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Planting date, cultivar, seed treatment, and seeding rate effects on soybean growth and yield

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Abstract

Soybean [*Glycine max* (L.) Merr.] yield is a function of many factors including genetic attributes of the cultivar, environmental conditions, and management practices. Temporally variable weather patterns in North America, especially in the northern Great Plains, have resulted in the re-examination of how spring production practices interact with the environmental conditions to influence yield. This study evaluated the impact of four plantings dates, four seeding rates, and two soybean maturity groups (MGs) using treated and untreated (control) seed on soybean growth, seed yield, and composition. The study was conducted at Volga, SD, in 2014, 2015, and 2016. The planting dates in the study ranged from early May to early July and the four seeding rates were 247,000; 333,500; 420,000; 506,500 seeds ha^{-1}. Stand establishment decreased as seeding rate increased irrespective of planting date. The number of growing degree days (GDDs) to R1 decreased with delayed planting. Delayed planting also decreased the number of GDDs to R8, the length of the reproductive phase (R1–R8), and seed yield. Delayed planting decreased seed yield for both MGs but the rate of decrease was greater for MG 2.4 than MG 1.4. Seed treatment increased seed yield irrespective of planting date. Seed protein was variable among planting dates and between MGs while seed oil decreased with delayed planting. The research documents the impact of delayed planting on soybean yield and quality and highlights the importance of early planting in soybean irrespective of maturity group and growth habit.

1 | INTRODUCTION

As soybean [*Glycine max* (L.) Merr.] production in the Midwest continues to increase, producers continue looking for ways to improve yields and enhance profitability. Early season production practices, such as those at planting, are by far the most important factors affecting yield. Numerous research studies (Bastidas et al., 2008; Bruns, 2011; De Bruin & Pedersen, 2008; Egli & Cornelius, 2009; Gaspar & Conley, 2015; Mourtzinis, Gaspar, Naeve, & Conley, 2017; Oplinger & Philbrook, 1992; Vossenkemper et al., 2016) have been conducted on the effect of planting date on soybean yield. While some of this prior research was conducted with soybean of indeterminate growth habit, very rarely were such cultivars of maturity group (MG) 2 or lower. Maturity groups 1 and

Abbreviations: CIPAR, cumulative intercepted photosynthetically active radiation; CumNDVI, cumulative normalized difference vegetation index; DOY, day of year; GDD, growing degree day; MG, maturity group.

2 soybean cultivars are earlier maturing and better adapted to South Dakota than MG 3 cultivars used in most studies and that are adapted to major soybean-producing states including Nebraska, Iowa, Illinois, and Indiana (Mourtzinis & Conley, 2017). Due to differences in MG as well as region of adaptation, it is likely that findings using later maturing cultivars may not be directly transferable to early maturing types grown in South Dakota.

Planting soybean in late May or early June in the upper Midwest generally results in significant yield losses (Mourtzinis et al., 2017; Pederson & Lauer, 2004; Whigham, Farnham, Lundvall, & Tranel, 2000). Egli and Cornelius, (2009) reported a rapid decline in yield for soybean cultivars of MG 00 to 3 in the Midwest when planting dates were delayed past May. The major reasons for varying degrees of yield response to planting date is because responses can depend on climatic conditions, location, cultivar MG and growth characteristics (Grau, Oplinger, Adee, Hinkens, & Martinka, 1994; Lueschen et al., 1992; Pederson & Lauer, 2003; Vossenkemper et al., 2016). Frequently, growth characteristics and MG are often linked. For example, soybean with MG $\leq$ 4 are generally indeterminate, whereas cultivars with MG $\geq$ 5 are often determinate. Determinate cultivars finish vegetative growth when the plant enters reproductive stages, whereas indeterminate growth habit cultivars have simultaneous vegetative growth and flowering during the reproductive phase. Because of their growth habit, indeterminate soybean cultivars are more suited to stressful conditions associated with late planting. One of the important differences in yields between the MGs is the length of time of the vegetative stage (planting to R1) relative to the reproductive stages (R1–R8) (Heatherly, 2005; Nleya, Sexton, Gustafson, & Moriles, 2013).

Temperature and photoperiod are the two dominant abiotic factors influencing soybean development. As temperature increases, the rate of crop development increases. Photoperiod on the other hand, modifies the temperature response in soybean, a short-day plant, with longer daylength decreasing the development rate through delaying reproductive development (Setiyono et al., 2007). However, the delay in flowering due to longer daylength at later planting dates is not noticeable because higher temperatures later in the growing season shorten the reproductive phase (Setiyono et al., 2007). Therefore, late-planted soybean plants have reduced light interception due to shortened growing season which partially accounts for yield decline with delayed planting (Gaspar & Conley, 2015). Delayed planting can result in reduced pod number per plant, plant height, number of branches, pod-set, seed weight, and time from planting to flowering and maturity which can reduce yields and total biomass production (Bhatia, Tiwari, & Joshi, 1999; Chen & Watriak, 2010). Of all these, seed and pod numbers are strongly correlated with yield (Kantolic & Slader, 2007).

Core Ideas

- The length of the growing season in the northern Great Plains has increased.
- Planting date is influenced by season length and affects seed yield and quality.
- Delaying planting shortened the growing season and reduced soybean yield.
- Seed yield decreased linearly with delayed planting, at rates of 16.5 to 71.5 kg ha^{-1} d^{-1} depending on maturity group.

Another factor that can significantly impact yield of soybean planted at different dates is MG of the soybean cultivar. Heatherly (2005) suggested that the performance of soybean cultivars of MG 4–6 might be linked to the length of the vegetative phase (planting to R1) as compared to length of the reproductive stages (R1–R8). Other studies, however, have found a positive correlation between duration of reproductive stages and grain yield (Bastidas et al., 2008; Kantolic & Slader, 2007). A combination of early planting dates with a MG that maximize the number of days of growth before full maturity, maximizes the duration of seed filling period (R5–R7) and therefore increase soybean seed yield (Robinson, Conley, Volenec, & Santini, 2009). The change in yield with delayed planting is not the same for full-season and short-season soybean cultivars (Vossenkemper et al., 2016). While full-season cultivars yielded more than short-season cultivars at both early and late planting dates, the differences in yield between the two MGs were much greater at early planting dates when compared to late planting dates.

Seeding rate is an important factor that growers have to consider at planting. Few studies have evaluated interactions between seeding rate and planting date for indeterminate soybean cultivars. In a study conducted in Iowa where the growth characteristics and MGs were not identified, De Bruin and Pederson (2008) evaluated four seeding rates at four planting dates ranging from late April to mid-June and reported that harvest plant population and seed yield were not influenced by planting date. Gaspar and Conley (2015) reported diminished yield potential of later planted soybean partially due to reduced cumulative intercepted photosynthetically active radiation (CIPAR) and cumulative normalized difference vegetation index (CumNDVI). They reported that increasing seeding rate increased seed yield through increases in CIPAR and CumNDVI but that planting as soon as conditions allow was more advantageous that increasing seeding rate.

Seed treatment use in soybean is an increasingly popular option among growers in the United States with approximately 70% of soybean seed sold in the Midwest containing some seed treatment (Gaspar, Marburger, Mourtzinis, & Conley, 2014). However, research results show that seed treatment effects depend on the environment (year/location) (Cox & Cherney, 2014) and cultivar susceptibility to disease (Esker & Conley, 2012). Gaspar and Conley (2015) reported seed treatment with a fungicide/insecticide mix (CruiserMaxx) generated adequate stands and increased CIPAR in soybean planted before 10 May in Wisconsin. Vossenkemper et al. (2016) found an increase of 80.6 kg ha^{-1} in soybean yield due to seed treatment. However, they did not find an interaction between planting dates, MG, and seed treatment.

In the Midwest, timely planting of corn (*Zea mays* L.) can delay planting of soybean. Planting can further be delayed to dates later than early May due to the cold, wet soils and the potential of an increased exposure to seedling diseases (Vossenkemper et al., 2016). In addition, the length of the growing season has increased by 1 to 3 wk in the Midwest (Kucharik, Serbin, Vavrus, Hopkins, & Motew, 2010) and this is accompanied by year-to-year variability in climate which require changes in management practices or the need to re-plant in certain years (Mourtzinis et al., 2015). Late planting may necessitate use of different soybean cultivar MG, seed treatment or adjustment of seeding rates to maintain optimal yields. The objectives of this study were to (a) determine the influence of delayed planting on growth and yield of two indeterminate soybean cultivars differing in MG, and (b) determine how planting date interacts with seeding rate, MG, and seed treatment in influencing soybean performance.

2 | MATERIALS AND METHODS

The study was conducted at Volga Research Farm, (44.3236° N, 96.9264° W), near Brookings, SD, in the growing seasons of 2014, 2015, and 2016. Soil textural classification was a Brandt silty clay loam (fine-silty, mixed, superactive, frigid Calcic Hapludoll) with a pH of 5.7. Soil analysis results showed that the soil had 42–47 g organic matter kg^{-1}, 11.2–15.0 mg P kg^{-1}, and 104–115.25 mg K kg^{-1}. The experimental fields were chisel plowed in the fall and cultivated twice in the spring prior to planting soybean. The research plots were not irrigated. Total rainfall and mean air temperature for each growing season are shown in Table 1.

The experimental design was a randomized complete block in a split-plot arrangement with treatments replicated four times. Main plots were four planting dates and subplots were: four seeding rates of 247,000; 333,500; 420,000; and 506,500 viable seeds ha^{-1} in 2014 and 2015 with 185,000 seeds ha^{-1} added in 2016 at the request of soybean growers; two soybean cultivars of MGs of 1.4 and 2.4 and treated and untreated (control) seed arranged in a factorial design. Soybean cultivars used in the study were 1405 R2 and 2402 R2 (Channel). Seed for the seed treatment, was treated with Acceleron Seed Applied Solutions (Basic) (a.i. pyraclostrobin, metalaxyl, and fluxapyroxad). The seed treatment was designed to provide protection from root rot pathogens including *Fusarium* spp., *Rhizoctonia* spp., *Pythium* spp., and *Phytopthora* spp. The first planting date was targeted to be planted when soil temperature was >10 °C. The actual planting dates were 16 May, 30 May, 13 June, and 27 June in 2014; 4 May, 20 May, 2 June, and 16 June in 2015, and 16 May, 1 June, 15 June, and 1 July in 2016. Soybean was planted in four rows 76 cm apart by 6.4 m long.

Weeds were managed with pre-emergent herbicide application of S-metolachlor [2-chlroro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)-acetamide] at 1.9 kg a.i. ha^{-1} and two in-season application of glyphosate [*N*-(phosphonomethyl)glycine] at a rate of 2.3 L ha^{-1} each. The insecticide cyflutrin [cyano (4-fluoro-3-phenoxyphenyl) methyl-3-(2,2-dichloro ethenyl)-2,2-dimethyl-cyclopropanecarboxylate] was applied at a rate of 0.11 a.i. ha^{-1}when soybean aphids (*Aphis glycines*) reached economic thresholds.

Plots were trimmed back to a 5.5-m length at the V4 stage of plant development. The two center rows were harvested for final seed yield. Data collected from the plots included number of plants ha^{-1} at the V4 (2014 and 2015) growth stage, the number of days when 50% or more of the plants in each plot reached R1 and R8, yield, and moisture, protein, and oil content. Seed moisture was determined by drying samples at 60 °C for 48 h and adjusting seed moisture to 13 g kg^{-1}. Seed protein and seed oil were determined using a Near-Infrared Transmittance (NIR) Spectrosopy (Infratec 1229 Grain Analyzer).

Stand establishment, GDD, yield, seed protein and seed oil data were analyzed using ANOVA by PROC MIXED of SAS Version 9.4 (SAS Research Institute). Due to the fact that planting dates were very different each year, data collected each year were analyzed separately. Replications were considered random while all other effects were considered fixed. All mean separation was performed using Fisher's protected LSD (.05).

Regression analysis was used on stand establishment data to examine response to seeding rate and on seed yield data to examine response to planting date using SigmaPlot Version 14.0 (Systat Software, Inc.). The choice of the best model was based on model significance (significantly different from zero based on t test at P = .05), and coefficient of determination (R^2) (Belanger, Walsh, Richards, Milburn, & Ziadi, 2000; St. Luce et al., 2015). A Shapiro–Wilk test was used to test for normality. An exponential decay curve best described the stand establishment relationship to seeding rate while linear models were considered the best choice to describe seed yield relationship to planting date each year.

TABLE 1 Monthly average air temperature and rainfall at Volga, SD, for 2014 and 2015 (numbers in parentheses indicate difference from 1981–2010 average)

Rainfall	May	June	July	August	September	October	Total annual rainfall/avg. temp.
	mm						
2014	75.9 (+0.5)	184.4 (+75.2)	56.7 (−25.9)	67.1 (−10.9)	47.2 (−33.8)	16.5 (−34.7)	450.8 (−26.6)
2015	111.8 (+36.4)	53.8 (−55.4)	93.5 (+10.9)	160.8 (+82.8)	40.6 (−40.4)	33.0 (−18.2)	493.5 (+16.1)
2016	60.2 (−15.20	66.0 (−43.2)	124.5 (+41.9)	142.2 (+64.2)	105.0 (+24.0)	51.7 (+0.5)	549.6 (+72.2)
Avg. air temp.							
	°C						
2014	13.5 (+0.1)	18.8 (+0.1)	19.7 (−1.6)	20.2 (+0.1)	15.2 (+0.2)	8.9 (+1.2)	16.1 (+0.1)
2015	13.0 (−0.4)	19.6 (+0.9)	21.7 (+0.4)	19.5 (−0.6)	18.4 (+3.4)	9.9 (+2.2)	17.0 (+1.0)
2016	14.6 (+1.2)	21.3 (+2.6)	21.6 (+0.3)	20.9 (+0.8)	16.1 (+1.1)	9.3 (+1.6)	17.3 (+1.3)

TABLE 2 Growing degree days (GDD, °C) from planting to maturity for soybean grown at four different planting dates in 2014, 2015, and 2016 at Volga, SD

Planting date	2014 GDD	Planting date	2015 GDD	Planting date	2016 GDD
	°C		°C		°C
16 May	1,164	4 May	1,345	16 May	1,233
30 May	1,096	20 May	1,228	1 June	1,164
13 June	1,010	2 June	1,112	15 June	1,123
27 June	877	16 June	968	1 July	1,041

3 | RESULTS

3.1 | Weather

In 2014, the rainfall was higher than the 30-yr average early in the growing season with a combined total of 260 mm for May and June, 94.7 mm more rainfall than the same months in 2015 and 134.1 mm more than the same months in 2016 (Table 1). The rest of the 2014 growing season was drier than the long-term average while the 2015 and 2016 growing seasons were wetter than long-term average (Table 1). Average air temperatures were approximately 1 °C cooler in 2014 than in 2015 and 2016 resulting in fewer growing degree day accumulation in 2014 than in 2015 and 2016 (Table 2). Overall, delaying planting reduced growing degree days in all 3 yr.

3.2 | Stand establishment

In 2014, seeding rate (P = .001) and seeding rate × planting date (P = .001) interaction significantly affected percent established stands at V4 stage (Supplemental Table S1). Percent stand establishment decreased as seeding rates increased. The decrease in percent stand establishment with increase in seeding rate followed an exponential decay curve (Figure 1), with the two highest seeding rates showing lower percent established plants compared to lower two seeding rates. The interaction between seeding rate and planting date was likely due to higher level of variation in stand establishment for the 13 June planting date when compared to other planting dates (Figure 1).

In 2015, seeding rate (P = .001) and planting date × MG (P = .007) had significant effects on percent stand establishment (Supplemental Table S1). Again, percent established plants decreased with increasing seeding rate following an exponential decay curve (Figure 1). The planting date × MG interaction for percent established plant population was due to a lower percent established plant population for last planting date of 16 June for the MG 1.4 as compared to MG 2.4 (85.7 vs. 89.2%, respectively).

3.3 | Duration of vegetative and reproductive growth

The length of the vegetative phase decreased as planting date was delayed (Table 3). The reduction in number of GDDs required to reach R1 from first to last planting dates ranged from 20 to 53 units with no clear differences between the two MGs within a year. The fewer number of GDDs required to reach R1 in some early planting dates is likely related to delayed emergence. As planting was delayed, the length of the reproductive phase decreased for both MGs though the decrease was not the same for the two cultivars or among years

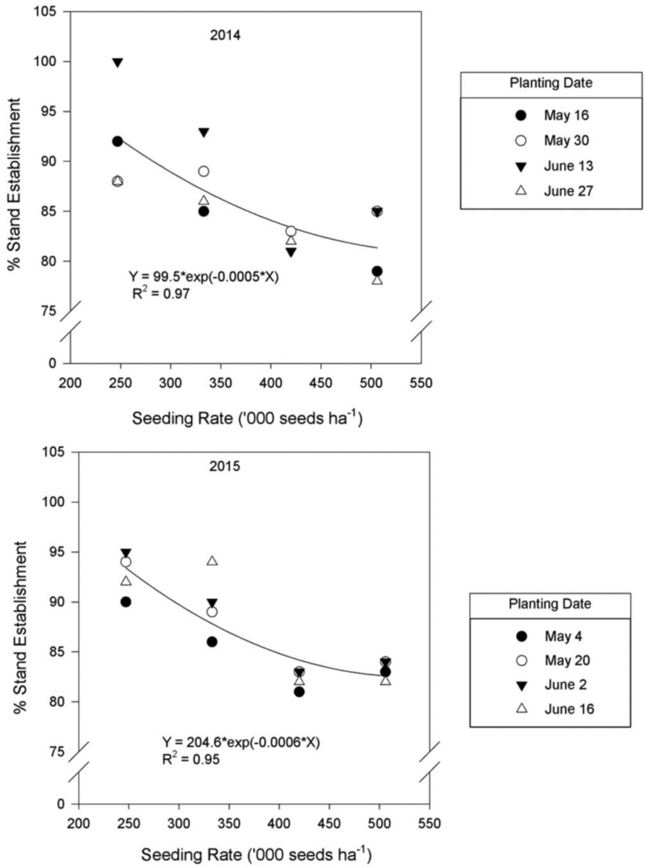

FIGURE 1 Percent stand establishment of soybean grown at four planting dates and four seeding rates at Volga, SD, in 2014 and 2015

(Table 3, Supplemental Table S2). In 2014, when planting was delayed by 42 d (from 15 May to 27 June), the number of GDDs during reproductive phase (R1–R8) were 29% less for the MG 1.4 and 42% less for MG 2.4 compared the earliest planting date. In 2015, the 43-d delay in planting (from 4 May to 16 June) reduced the number of GDDs during the reproductive phase by 15 and 25% for MG 1.4 and MG 2.4, respectively, when compared to the earliest planting date. In 2016, the number of GDDs during the reproductive phase were reduced by the same amount for the two MGs, by 39 and 40% for MG 1.4 and MG 2.4, respectively when planting was delayed by 46 d (from 16 May to 1 July). The number of GDDs required to reach maturity were progressively less with each day of delay in planting for both MGs and in all 3 yr (Table 3). In 2014 and 2015, hard freezing (–2.2 °C) occurred much earlier (10 October in 2014 and 16 October in 2015) compared to 2016 when hard freezing was not recorded until 8 November. The earlier freezing reduced the number of GDDs to maturity by more for the MG 2.4 cultivar when compared to the MG 1.4 cultivar. When planting was delayed by approximately 6 wk, the number of GDDs to maturity was 27% less for MG 2.4 compared to 22% less for MG 1.4 in 2014, 18% less for MG 2.4 compared to 12% less for MG 1.4 in 2015, and the same (28% less for both MGs) in 2016 when freezing was much later.

TABLE 3 Growing degree days (GDD) in vegetative stage, GDD in reproductive stage, and GDD to maturity for two soybean cultivars planted at four different planting dates at Volga, SD, in 2014–2016

Planting date	Days to R1		R1–R8		Days to maturity	
(day of the year)	1405 R2	2402 R2	1405 R2	2402 R2	1405R2	2402R2
	GDD					
2014						
16 May (136)	461a	497a	664a	706a	1,125a	1,203a
30 May (150)	422b	465c	660a	645b	1,082b	1,110b
13 June (164)	414c	480b	592b	534c	1,106c	1,014c
27 June (178)	409c	472b	468c	406d	877d	878d
2015						
4 May (124)	468a	525b	702a	773a	1,169a	1,297a
20 May (140)	458b	546a	635b	689b	1,093b	1,235b
2 June (153)	467a	516c	607c	655c	1,075c	1,171c
16 June (167)	426c	487d	593d	576d	1,018d	1,063d
2016						
16 May (137)	458b	543a	858a	830a	1,316a	1,373a
1 June (153)	419d	485c	801b	750b	1,221b	1,235b
15 June (167)	476a	501b	628c	619c	1,104c	1,121c
1 July (183)	427c	490c	520d	499d	947d	990d

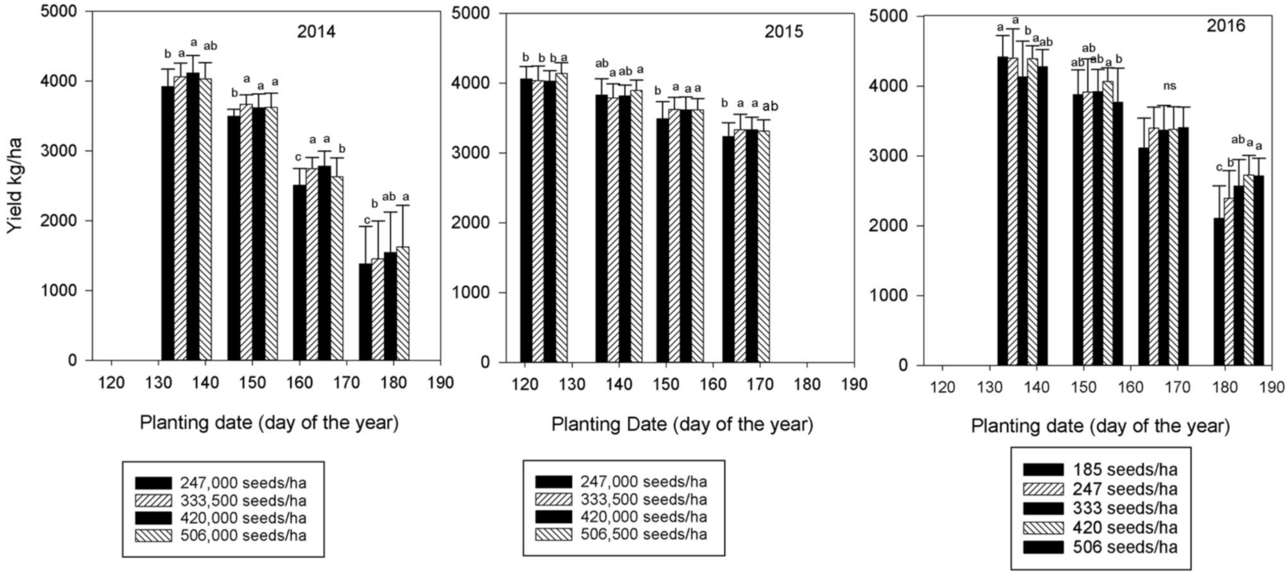

FIGURE 2 Seed yield of soybean grown at four planting dates and different seeding rates at Volga, SD, in 2014, 2015, and 2016

3.4 | Seed yield

An interaction between planting date and seeding rate was detected in all 3 yr, indicating that seed yield at each planting date was influenced by the seeding rates (Supplemental Tables S1 and S3). In 2014, the seeding rate of 247,000 seeds ha^{-1} had significantly lower seed yield across planting dates (Figure 2). The yield for the other three seeding rates varied depending on the planting date. As planting date was delayed from 16 May (day of year [DOY] 136) to 30 May (DOY 150) the seeding rates of 333,500; 420,000; and 506,000 seeds ha^{-1} had similar yield. A further delay in planting to 13 June (DOY 164), shifted the best yields to seeding rates of 333,500 and 420,000 seeds ha^{-1}. More delay to 27 June further shifted the best yield to the highest seeding rate of 506,500 seeds ha^{-1}. In 2015, the first planting date was 4 May, 12 d earlier than the first planting in 2014, and the differences among seeding rates within each planting date were much smaller. However, the highest seeding rate of 506,500 seeds ha^{-1} was among the top yielders in all planting dates (Figure 2). Again, the trends were for lower seed yield for the lowest seeding rate of 247,000 seeds ha^{-1} as planting was delayed to late dates of 2 June (DOY 153) and 16 June (DOY 167). The planting trends in 2016 were closer to 2014 planting dates than of 2015, when a lower seeding rate of 185,000 seeds ha^{-1} was added. The results showed significant differences among seeding rates with 16 May (DOY 137) and 1 June (DOY 153) planting dates but with no clear trends (Figure 2). But when planting was delayed to 15 June (DOY 167), the lowest seeding rate of 185,000 seeds ha^{-1} had lower but not significant yield when compared to the other three seeding rates. With further delayed planting to 1 July (DOY 183), seed yield increased with increase in seeding rate with the three highest seeding rates yielding significantly greater than the two lower seeding rates.

Seed yield was significantly affected by interactions between planting date × MG in all 3 yr (Figure 3). This was due to the fact that the linear decline in yield with delayed planting was steeper for the MG 2.4 cultivar compared to the MG 1.4 cultivar in all 3 yr (Figure 3) though the rate of decline in yield was not the similar among years. In 2014, the yield decline with planting delay was 71.5 kg ha^{-1} d^{-1} for MG 2.4 and lower at 50.5 kg ha^{-1} d^{-1} for MG 1.4. The most significant decline of 1547 kg ha^{-1} for MG 2.4 occurred between 13 June (DOY 164) and 27 June (DOY 176) planting dates. For the earlier maturing (MG 1.4) cultivar the difference in yield between the same two planting dates was only 786.8 kg ha^{-1}. In 2015, the planting dates were earlier than in 2014, 5 May (DOY 124) for the first planting date to 16 June (DOY 167) for the last planting date. Yield declined with delayed planting was at a lower rate than in 2014, 16.5 kg ha^{-1} d^{-1} for the MG 1.4 cultivar and 19 kg ha^{-} d^{-1} for the MG 2.4. The year 2015 was also different from 2014 in that the MG 2.4 cultivar yielded higher than the MG 1.4 for all four planting dates (Figure 3). In 2016, planting dates were more similar to the 2014 planting dates ranging from 16 May (DOY 137) to 1 July (DOY 183) but the seed yield decline with delayed planting was less steep than in 2014, 42.7 kg ha^{-1} d^{-1} for the MG 2.4 cultivar and 36.8 kg ha^{-1} d^{-1} for the MG 1.4 cultivar. Comparatively, the total yield reduction arising from a 42-d delay in planting was 2050 kg ha^{-1} for the MG 1.4 and 3000 kg for the MG 2.4 in 2014. In 2015, the yield reduction from a 43-d delay in planting was 810 kg ha^{-1} for MG 1.4 and slightly lower at 710 kg ha^{-1} for the MG 2.4 variety. In 2016, the delay of planting was 46 d and the yield

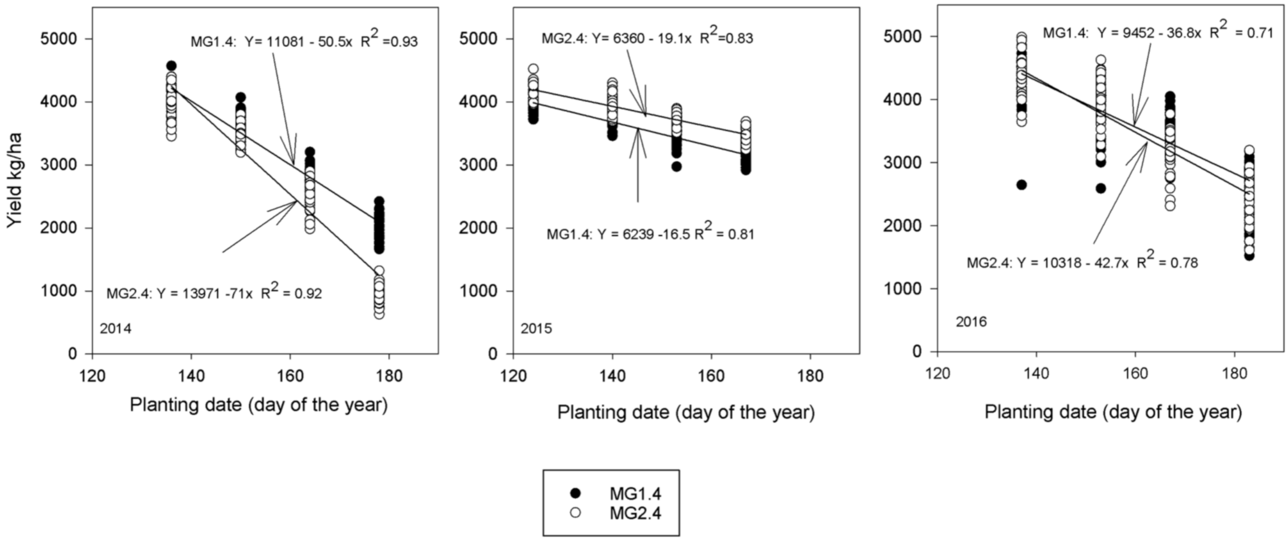

FIGURE 3 Seed yield of soybean of two maturity groups grown at four planting dates at Volga, SD, in 2014, 2015, and 2016

reduction was 1757 kg ha^{-1} for MG 1.4 and 1890 kg ha^{-1} for MG 2.4.

In 2014 and 2015, seed yield was affected by interactions between seeding rate and MG (Table 4). In 2014, seed yield for MG 1.4 increased with each increase in seeding rate, with the best yield observed at a seeding rate of 420,000 seeds ha^{-1}. For the MG 2.4, on the other hand, seed yield for the top three seeding rates was similar and significantly greater than seed yield for lowest seeding rate of 247,000 seeds ha^{-1} (Table 4). In 2015, the seed yield response to seeding rate for the MG 1.4 cultivar was very similar to what was observed in 2014 with the exception that the greatest yield was recorded at the highest seeding rate of 506,000 seeds ha^{-1}. No differences were observed in seed yield among seeding rates for MG 2.4.

Seed treatment main effects on seed yield were significant in 2014 and 2015 but not in 2016. The increase in seed yield as a result of using treated seed was 45 and 51 kg ha^{-1} in 2014 and 2015, respectively, when compared to untreated control (Table 5). A four-way interaction of planting date × seeding rate × seed treatment × MG was observed. A close analysis of the results showed that in 9 of 32 instances, treated seed resulted in lower seed yield when compared to the control. This was observed in both soybean cultivars with no clear trend on planting date or seeding rate effects.

3.5 | Seed quality

In 2014, seed protein content and seed oil concentration were significantly influenced by planting date, seeding rate, and planting date × MG (Tables 5 and 6, Supplemental Table S1). Seed protein content increased with increasing seeding rate while seed oil content decreased (Table 5). Both planting date and MG influenced seed protein and oil concentration in 2014 (Table 6). The MG 2.4 cultivar had consistently lower seed protein than the MG 1.4 cultivar at all planting dates. The planting date × MG interaction for seed oil concentration was due to a large drop in seed oil concentration for MG 2.4 compared to MG 1.4 between the third and fourth planting dates (16 g kg^{-1} for MG 2.4 vs. 5 g kg^{-1} for MG 1.4 when planting delayed from 13 to 27 June) (Table 6). In 2015, planting date significantly influenced both protein and oil content while seeding rate had a significant effect on protein only (Table 5, Supplemental Table S1). Seed protein concentration increased with increase in seeding rate peaking at the highest seeding rate while planting date effects on seed protein were not clear (Table 5). In 2016, seed protein and seed oil concentration were influenced by MG and the MG × planting date interaction (Table 6, Supplemental Table S3). The 1 June planting date had the greatest seed protein content for MG 1.4 and the lowest seed protein for MG 2.4 showing the inconsistence response of seed protein to planting date. For seed oil concentration, the interaction was due to change in magnitude rather than rank change, with the MG 2.4 cultivar having significantly lower seed oil concentration compared to MG 1.4 cultivar at all four plating dates.

4 | DISCUSSION

Increasing seeding rate decreased stand establishment following an exponential decay curve irrespective of planting date in 2014 and 2015. Although this has not been widely reported in recent literature, a quick analysis of the results of recent studies (Bruns, 2011; De Bruin & Pederson, 2008) support the present findings. Bruns (2011) tested two row types for a MG 4 cultivar at four seeding rates and three planting dates

TABLE 4 Seeding rate and cultivar maturity group effects on seed yield of soybean at Volga, SD, in 2014 and 2015

Seeding rate ha^{-1}(× 1,000)	2014		2015	
	Maturity 1.4	Maturity 2.4	Maturity 1.4	Maturity 2.4
	yield, kg ha^{-1}			
247	3,004c	2,653b	3,490c	3,850
333	3,160b	2,803a	3,543bc	3,835
420	3,242a	2,789a	3,580b	3,822
506	3,212ab	2,442a	3,650a	3,818

TABLE 5 Seeding rate, planting date, and seed treatment effects on seed protein and seed oil content for soybean planted at Volga, SD, in 2014, 2015, and 2016

Seeding rate ha^{-1} (×1,000)	Seed protein	Seed oil	Seed yield
	g kg^{-1}		kg ha^{-1}
2014			
247	338b	167a	2,828b
333	341b	164b	2,982a
420	345a	162c	3,016a
506	346a	163bc	2,977a
2015			
247	339b	185	3,654c
333	343ab	185	3,697b
420	341b	184	3,701b
506	344a	184	3,743a
Planting date (day of year)			
2015			
4 May (124)	342ab	186a	4,068a
20 May (140)	341ab	183b	3,834b
2 June (153)	345a	185ab	3,588c
16 June (167)	338b	184b	3,304d
Seed treatment			
2014			
Control	342	164	2,928b
Treated	343	164	2,973a
2015			
Control	341	185	3,673b
Treated	343	185	3,724a
2016			
Control	354	185	3,528
Treated	357	174	3,514

and showed a decrease in percent established plant stands as seeding rate increased from 20 seeds m^{-2} to 50 seeds m^{-2} under both row types supporting the present results. Similarly, the results of De Bruins and Pederson (2008)'s study conducted at six locations testing planting date and seeding rate reported no seeding rate × planting date interaction though percent harvest plant population decreased from 92 to 75% as seeding rate increased from 185,300 to 556,000 viable seeds ha^{-1}. The reason for the decrease in stand establishment with increased seeding rate irrespective of planting date is not clear but may be related to seed dropping in clumps at high seeding rates. Clumped seeds may compete for resources leading to self-thinning due to limited nutrients or water availability. Under very wet conditions, on the other hand, clumped seedlings may die due to spread of seedling diseases.

Delaying planting shortened vegetative and reproductive phases and consequently the days to maturity for both MG 1.4 and MG 2.4 cultivars. While the vegetative period was shortened by about the same duration for both MGs, the reproductive phase was shortened more for the MG 2.4 cultivar than the MG 1.4 cultivar in 2014 and 2015 (by 300 vs.196 GDDs in 2014 and 196 vs.109 GDDs for MG 2.4 and MG 1.4 respectively). The shorter duration of late-planted soybean is due to warmer temperatures during later planting dates hastening plant development but the sharp reduction in the duration of reproductive phase in 2014 was due to early frost. The higher temperatures later in the growing season mask the delay in flowering due to longer daylength at later planting dates (Setiyono et al., 2007). Thus, late-planted soybean plants have reduced light interception which partially accounts for yield decline with delayed planting (Gaspar & Conley, 2015). The decline in seed yield observed as planting was delayed in all 3 yr in this study shows the importance of early planting for maximizing yield potential. While planting early (early to Mid-May) lengthens the days from planting to maturity, it also advances the initiation of the reproductive phase on a calendar basis. For example, in 2015 R1 (flowering) was reached on 15 July for the 4 May planting date compared to 23 July for the 20 May planting date. Bastidas et al. (2008) suggested yield potential is enhanced when the R1–R7 interval is lengthened and that planting early is a means of reaching the R1 stage early and thus lengthening the reproductive phase.

Another way of lengthening the reproduction phase is to utilize longer duration cultivars. Our results suggest that the longer duration cultivar (MG 2.4) has the potential for equal or even higher seed yield compared to the shorter duration cultivar (MG 1.4) if planted early May to early June. However, yield declined at a higher rate with each day of delay in planting for MG 2.4 than for MG 1.4 in all 3 yr.

TABLE 6 Planting date and cultivar maturity group effects on seed protein and seed oil content of soybean at Volga, SD, in 2014 and 2016

Planting date	Maturity group		Maturity group	
(day of year)	1.4	2.4	1.4	2.4
	seed protein g kg^{-1}		seed oil g kg^{-1}	
2014				
16 May (136)	344b	340ab	182a	173a
30 May (150)	354a	345a	173b	175a
13 June (164)	362a	323c	162c	159b
27 June (178)	340b	332b	157d	141c
2016				
16 May (137)	357b	350b	185a	177a
1 June (153)	364a	346c	185a	175a
15 June (167)	359ab	356a	178b	169b
1 July (183)	359ab	354ab	170c	161c

This yield decline was even greater at planting dates later than mid-June although the responses to delayed planting were not the same among years. The decline in yield with delayed planting is due to changes in the plant as well as changes in the environmental conditions or a combination of both (Egli & Cornell, 2009). As shown in the current study and by others (Bastidas et al., 2008; Rowntree et al., 2014), soybean plants planted later in the year have a shorter reproductive period (R1–R8) and therefore lower yield, since a longer reproductive phase is associated with enhanced yield. These results further confirm this positive association between reproductive phase and yield in that the longer duration cultivar yielded greater than or the same as the shorter duration MG in years when the R1–R8 period for the MG 2.4 was much longer (2015 and 2016) and not shortened by early freezing as experienced in 2014. However, it must be noted that since only one cultivar of each MG was used in the study, these results may reflect the specific characteristics of the cultivars used rather than the MG. The second reason for decline in yield with delayed planting is related to the fact that later planted soybean finishes the critical reproductive phase under less favorable environmental conditions (Egli & Cornelius, 2009). Robinson et al. (2009) showed that early planting allows the reproductive period to initiate earlier, under longer days and higher light intensity, than when planting was later. Other researchers have suggested that temperatures lower than 20 °C reduce yield potential by reducing photosynthesis (Boote, Jones, & Hoogenboom, 1998). While this is not universally true in all soybean-producing regions, in the current study soybean planted after mid-June had seed-filling period in September when average temperatures were lower than 20 °C supporting the above theory.

One potential way to compensate for yield loss with delayed planting would be to use higher seeding rates. However, our findings and earlier findings (Corassa, Amadoa, & Strieder, 2018; Oplinger & Philbrook, 1992) suggest that later planting decreased grain yield regardless of management, such as seeding rates. Pedersen and Lauer (2004) and Bastidas et al. (2008) explained that even though delayed planting resulted in more rapid growth than earlier, presumably due to warmer temperature, plants were never able to compensate for the shorter growing season. In the present study however, seeding rate increased seed yield when planting date was mid-June or later, suggesting that increasing seeding rate can be a useful tool for growers. The current study also found that seed treatment increased seed yield but did not interact with planting date meaning growers would benefit from using treated seed irrespective of planting date. Vossenkemper et al. (2016) reported that seed treatment increased stand more in early planting, although stands were adequate irrespective of planting date. It is important to note that the current study only evaluated yield and did not evaluate how additional cost of seed in higher seed rates or cost of seed treatment would impact the economics of soybean production.

Seed quality response to planting date and seeding rate differed between MGs and among years. There was no clear trend on the effect of planting date on seed protein. Seed oil concentration on the other hand, decreased with delayed planting. Seed protein and seed oil concentration were inconsistent among MGs in 2014 and 2016. Research has shown that delaying the planting date can result in no change in the protein content (Bajaj et al., 2008), decreased protein (Muhammad et al., 2009), and increased protein (Mourtzinis et al., 2017; Robinson et al., 2009; Tremblay, Beausoleil, Filion, & Saulnier, 2006). Seed oil concentration on the other hand, generally decreases with delayed planting (Mourtzinis et al., 2017; Robinson et al., 2009). Other researchers have reported that oil and protein concentration change according to MG and cultivar (Bastidas et al., 2008; Yaklich, Vinyard, Camp, & Douglas, 2002). One consistent relationship, among studies, has been a negative correlation between protein and oil. This negative correlation can be attributed to various genetic and environmental factors (Watanabe & Nagasawa, 1990). One possible explanation for the inconsistent relationship between planting date and grain quality could be explained by environmental conditions during seed filling. Depending on the planting date and MG, the soybean cultivar is put in a different environment during seed filling and this changes the quality of seed components. For example, Rotundo and Westgate (2009) found that water stress during seed filling (R5–R7) reduced protein and oil accumulation in soybean.

5 | CONCLUSIONS

Based on these results, we can conclude that planting indeterminate soybean cultivars early in combination with latest MG adapted to the region is a reliable way to increase yield. Our study showed a yield decline for both soybean MGs when planting was delayed albeit at a slightly higher rate with each day of delay for MG 2.4 than for MG 1.4. This suggests that there is no clear advantage of planting one MG over the other when planting late due to weather or when replanting. However, since we only used one cultivar of each MG in this study these results may reflect the particular characteristics of cultivars used rather than the MG. The current study also showed that stand establishment decreases with increasing seeding rates irrespective of planting date. Still, utilizing higher seeding rates at planting dates later in June increased seed yield and is therefore a useful tool for increasing yield when planting late or replanting. Seed treatment increased seed yield independent of planting date meaning that growers would benefit from using treated seed whether planting early or late.

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CONFLICT OF INTEREST

The authors have no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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