injurious to some plants.

The early-season plant population is not likely to be the actual population contributing to yield at harvest. The NDSU recommendation for an established population of at least 370 600 plants ha^{-1}, does not account for an expected in-season plant loss of 7.9%. Results from the managed experimental trials observed similar findings with an average in-season plant loss of 4.5%. Compared to higher mortality rates in producer fields, these findings may suggest that producer fields may require additional observation and adapted crop management to ensure plant losses are minimized throughout the growing season.

In-season plant losses varied by soybean growing region within North Dakota. Low-yielding environments (GR 8 to GR 10) can expect plant losses averaging 10.5%; compared to 5.0% in high-yielding areas (GR 1 to GR 3) within the state. There are numerous environmental factors differing between these environment types including annual rainfall accumulation, soil type, and growing season length. Further exploratory research through quantification of differences in these environmental factors across environments may provide for associations explaining the varying amounts of in-season plant losses observed in growing regions throughout the state.

CONCLUSION

Soybean yields and yield potentials in North Dakota are limited by producer management of timing of planting, cultivar relative maturity selection, and seeding rate. North Dakota producers are likely to improve soybean yield potential by adjusting current management practices of these factors. Producers should plant soybean when conditions are favorable and closest to 1 May to avoid daily yield reductions from delayed plantings. Selecting the latest-maturing cultivar adapted for local growing conditions, and seeding at a rate to maximize seed germination and plant establishment will likely improve soybean yield potential. After the soybean plant population has established early in the growing season, producers should determine if plant losses occur during the remainder of the season, and identify causes to adjust crop management practices if necessary.

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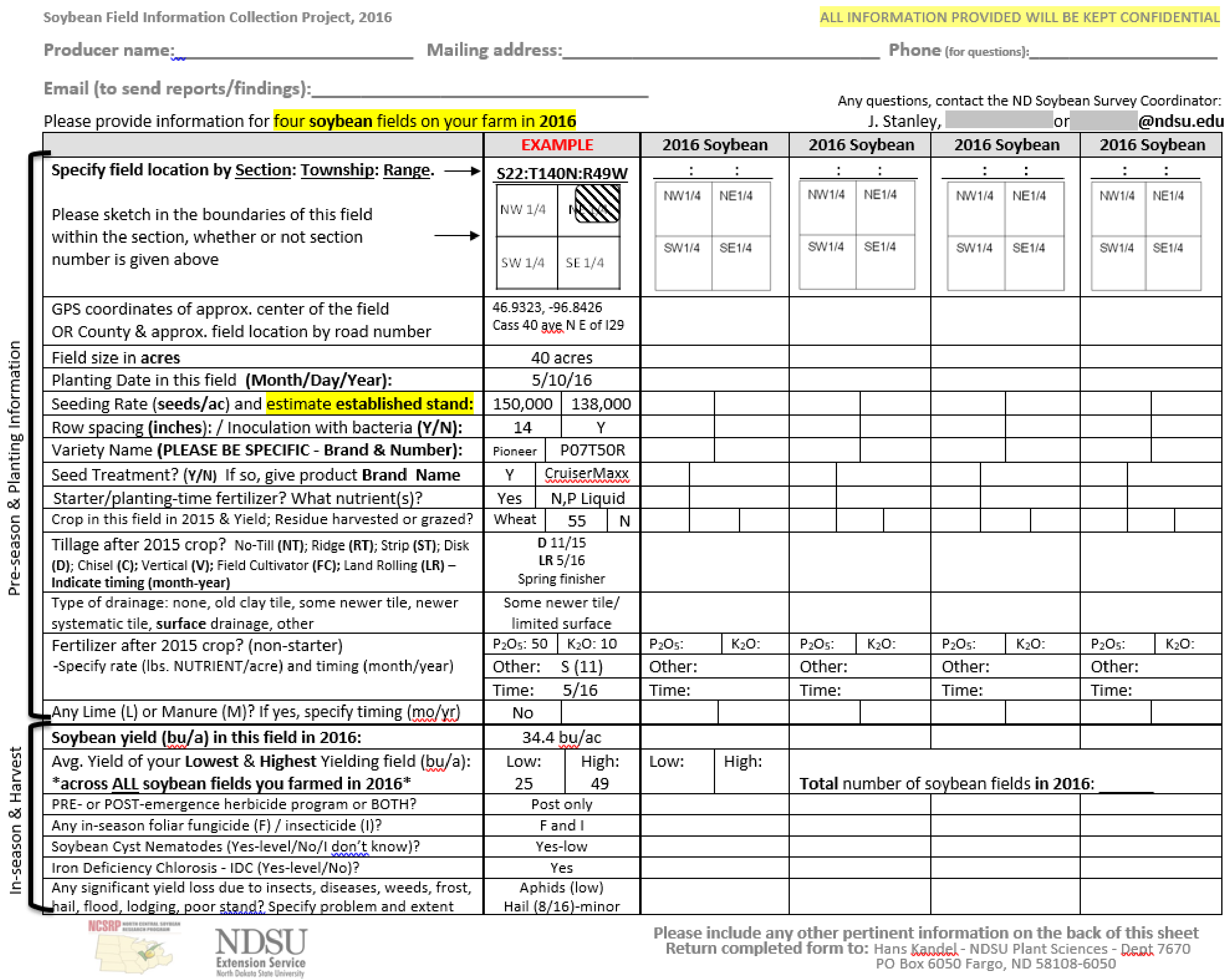
APPENDIX



Soybean Field Information Collection Project, 2016

ALL INFORMATION PROVIDED WILL BE KEPT CONFIDENTIAL

Producer name:________ Mailing address:________ Phone (for questions):________

Email (to send reports/findings):________

Any questions, contact the ND Soybean Survey Coordinator: J. Stanley, or @ndsu.edu

Please provide information for four soybean fields on your farm in 2016

		EXAMPLE	2016 Soybean	2016 Soybean	2016 Soybean	2016 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, 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
	GPS coordinates of approx. center of the field OR County & approx. field location by road number	46.9323, -96.8426 Cass 40 ave N E of I29				
	Field size in **acres**	40 acres				
	Planting Date in this field **(Month/Day/Year):**	5/10/16				
	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 2015 & Yield; Residue harvested or grazed?	Wheat / 55 / N				
	Tillage after 2015 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 11/15 LR 5/16 Spring finisher				
	Type of drainage: none, old clay tile, some newer tile, newer systematic tile, **surface** drainage, other	Some newer tile/ limited surface				
	Fertilizer after 2015 crop? (non-starter) -Specify rate (lbs. NUTRIENT/acre) and timing (month/year)	P_2O_5: 50 / K_2O: 10	P_2O_5: / K_2O:	P_2O_5: / K_2O:	P_2O_5: / K_2O:	P_2O_5: / K_2O:
		Other: S (11)	Other:	Other:	Other:	Other:
		Time: 5/16	Time:	Time:	Time:	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 2016:**	34.4 bu/ac				
	Avg. Yield of your **Lowest** & **Highest** Yielding field (bu/a): ***across ALL soybean fields you farmed in 2016***	Low: 25 / High: 49	Low: / High:	**Total** number of soybean fields **in 2016**: ______		
	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 (8/16)-minor				

NCSRP 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 A1. North Dakota soybean producer survey.

Table A1. Regression summary of single factor analysis of crop management factor influence on soybean yield in soybean growing regions in North Dakota, 2014-2016.

Year		Crop management factor‡			
		PD	RM	SR	Yield
		——— r^{2}§ ———			kg ha^{-1}
1	(n=145)	ns	ns	ns	3193
2	(n=53)	ns	ns	ns	3062
3	(n=104)	0.42	ns	ns	2849
4	(n=148)	0.11	0.08	ns	2753
5	(n=61)	0.12	ns	ns	2695
6	(n=158)	ns	0.05	ns	2544
7	(n=45)	ns	ns	ns	2430
8	(n=28)	ns	ns	ns	2424
9	(n=27)	ns	ns	0.20	2339
10	(n=38)	0.25	ns	ns	2068

†Results based on 2014-2016 producer survey data.
‡PD, planting date; RM, cultivar maturity group; SR, seeding rate.
§Models and variables with r^2 value are significant at $P<0.05$.
¶ns, nonsignificant.

Table A2. Regression summary of single factor analysis of associated growth and management factors observed in producer soybean fields in North Dakota, 2016-2017.

Variable		Year		
Response[‡]	Predictor	2016	2017	Combined
			r^2	
Pop., Early				
	GR	0.02	0.08**	0.01
	Row spacing	0.15***	0.31***	0.24***
Pop., Late				
	Pop., Early	0.82***	0.65***	0.71***
	GR	0.06**	0.03*	0.0004
	Row spacing	0.08**	0.28***	0.18***
Plant loss				
	Pop., Early	0.003	0.15***	0.07***
	GR	0.02	0.02	0.02*
	Row spacing	0.002	0.004	0.001
Canopeo				
	Pop., Early	0.09**	0.01	0.002
	Stage, Early	0.009	0.50***	0.02*
	Vigor, Early	0.26***	0.13***	0.16***
	Row spacing	0.09**	0.001	0.0003

[†]*, **, and ***, indicate significance at P<0.05, P<0.01, and P<0.001 respectively.
[‡]Pop., Plant population.

Table A3. Degrees of freedom and error term equations for ANOVA for Ransom County, Sargent County, and Casselton, ND 2017 research environments.

Source	df	df equation	Error term
Rep	3	r-1	
SR [Seeding rate]	6	sr-1	SR MS/Error MS
Error	39	(sr-1)(r-1)	
Total	55	(sr*r)-1	

Table A4. Degrees of freedom and error term equations for ANOVA for combined 2016-2017 research environments.

Source	df	df equation	Error term
Env [Environment]	7	Env-1	Non-valid
Rep(Env)	24	Env(r-1)	Non-valid
SR [Seeding rate]	6	sr-1	SR MS/Env*SR MS
Env*SR	42	(env-1)(sr-1)	Env*SR MS/Error MS
Residual error	284	[(env*sr)-1](r-1)	
Total	363	(env*sr*r)-1	