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Row spacing and seeding rate effect on soybean seed yield in North Dakota

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Abstract

North Dakota soybean [*Glycine max* (L.) Merr.] seeding rate and row spacing varies across the state due to climate factors. Eight soybean seeding rates (starting at 80,000 and increasing by 20,000 live seeds ac^{-1} increments) and row spacing (12 and 24 inches) were evaluated in 15 environments in 2017–2018 to quantify established plant densities, seed yield, and plant loss occurring during the season. Planting at a 12-inch row spacing yielded 2.7 bu ac^{-1} greater than 24-inch row spacing and provided $33 ac^{-1} greater net profit on average. Following plant establishment, 6.6% in-season plant loss occurred on average. Using 180,000 to 200,000 live seed ac^{-1} had higher yields than seeding rates of 120,000 or less. Maximum net partial profit based on seeding rate was 80,800, 105,300, and 167,500 live seed ac^{-1} for seed costs of $57.80, $50.80, and $33, respectively, for 140,000 seeds. North Dakota's current recommendation of 150,000 established plants ac^{-1} is in the range to optimize yield but will likely not optimize profit based on seed costs and current market values. North Dakota farmers are recommended to use 12-inch row spacing instead of 24 inches.

1 | INTRODUCTION

Producing soybean [*Glycine max* (L.) Merr.] in North Dakota is challenging due to adverse climate conditions. Soybean production can be separated into narrow- and wide-row spacing classes. Cooper (1977) in Illinois defined narrow spacing of soybean as rows <20 inches apart and wide row spacing as rows ≥20 inches apart. Planting soybean in narrow rows leads to quicker canopy closure, thus increasing seasonal light interception (Andrade, Calviño, Cirilo, & Barbieri, 2002; Bullock, Khan, & Rayburn, 1998), equidistant plant spacing (Shibles & Weber, 1966), and increased yields with adequate rainfall and appropriate air temperatures (Bullock et al., 1998; Cooper, 1977; Cox & Cherney, 2011; De Bruin & Pedersen, 2008; Devlin et al., 1995; Ethredge, Ashley, & Woodruff, 1989). However, the use of narrow soybean row spacing can reduce yields under soil water deficit conditions (Alessi & Power, 1982).

Soybean in wide rows has improved water use efficiency, is more tolerant to drought conditions, and has higher yield under water deficit conditions (Alessi & Power, 1982; Devlin et al., 1995). Agricultural environments experiencing drought and water deficiency are likely to have soybean planted in wide rows. Planting wide-row soybean has been observed to reduce biotic stress such as soybean cyst nematode and sudden death syndrome (Pedersen & Lauer, 2003; Swoboda, Pedersen, Esker, & Munkvold, 2011). However, in the absence of disease pressure, wide row spacing does not provide a significant yield improvement over narrow spacing when planted north of Iowa (Lee, 2006).

The relationship between seeding rates, yield, and iron deficiency chlorosis (IDC) have been explored in several soybean studies (Cox & Cherney, 2011; De Bruin & Pedersen, 2008; Devlin et al., 1995; Ethredge et al., 1989; Goos &

Abbreviation: IDC, iron deficiency chlorosis.

TABLE A Useful conversions

To convert Column 1 to Column 2, multiply by	Column 1 Suggested Unit	Column 2 SI Unit
2.54	inch	centimeter, cm
0.304	foot, ft	meter, m
0.405	acre	hectare, ha
67.19	60 lb bushel per acre, bu ac^{-1}	kilogram per hectare, kg ha^{-1}

Core Ideas

- Narrow 12-inch row spacing produced 6% more yield than 24-inch row spacing.
- Narrow row spacing resulted in higher net revenue.
- Seed yield was maximized at 200,000 live seed ac^{-1}.
- The optimal seeding rate is highly dependent on seed cost.

Johnson, 2001). Soybean seeding rate describes the number of seeds planted in a given area. Soybean plants display variable amounts of branching depending on the amount of space for growth, which may result in no yield response from increased seeding rates (Carpenter & Board, 1997). Increasing seeding rates to 210,000 seeds ac^{-1} has been found to increase soybean chlorophyll levels, reduce plant chlorosis, and increase seed yield in soils producing iron deficiency symptoms (Goos & Johnson, 2001). In general, varying soybean seeding rates has produced similar yield levels with rates as low as 76,000 seeds ac^{-1} in Kentucky (Lee, Egli, & TeKrony, 2008) and as high as 300,000 seeds ac^{-1} in Wisconsin (Oplinger & Philbrook, 1992). The objectives of this research were to determine the effect of row spacing and seeding rate on soybean seed yield, net revenue, and agronomic characteristics in diverse environments across North Dakota.

2 | MATERIALS AND METHODS

Studies were conducted in eight environments in 2017 and seven in 2018. The Fargo location was partitioned into four environments due to tile-drained and undrained soils and two soybean relative maturities differing by 0.3 units. Each experiment per location-year is being called an environment (Figure 1; Table 1). A randomized complete block design with a factorial arrangement was used. Factors were row spacing (12 and 24 inches) and seeding rates (80,000, 100,000, 120,000, 140,000, 160,000, 180,000, and 200,000 live seed ac^{-1}). Soybean seed was of a cultivar with adapted maturity for each environment (0.3–0.8); all cultivars were obtained from one company with a 98% seed germination average.

Plots were planted in early to mid-May using a four-row plot planter with 12-inch row spacing or using two rows with 24-inch row spacing. The plots were planted with a Hege 1000 no-till planter (Hege Company). Seeds were sown to a depth between 1 and 1.5 inches. Plot size was 5 ft wide by 20 ft long. Seeds planted were treated with a fungicide and insecticide treatment of 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 [1*H*-pyrazole-4-carboxamide, 3-(difluoromethyl)-1-methyl-*N*-(3′,4′,5′-trifluoro[1,1′-biphenyl]-2-yl)], and imidacloprid [*N*-[1-[(6-chloropyridin-3-yl)methyl]-4,5-dihydroimidazol-2-yl]nitramide] (Acceleron Seed Applied Solutions, Monsanto Company). Seeds were inoculated with *Bradyrhizobium japonicum* in the form of Vault SP (BASF) at a rate of 1.4 oz per 50 lb of seed.

Glyphosate was applied twice during the season for weed control. Insecticide [a.i. 9.15% *S*-cyano (3-phenoxyphenyl)methyl (+/-)-cis/trans-3-(2,2-dichloethenyl) -2,2-dimethylcyclopropanecarboxylate] (FMC Corporation) was applied at a rate of 24 fluid oz ac^{-1} to environments surpassing the economic threshold level of soybean aphid (*Aphis glycines* Matsumura) (Ragsdale et al., 2007) and to control grasshopper (Orthoptera: Acrididae).

Emerged plants were counted from a 3.3-ft length along the planted soybean row. To maintain consistent plant density observations within the experimental unit, two stakes were placed apart within the soybean rows. Soybean emergence counts were performed on the two innermost rows of each treatment (four-row plots) or in each row of the two-row plots (24-inch row spacing).

Vigor scores, as a visual assessment for yield, were recorded at the V2–V3 and the V5–V6 stages (Fehr, Caviness, Burmood, & Pennington, 1971). Vigor scores were based on a scale ranging from 1 to 9, with 1 being the least vigorous and 9 being the highest obtainable score based on visual assessment of plant height, biomass, and color. Scores were based on relative vigor within replicates.

Ratings for IDC were made visually on a 1–5 scale, with 1 representing no chlorosis and 5 being complete necrosis (Goos & Johnson, 2000; Rodriguez de Cianzio, Fehr, & Anderson, 1979). Ratings were taken from the V2–V3 stages. Canopeo measures the fractional green canopy cover through an image processed through the Canopeo application, providing a green canopy coverage percentage (Patrignani & Ochsner, 2015). Canopeo pictures were taken approximately 5 ft from the soil surface. Images were captured in the middle of the plot. Matlab (MathWorks, Inc.) was used to measure the canopy cover by fractional green canopy cover. The Canopeo canopy coverage data were recorded at the V5–V6 stage. Plant

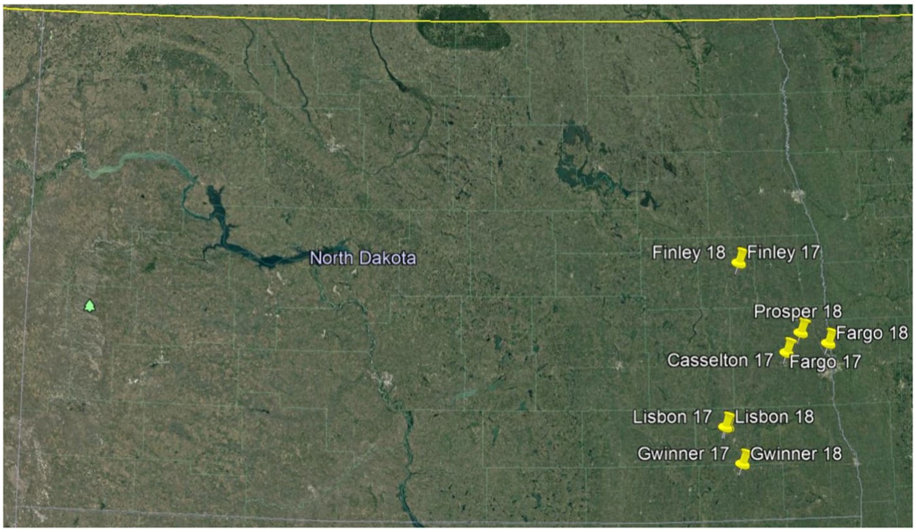

FIGURE 1 Research environments for 2017 and 2018 in North Dakota

heights were obtained from an average of three samples within each plot at physiological maturity. Three separate measurements from the soil surface to the uppermost node on the plant were recorded within each experimental unit. Measurements were then averaged.

Soybean plots were harvested following physiological maturity (Fehr et al., 1971) once seed moisture levels were acceptable, using a Wintersteiger Classic plot combine (Wintersteiger Ag). Dates of important management procedures and measurements are presented in Table 2.

Before weighing, soybean seed was cleaned using a Clipper seed cleaner (Ferrell-Ross). A Perten Instruments DA 7250 NIR analyzer was used to measure the oil and protein content (Perten Instruments, Inc.). Moisture was determined using a GAC 2100 moisture tester (DICKEY-John Corp.), and yield, protein, and oil content were adjusted to 13% moisture content. Weather data for each environment were collected from the nearest North Dakota Agricultural Weather Network station. Each environment's soil test reported no nutrients to be yield limiting according to the standards of Kandel and Endres (2019).

Statistical analysis was conducted using PROC GLM, and *F* tests from Type 3 ANOVA were used to analyze treatment data with the SAS statistical software (SAS Institute). Row spacing and seeding rates were analyzed as fixed factors. All other factors such as replicate and environment were random variables. Homogeneity of variance for each environment was confirmed by comparing the error mean squares

TABLE 1 Soil series, soil taxonomy, and previous crop for experiments in Fargo, Casselton, Prosper, Lisbon, Gwinner, and Finley, ND, in 2017 and 2018

Location	Year	Soil series	Soil Taxonomy	Previous crop[a]
Fargo[b]	2017 & 2018	Fargo–Ryan	fine, smectitic, frigid Typic Epiaquert	wheat
			fine, smectitic, frigid Typic Natraquert	
Casselton	2017	Kindred–Bearden	fine-silty, mixed, superactive, frigid Typic Endoaquoll	soybean
			fine-silty, mixed, superactive, frigid Aeric Calciaquolls	
Prosper	2018	Bearden–Lindaas	fine-silty, mixed, superactive, frigid Aeric Calciaquoll	wheat
			fine, smectitic, frigid Typic Argiaquoll	
Lisbon	2017	Barnes–Svea	fine-loamy, mixed, superactive, frigid Calcic Hapludoll	corn
			fine-loamy, mixed, superactive, frigid Pachic Hapludoll	
Gwinner	2017 & 2018	Hamerly–Tonka	fine-loamy, mixed, superactive, frigid Aeric Calciaquoll	corn
			fine, smectitic, frigid Argiaquic Argialboll	
Finley	2017 & 2018	Fram–Wyard	coarse-loamy, mixed, superactive, frigid Aeric Calciaquoll	dry bean
			fine-loamy, mixed, superactive, frigid Typic Endoaquolls	

Note: Soil data from (USDA–NRCS, 2019).

[a]Wheat, *Triticum aestivum* (L.) emend. Thell; corn, *Zea mays* (L.); dry bean, *Phaseolus vulgaris* (L.).

[b]The Fargo location had four experiments in each year.

TABLE 2 Dates of important measurements and field operations at Fargo, Casselton, Prosper, Lisbon, Gwinner, and Finely, ND, in 2017 and 2018

Operation	Fargo[a]	Casselton	Prosper	Lisbon	Gwinner	Finley
2017						
Plant	8 May	10 May	–	12 May	12 May	15 May
Established stand count	16 June	16 June	–	14 June	17 June	14 June
Vigor 1	26 June	30 June	–	29 June	29 June	29 June
Vigor 2	13 July	13 July	–	11 July	11 July	11 July
IDC[b]	26 June	–	–	–	–	–
Canopeo	13 July	7 July	–	11 July	11 July	11 July
Height measurement	19 Sept.	27 Sept.	–	22 Sept.	22 Sept.	24 Sept.
Fall stand count	19 Sept.	27 Sept.	–	22 Sept.	22 Sept.	24 Sept.
Harvest	9 Oct.	4 Oct.	–	5 Oct.	30 Sept.	4 Oct.
2018						
Plant	14 May	–	11 May	–	11 May	15 May
Established stand count	6 June	–	7 June	–	6 June	6 June
Vigor 1	28 June	–	18 June	–	28 June	2 June
Vigor 2	17 July	–	17 July	–	28 June	17 July
IDC	14 July	–	–	–	–	–
Canopeo	14 July	–	28 June	–	17 July	2 July
Height measurement	7 Sept.	–	21 Sept.	–	13 Sept.	26 Sept.
Fall stand count	7 Sept.	–	13 Sept.	–	13 Sept.	14 Sept.
Harvest	18 Sept.	–	24 Sept.	–	1 Oct.	28 Sept.

[a]The Fargo location had four experiments in each year.
[b]IDC, iron deficiency chlorosis.

for each measured agronomical trait observation. Combinable data were analyzed across all environments possible, using procedures described by Carmer, Nyquist, and Walker (1989) to identify the correct F-test denominator. Treatment means were separated using Tukey's multiple comparison test with $P = .05$. Means separation for environments and combined data used their respective Tukey's honestly significant difference (HSD) test values.

Soybean market prices represent a range of historic and potential grain prices. The market prices solely reflect market value based on the Chicago Board of Trade on 1 Jan. 2020 at \$9 bu^{-1} and a potential price of \$8 and \$10 bu^{-1}. Seed costs were obtained from Sebesta (2020), Plastina (2019), and Haugen and Swenson (2020), who estimated herbicide-tolerant seed prices to be \$33, \$50.80, and \$57.80 per soybean unit (140,000 seeds), respectively. Price per seed was calculated and multiplied by the live seeding rate. Net revenue was calculated by subtracting the live seed cost from gross revenue (yield multiplied by estimated market price). Net revenue in dollars for each experimental unit was analyzed using PROC GLM with SAS. Regression analysis for seeding rate effect on net profit was performed using PROC REG with SAS. Maximum values from regression equations were calculated using the quadratic equation. Means were separated using Tukey's HSD with $P = .05$. All error mean squares were analyzed across 15 environments from 2017 and 2018 using procedures described by Carmer et al. (1989).

3 | RESULTS AND DISCUSSION

3.1 | Weather

Weather data for 2017 and 2018 were similar at each environment throughout the growing season (Table 3). The rainfall during May, the planting month, was below normal in both years. The 2017 growing season provided, on average, 0.04 inches of rainfall prior to and during planting, and low temperatures delayed soybean emergence and the time to an established plant density compared with 2018. The 2018 growing season had adequate growing conditions around planting time considering the below-normal precipitation for the environments. Above-normal temperatures in 2018 were more favorable for rapid emergence and stand establishment, setting up the plants for a successful growing season.

3.2 | Row spacing

Combined across all seeding rates for 15 environments in 2017 and 2018 (Table 4), there were significant differences

TABLE 3 Mean monthly air temperatures and rainfall during the growing season in 2017 and 2018 for each environment

Month	Mean monthly max. air temperature			Mean monthly min. air temperature			Precipitation		
	2017	2018	Normal	2017	2018	Normal	2017	2018	Normal
	°F						inches		
Fargo[a]									
May	70	77	70	45	50	45	1	2	3
June	79	81	77	55	61	55	2	5	4
July	84	82	82	61	61	59	1	3	3
Aug.	77	81	81	55	59	57	2	4	3
Sept.	72	70	72	52	48	48	3	3	3
Total							9	16	15
Casselton and Prosper									
May	70	77	70	43	48	43	1	2	3
June	79	81	77	54	57	54	3	3	4
July	82	81	82	57	57	57	2	3	3
Aug.	77	81	82	52	54	55	2	3	3
Sept.	72	70	72	46	45	46	6	3	3
Total							14	14	16
Gwinner									
May	68	77	70	45	50	45	1	1	3
June	81	81	79	55	59	55	2	4	3
July	84	81	84	59	59	59	1	4	3
Aug.	77	81	82	55	55	57	4	1	2
Sept.	72	70	72	48	46	46	2	2	3
Total							10	11	14
Finley									
May	68	77	68	43	46	43	1	1	3
June	79	82	77	54	57	54	4	3	4
July	82	82	81	57	55	57	3	2	3
Aug.	77	81	81	52	52	55	0	3	3
Sept.	72	64	70	48	45	45	4	1	2
Total							11	11	14
Lisbon									
May	70	77	70	43	50	43	1	1	3
June	81	81	77	54	59	54	2	4	4
July	84	81	84	59	59	57	1	4	3
Aug.	77	81	82	54	55	55	4	1	2
Sept.	72	70	72	48	46	45	3	2	3
Total							11	11	15

Note: Normal represents a 30-yr average from 1981–2010. Data obtained from North Dakota Agricultural Weather Network.
[a]The Fargo location had four experiments in each year.

between the row spacing main effect for established stand, seed yield, and in-season plant loss. Soybean yield was 2.7 bu ac^{-1} greater with narrow row spacing than wide row spacing (Table 5). Similar research found that yield increased with narrow row spacing and maximized light interception (Board, Harville, & Saxton, 1990; Oplinger & Philbrook, 1992; Wells, 1991). Plants in the 24-inch row spacing provided 4000 more plants at plant establishment compared with the 12-inch row spacing. In-season plant loss was significantly different for row spacing. The 24-inch row spacing experienced 7.6% loss between the established plant density and the end of the season measured density, which was 2.0% more than the 12-inch row spacing (data not shown). Narrow row spacing had less plant loss at all seeding rates than the 24-inch row spacing.

TABLE 4 Sources of variation, degrees of freedom, and levels of significance for the ANOVA of agronomic traits for 15 environments in 2017 and 2018

Source of variation	df	df[a]	ES	FS	EV	LV	CC	HT	Yield	PC	OC	Loss	IDC
Env [environment]	14	7											
Spacing [row spacing]	1	1	*	ns	ns	ns	ns	ns	***	ns	ns	**	ns
Rate [seeding rate]	6	6	***	***	ns	ns	ns	ns	***	***	***	ns	ns
Spacing*rate	6	6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Residual error	588	315											

Note: ES, established stand; FS, final stand; EV, early vigor; LV, late vigor; CC, canopy coverage; HT, plant height; PC, protein content; OC, oil content; IDC, iron deficiency chlorosis, averaged across eight environments at Fargo due to no visual differences at other environments.

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

*$P \leq .05$. **$P \leq .01$. ***$P \leq .001$. †ns = not significant at $P = .05$.

TABLE 5 Mean agronomic trait observations for two row spacings averaged across seven seeding rates and 15 environments

Row spacing	ES	FS	EV	LV	CC	HT	Yield	PC	OC	IDC	Loss
inches	plants ac^{-1} x 1000		——1–9[a]——		%	inches	bu ac^{-1}	———%———		1–5[b]	%
12	134.4b	126.4a	5.2a	5.2a	68a	30a	46.8a	33.1a	18.1a	2.3a	5.6b
24	138.2a	126.6a	5.5a	5.7a	62a	31a	44.1b	33.1a	18.1a	2.3a	7.6a

Note: ES = established stand; FS = final stand; EV = early vigor; LV = late vigor; CC = canopy coverage; HT = plant height; PC = protein content; OC = oil content; IDC = iron deficiency chlorosis, which is averaged across eight environments at Fargo due to no visual differences at other environments. Within columns, means followed by the same letter are not significantly different at $P \leq .05$.

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

[b]Visual scale from Goos and Johnson (2000), with 5 being the most chlorotic.

TABLE 6 Agronomic observations averaged across seeding rate across all 15 environments

Seeding rate	ES[c]	FS	EV	LV	CC	HT	Yield	PC	OC	IDC	Loss
live seed ac^{-1}	plants ac^{-1}x 1000		——1–9[a]——		%	inches	bu ac^{-1}	———%———		1–5[b]	%
80,000	77.2e	72.1e	3.5	3.4	56	76	43.2c	33.01bc	18.16a	2.4	5.8
100,000	94.0de	88.1de	4.2	4.3	60	77	44.1bc	32.99c	18.16ab	2.5	5.5
120,000	114.0cd	107.7cd	4.8	5.0	63	76	44.9bc	33.01bc	18.10a	2.4	5.5
140,000	132.8c	122.6c	5.2	5.7	66	77	45.8ab	33.15abc	18.14a	2.3	7.3
160,000	161.9b	150.8b	6.0	6.2	68	77	45.9ab	33.09bc	18.16a	2.2	6.8
180,000	178.1ab	165.0ab	6.4	6.5	69	78	47.0a	33.24ab	18.06ab	2.3	7.3
200,000	197.0a	181.2a	7.1	7.0	72	79	47.2a	33.36a	18.00b	2.1	7.8
Tukey's HSD (0.05)	21.3	20.0	ns[c]	ns	ns	ns	2.1	0.23	0.12	ns	ns

Note: ES = established stand; FS = final stand; EV = early vigor; LV = late vigor; CC = canopy coverage; HT = plant height; PC = protein content; OC = oil content; IDC = iron deficiency chlorosis, which is averaged across eight environments at Fargo due to no visual differences at other environments. Within columns, means followed by the same letter are not significantly different at $P \leq .05$.

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

[b]Visual scale from Goos and Johnson (2000), with 5 being the most chlorotic.

[c]ns = not significant at $P = .05$.

TABLE 7 Estimated soybean net revenue per acre based on row spacing and seeding rate yields averaged across 15 environments for estimated seed prices of $33.00, $50.80, and $57.80 for 140,000 seeds (Sebesta, 2020; Plastina, 2019; Haugen & Swenson, 2020)

	Seed price [$ (140,000 seeds) −1]								
	$33.00			$50.80			$57.80		
Row spacing	Market price ($ bu^{-1})								
inches	8	9	10	8	9	10	8	9	10
	Net revenue per acre in $ bu^{-1}								
12	345a	392a	440a	327a	374a	421a	319a	367a	414a
24	316b	359b	403b	297b	341b	385b	290b	334b	378b

Note: Means in a column followed by a different letter are significantly different at $P \leq .05$.

3.3 | Seeding rate

Seeding rate significantly influenced established and fall plant densities, seed yield, and protein and oil content (Table 4). Increasing seeding rates, as expected, resulted in increased plant density at both the beginning and end of the growing season. On average there was a 6.6% loss between the established plant density and end of the season density. The seed yield at the 180,000 and 200,000 live seed ac^{-1} seeding rate were significantly greater than yields at 120,000 live seed ac^{-1} and lower. Seed yield at seeding rates between 140,000 and 200,000 live seed ac^{-1} were not significantly different (Table 6). Protein content was the greatest for the 200,000 and 180,000 live seed ac^{-1} seeding rates, while few differences between seeding rate and oil content were observed. Currently, producers are not directly compensated for protein or oil content in their soybean seed.

3.3.1 | Economic analysis

With only seed costs in consideration, a partial economic analysis determined the soybean net revenue for the main effects of row spacing and seeding rate. Three estimated market prices provided the net revenue per acre for each treatment analyzed. Soybean producers should consider additional costs customized to their management.

The net revenue for 12-inch row spacing was, for the three market prices and seed costs, more profitable than that for the 24-inch row spacing, assuming the costs to plant both row spacings are the same. Net profit per acre increased as estimated market prices increased, and reducing seed costs provided greater net profit (Table 7). Across all market prices and seed prices, 12-inch row spacing profited $33 ac^{-1} more than the 24-inch row spacing.

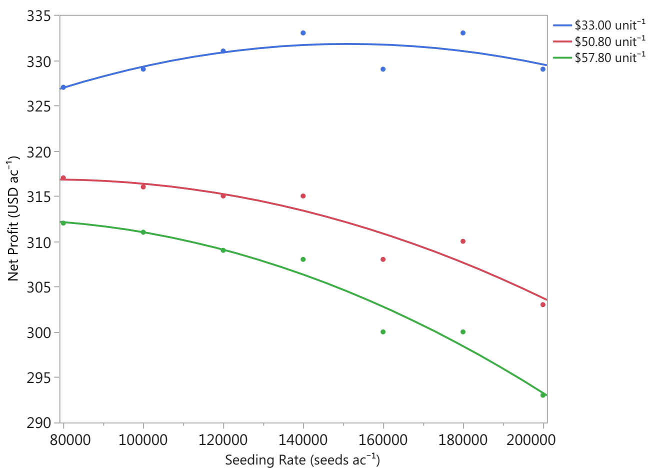

FIGURE 2 Seeding rate effect on net profit based on three different seed costs and assuming a market price of $8 bu^{-1}

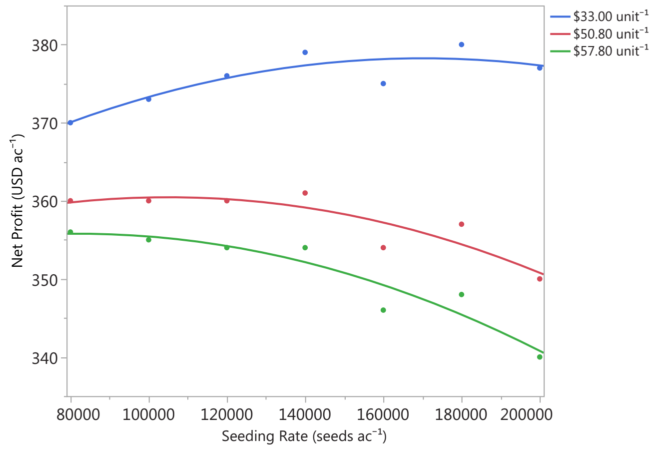

FIGURE 3 Seeding rate effect on net profit based on three different seed costs and assuming a market price of $9 bu^{-1}

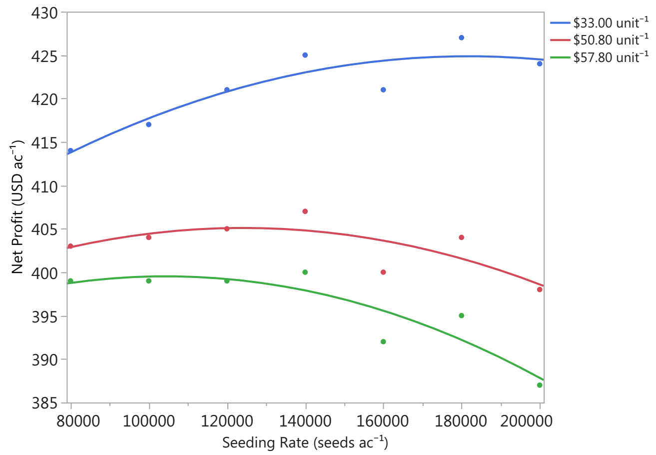

FIGURE 4 Seeding rate effect on net profit based on three different seed costs and assuming a market price of $10 bu^{-1}

Quadratic regression between seeding rate and net profit was performed. The quadratic regression analysis (Figures 2, 3, and 4) show net profit decreasing after the function maximizes. Based on the quadratic regression equations (Table 8), net profit maximizes at lower seeding rates as the seed cost increases. Economic returns based on soybean seeding rates suggest opportunities to increase producer profit with seeding rate adjustments. As market prices increase, the benefit of lower seeding rates will diminish, as shown by the $86 maximum profit difference between $8 and $9 bu^{-1} market prices for a seed cost of $57.80 unit^{-1}. With seed costs of $50.80 and $57.80, seeding rates between 80,000 and 123,000 live seed ac^{-1} will provide the maximum net profit, suggesting less dense seeding rates than NDSU's recommended rate of 150,000 live seed ac^{-1}. However, North Dakota has IDC-prone soils, and research has shown that reducing the seeding rate will increase IDC expression and lower yields when IDC is present (Goos & Johnson, 2001). Our calculations

TABLE 8 Summary of quadratic regression models from field survey data

Seed cost	Market price	Quadratic equation[a]	*P*	r^2	CV	Max. seeding rate	Max. profit
	\$ bu^{-1}					live seed ac^{-1}	\$
33.00	8	$\hat{Y} = (-9.31 \times 10^{-10})x^2 + (2.85 \times 10^{-4})x - 310$	.187	.56	0.61	153,118	332
	9	$\hat{Y} = (-1.05 \times 10^{-9})x^2 + (3.52 \times 10^{-4})x - 349$	.064	.74	0.60	167,496	378
	10	$\hat{Y} = (-1.16 \times 10^{-9})x^2 + (4.17 \times 10^{-4})x - 388$	.027	.83	0.59	179,074	425
50.80	8	$\hat{Y} = (-9.33 \times 10^{-10})x^2 + (1.55 \times 10^{-4})x - 310$	.008	.91	0.59	123,095	316
	9	$\hat{Y} = (-1.05 \times 10^{-9})x^2 + (2.20 \times 10^{-4})x - 349$	.037	.71	0.58	105,300	360
	10	$\hat{Y} = (-1.17 \times 10^{-9})x^2 + (2.87 \times 10^{-4})x - 408$	.144	.30	0.58	83,209	426
57.80	8	$\hat{Y} = (-9.31 \times 10^{-10})x^2 + (1.03 \times 10^{-4})x - 310$	.002	.95	0.56	80,000	313
	9	$\hat{Y} = (-1.05 \times 10^{-9})x^2 + (1.69 \times 10^{-4})x - 349$	.007	.91	0.55	80,880	356
	10	$\hat{Y} = (-1.16 \times 10^{-9})x^2 + (2.35 \times 10^{-4})x - 388$	.027	.83	0.55	101,029	399

[a]Equations from PROC REG, where $\hat{Y}$ = yield (bu ac^{-1}) and x = seeding rate.

compare prices from North Dakota's Foundation Seedstock Program (glyphosate-tolerant soybean), an Iowa State University crop budget estimate, and a North Dakota State University farm management guide. Seed with commercial specialty traits were found to have higher costs per unit. There are possibilities to obtain less expensive seed, for instance conventional public or glyphosate-tolerant cultivars, which would also change the calculated profit. On a farm scale, higher production with higher seeding rates will likely reduce the harvest cost per bushel, and the lower harvest cost may offset some of the additional seed cost with higher seeding rates. In this study, we analyzed the yield based on seeding rate. However, not all live seed planted will develop into an established plant. If producers can increase their planting accuracy and have a better establishment rate, the amount of live seed needed could also be reduced.

Seeding rate reduction provides added risk because possible stand-reducing events throughout a season may jeopardize yields and profit. The optimal seeding rate and established plant densities vary among regions. Research in Kentucky suggests that optimal profits are observed with seeding rates of 171,000 to 264,000 seed ac^{-1} (Lee et al., 2008). Currently, 150,000 established plants ac^{-1} is recommended in North Dakota. This recommendation is in the range to optimize yield and net revenue in this study (Table 6; Figure 2). South of North Dakota, seeding rates and plant densities are trending toward fewer seeds and plants. Plant densities ranging from 80,000 to 100,000 plants ac^{-1} are recommended in Indiana (Conley & Robinson, 2007). However, increased profit from seeding rate reductions are promoted with caution, as unexpected environmental conditions may result in less profit than greater seeding rates would.

4 | CONCLUSION

Soybean is a relatively new crop for North Dakotan farmers, emphasizing the importance of how seeding rate and row spacing influences soybean yield, plant stand, protein and oil content, and plant loss. Seeding rate × row spacing interactions were not observed. Soybean producers are likely to improve yields by using 12-inch row spacing rather than 24-inch. In-season plant loss is expected, and there was 2% more plant loss occurring at 24-inch row spacing than at 12 inches. Net revenue was higher at 12-inch row spacing than at 24 inches. Seed yields from 140,000 to 200,000 live seed ac^{-1} were not significantly different. Economic returns were found to increase with lower seed costs. The economic optimal seeding rate at \$9 bu^{-1} was between 80,800, 105,300, and 167,500 live seed ac^{-1} for seed costs of \$57.80, \$50.80, and \$33.00 per 140,000 seeds, respectively, which is lower than the NDSU recommended rate of 150,000 live seed ac^{-1} except when the seed cost is \$33 unit^{-1}. North Dakota soybean producers should consider current crop management practices and other input costs before making row spacing or seeding rate adjustments.

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