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Feasibility of a wider row spacing and recommended nitrogen in no-till wheat

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Abstract

The optimal row spacing aims to maximize profitability by balancing the reduction in production costs from a wider row spacing against a potential decline in yield and increased weed pressure. A wider row spacing should increase area seeded per day, improve residue flow around seeder openers and the success of seeding between stubble rows. This study investigated the feasibility of a wider row spacing by studying the effects of row spacing (25, 30, 35, 40 cm) and N fertilizer rates (20, 40, 80, 120, 160 kg N ha^{-1}) on development, yield, and quality of spring wheat (*Triticum aestivum* L.). The study was a two factorial in randomized complete block design. The experiment was conducted at Indian Head, SK, from 2013 to 2016. Row spacing affected plant, head, and seed density; however, the effects were generally inconsistent. One exception was biomass, which decreased as the row spacing increased in 3 of the 4 yr. Grain yield declined in 1 of the 4 yr, with the largest portion of the decrease occurring as the row spacing increased from 30 to 40 cm. As expected, increasing N rates produced greater grain yield, biomass, and grain protein. In conclusion, this study found that in most years the row spacing can be widened past 30 cm without a negative impact on grain yield in a no-till cropping system. However, to determine the probability of a grain yield decrease as row spacing is increased, a larger study over a wider geographic region is needed.

1 | INTRODUCTION

There is a limited amount of arable land available for food production worldwide, which has led to a strong push towards producing an ever-increasing quantity of food, feed, and fiber products per hectare of farmland. Intensifying agricultural production can also exacerbate global soil degradation. In an attempt to prevent damage to soil fertility due to erosion and nutrient deficiency, the Food and Agriculture Organization of the United Nations encourages use of conservation cropping systems, in particular no-till systems. In Canada in 2016, 19.5 million ha of farmland were seeded with no-till seeders (Statistics Canada, 2017). By adopting a system that leaves the previous years' crop residue intact, the soil surface is protected from wind and water erosion (FAO, 2007; Lafond, Boyetchko, Brandt, Clayton, & Entz, 1996). In semi-arid environments, no-till is credited for improving crop water-use efficiency (Lafond et al., 1996). Benefits of no-till beyond erosion control and conservation of soil moisture include preservation of soil structure and reduced labor costs and fossil fuel use (FAO, 2007), as well as higher yields and grain protein levels (Lafond, Walley, May, & Holzapfel, 2011). However, no-till systems must contend with prior crop residue while creating a suitable placement of the seed and fertilizer in the soil to facilitate crop establishment. Several aspects of crop management must be adjusted to maintain favorable levels of production, including the spacing between rows and fertilizer practices.

The optimal row spacing for a given crop generally aims to maximize profitability by obtaining the greatest yield and quality and/or reducing the cost of growing the crop. Factors that can interact to determine optimal spacing include crop, crop type, soil type, climate, and topography. In the past with a conventional tillage system, cereal producers favoured wider rows for ease of mechanical weed control, while narrower rows were preferred for their compatibility with some fertilizer practices and generally greater grain yield (Holliday, 1963). In a no-till cropping system, retained crop stubble has a tendency to complicate traditional seeding systems, as residue must be able to flow around the seed openers during seeding. In an attempt to rectify this issue, a wide row spacing is often employed to reduce plugging of seed openers. A wider row spacing also allows producers to utilize a wider air seeder without increasing the tractor size thereby increasing the potential land area that can be seeded in a day. In addition a wider row spacing can facilitate the seeding of the crop in between the stubble rows of the previous crop improving seed bed conditions for germination and emergence; however, a decrease in grain yield and weed control is a common concern with wider rows. A study in New South Wales, found that the grain yield of wheat decreased in 3 out of 4 yr as the row spacing increased from 18 to 36 cm in a humid subtropical climate (Doyle, 1980). In a semi-arid environment, Lafond (1994) demonstrated that durum (*Triticum durum* L.), barley (*Hordem vulgare* L.), and wheat grain yields can be sustained with wider rows (30 cm) in a no-till system over a variety of growing conditions. The contrast between these two studies may indicate that yield potential will interact with row spacing. Research in barley found that row spacing had little effect on either yield or weed control when row spacing was varied between 20 and 30 cm (Blackshaw, Semach, Li, O'Donovan, & Harker, 1999; O'Donovan et al., 2001b). In both of these studies increasing plant density increased weed control of annual weeds. With a perennial weed, Canada thistle [*Cirsium arvense* (L.) Scop.] row spacing in the absence of herbicide decreased weed control as the row width increased while seeding rate had little effect (O'Donovan, Blackshaw, Harker, McAndrew, & Clayton, 2001a).

Wheat has the ability to compensate to a widening row spacing by increasing kernels per head, when head density decreased as row spacing increased (Lafond, 1994). However, there are limitations to acceptable row spacings. When growing spring wheat in a semi-arid prairie climate, rows with 25- and 38-cm spacings resulted in superior yield than trials with a spacing of 51 cm (Xie, Rourke, & Hargrave, 1998) and Hu, Schoenau, Cutforth, and Si (2015) observed that wheat yield tended to be higher at a 30-cm row spacing compared to a 60-cm row spacing . In addition a wider row spacing may provide weeds with less competition as observed by Reinertsen, Cochran, and Morrow (1984).

Core Ideas

- Seed and fertilizer separation was maintained as both the row spacing widened and N rate increased.
- Row spacing has the potential to be increased over 30 cm without sacrificing yield in no-till systems in a semi-arid environment.
- Higher N rates produced greater yield, biomass, and grain protein.
- Wheat biomass decreased as the row spacing increased in 3 of the 4 yr.

Since the concentration of fertilizer per meter of seed row increases as row spacing widens, wider rows have also been associated with increased damage to emerging seedlings of canola (*Brassica napus* L.), oat (*Avena sativa* L.), and spring wheat when separation of seed and fertilizer is not maintained, due to the greater and potentially toxic concentration of N fertilizer (May, Mohr, Lafond, Johnson, & Stevenson, 2004; May Fernandez, Holzapfel, & Lafond, 2008; Xie et al., 1998). Nitrogen is of greatest concern since it is the largest component of applied fertilizer in spring wheat, and N fertilizer rate varies by the largest amount.

Nitrogen fertilizer is used to improve yield and quality of cereal crops. Nitrogen rates have a profound effect on the development and grain yield of spring wheat (Mooleki et al., 2010). The effect of N is measured through changes in plant density and the yield components, consisting of tiller number (tillers plant^{-1}), seed number (seeds head^{-1}), and kernel weight. The yield components integrate the effect of the applied treatment with the changing environmental conditions during the growth of the crop. Wheat grain yield and aboveground N uptake have been observed to rise as the rate of N fertilizer application increases (Lafond et al., 2011; St. Luce et al., 2015, 2016). A higher N rate has been observed to have a diminishing effect on seed weight, but increased grain N protein and biomass in oat when the N rate was greater than 80 kg ha^{-1} (Lafond, May, & Holzapfel, 2013). Other studies have observed an increasing N rate to reduce plant density in wheat (May et al. 2008) and oat (May et al., 2004).

In order to investigate the potential of wider row spacings for grain production, a study was undertaken to examine the effects of row spacing and rate of N fertilizer on the establishment, development, grain yield, N uptake, and grain quality of spring wheat in the semi-arid environment of the Canadian prairies.

2 | MATERIALS AND METHODS

2.1 | Experimental design and management

A 4-yr study (2013–2016) was conducted at the Agriculture and Agri-Food Canada Research Farm in Indian Head, SK, Canada (50°32′ N, 103°40′ W, 579 m elevation). The soil type was a Rego Black Chernozem (Udic Boroll) and the soil series is a Indian Head heavy clay (Mitchell, Mess, Clayton, & Edmunds, 1944). The soil texture was 630 g kg^{-1} clay, 270 g kg^{-1} silt, and 100 g kg^{-1} sand. All the fields on which the experiment was conducted were converted to a no-till production system on or before 1996.

In all 4 yr of this dryland study, wheat was seeded into canola stubble using a no-till system. Each year, the test plots were relocated to another site within the same general area of the farm. This study made use of a specially modified plot seeder which consisted of eight commercial no-till shank openers attached on two ranks (SeedMaster, 2018). To obtain the desired row spacing for a given plot, the openers were physically moved on the two ranks to the correct position. The lateral separation provided by the openers was 38 mm, and the horizontal separation between seed and fertilizer was 19 mm. The fertilizer band was located adjacent and below the seed, and seeding depth was approximately 19 mm under the soil surface at the bottom of a 25 to 33 mm grove cut into the soil by the no-till shank opener.

The treatments were four row spacings (25, 30, 35, and 40 cm) and five N fertilizer rates (20, 40, 80, 120, and 160 kg N ha^{-1}). The study used a split-plot randomized complete block design with four replicates. The main plots were row spacing treatments and the subplots were the N rate treatments. Row spacing, N rate, and year were considered fixed effects. The source of N was urea with an analysis of 46–0–0. A fertilizer blend with an analysis of 14–20–10–10 was side-banded across all treatments, at a rate of 143 kg ha^{-1}. With this application rate, the equivalent of 20 kg ha^{-1} N, 29 kg ha^{-1} P, 14 kg ha^{-1} K, and 14 kg ha^{-1} S was provided by the fertilizer blend. The quantity of urea used for the five different N rates was adjusted to accommodate the N present in the 14–20–10–10 fertilizer blend. The N present in the fertilizer blend accounted for all N in the 20 kg N ha^{-1} treatment. It is important to note that increasing the row spacing from 25 to 40 cm increases the amount of fertilizer product applied in the side-band by 60% per meter of row. The residual N and P prior to seeding ranged from 24 to 48 kg N ha^{-1} and 8 to 13 kg N ha^{-1} (Supplemental Table S1). The target seeding density was 250 plants m^{-2} and this resulted in changing the plants per meter of row as the row spacing changed. The germination of the seed lot and an assumed field mortality of 10% were accounted for when calculating actual seeding rates. The cultivar used in all 4 yr was Goodeve (DePauw et al., 2009). Goodeve was selected because at the time it had above-average yield and lodging with excellent resistance to wheat midge (*Sitodiplosis mosellana* (Géhin). The study was seeded in areas with excellent weed control in the previous year. All pesticides were applied with a tractor and three-point hitch sprayer. A pre-seed application of glyphosate [*N*-(phosphonomethyl)glycine] was applied to control emerged weeds. The incrop herbicide usage varied each year depending on the weed species prevalent at the study site. Good weed control was maintained in all 4 yr with the appropriate herbicide being used (Supplemental Table S1). Other relevant agronomic information related to this study can be found in Supplemental Table S1. Eight rows were seeded for each plot and outside rows were never harvested. Plots were 10.7 m long and 2.7 m wide for 25- and 30-cm row spacings, and 10.7 m long and 3.0 m wide for 35- and 40-cm row spacings.

2.2 | Data collection

Plant density was measured approximately 3 wk after seeding. The number of plants present in two separate 1-m row lengths were determined for each plot. For plant density and all other yield components the sample area in the calculation was adjusted as the row spacing changed. Head density was measured during grain filling. For each plot, the number of heads present in two separate 1 m of row lengths was determined and converted to heads m^{-2}. Tiller number was then calculated by dividing head density by plant density. Seed density was calculated by dividing grain yield (kg ha^{-1}) by the kernel weight (g 1000 K^{-1}). Seed number was calculated by taking the seed density (seeds m^{-2}) and dividing it by the head density (heads m^{-2}).

Total aboveground biomass was measured at physiological maturity. One-meter sections of two rows were cut per plot and samples were dried at 60 °C for 48 h. The resulting biomass yields were adjusted to accommodate varying row spacings.

Grain yield was determined with a self-propelled plot combine by harvesting five rows from the 25-cm row spacing plots, four rows from the 30- and 35-cm row spacing

TABLE 1 The average monthly air temperature and total monthly precipitation for the period 2013–2016 at the Indian Head Research Farm

Year	May	June	July	Aug.	Growing season	Growing season[a] (30-yr long-term avg.)
				Precipitation		
	mm					%
2013	17	104	50	6	177	69
2014	36	199	8	142	385	150
2015	16	38	95	59	208	81
2016	75	50	108	22	255	100
Long-term mean	36	98	65	57	256	
				Temperature		
	°C					%
2013	11.9	15.3	16.3	17.1	15.2	99
2014	10.2	14.4	17.3	17.4	14.8	96
2015	10.0	16.2	18.1	17.0	15.3	99
2016	12.8	16.9	17.6	16.9	16.1	105
Long-term mean	11.2	15.7	17.3	17.1	15.4	

[a]Environment and Climate Change Canada, 2018.

plots, and three rows from the 40-cm row spacing plots. The grain yields were adjusted to 14.5% grain moisture. Determination of grain yield accounted for the number of rows harvested and their respective row spacing. A 500-g subsample was retained for each plot to use for grain quality measurements.

Kernel weight was determined by counting between 500 and 600 seeds for each plot with a seed counter in 2013 and 2014 and approximately 1000 seeds in 2016 and then measuring the mass of the subsample. In 2015, kernel weight was evaluated by manually counting a 250-kernel subsample from grain yield, then measuring the mass of the subsample. Test weight was measured as specified by the Canadian Grain Commission's Official Grain Grading Guide (Canadian Grain Commission, 2018).

Grain N concentration was determined by grinding a 50-g grain yield subsample to <1 mm in a Wiley–Thomas mill (AACC, 1976), then employing the Kjeldahl digestion method (Noel & Hambleton, 1976). Grain N was multiplied by a conversion factor of 5.83 to estimate grain protein levels. Grain P concentration was determined by digesting ground grain in H_2SO_4–H_2O_2 (Varley, 1966). The resulting concentrations of N and P were multiplied by grain yield to estimate the total amount of N and P harvested in the grain.

Straw N concentration was determined by completely oxidizing a 12–15 mg subsample of ground straw by flash combustion in an microcube elemental analyzer. The proportional concentration of N in the subsample was multiplied by straw yield to estimate the total amount of N present in the straw.

2.3 | Statistical analysis

Data analysis was carried out with the SAS PROC MIXED procedure (Littell, Milliken, Stroup, & Wolfinger, 2006). The effects of row spacing, N fertilizer rate, and year were considered fixed, and the effects of replication were viewed as random. With only 4 yr of data at a single site, years were too few to be considered random. Linear and quadratic effects of row spacing and N fertilizer rate were assessed using contrasts. Treatment effects were declared significant at $p < .05$ and LSD were reported at $p = .05$ when years were declared significant as a main effect only.

3 | RESULTS AND DISCUSSION

3.1 | Environmental conditions and pests

Mean monthly temperatures and total monthly precipitation are summarized in Table 1. Growing season air temperatures were within 5% of the long-term average in all 4 yr, with 2013, 2014, and 2015 sitting slightly below average and 2016 slightly above average (Environment and Climate Change Canada, 2018). Growing season precipitation was below average in 2013 and 2015, at 69 and 61%, respectively. Precipitation was above average at 150% in 2014, while 2016 experienced an average amount of rainfall at 100%. However, in 2016 the precipitation in June and July resulted in flooding and saturated soils in the vicinity of the trial.

The observed severity of the leaf disease complex was low in all years and due to environmental conditions conducive for the development of fusarium head blight (FHB) in 2015 a fungicide (prothioconazole + tebuconazole) was applied at anthesis. Environmental conditions changed after the fungicide application occurred reducing disease pressure and the incidence of FHD was low within the plots. No major weed populations were observed within the plots.

3.2 | Plant density and yield components

Plant density (plants m^{-2}) was affected by row spacing, year, and the row spacing × year interaction, but not by N rate (Table 2). Row spacing affected plant density in 2013 and 2015 and in both the month of May and the entire growing season, precipitation was below the long-term average (Tables 1 and 2). There was a linear decrease in plant density from 260 to 202 plants as row spacing widened in 2013 (Table 3). In 2015, there was a curvilinear decrease in plant density from 210 to 161 plants m^{-2} as row spacing increased, with the largest proportion of the decrease occurring between the 25- and 30-cm row spacings. Only in 2015 did plant density fully drop below 200 plants m^{-2} as row spacing increased. In the 2 yr with average or above-average growing season precipitation, plant density was not negatively affected with a curvilinear increase in 2016 and no change in 2014. Similar results were found by Lafond (1994) when the plant density of common wheat, durum wheat, and barley decreased as the row spacing widen from 10 to 30 cm in years of below-average precipitation, similar to the precipitation received in 2013 and 2015. Xie et al. (1998) reported a decrease in plant density in 1 out of 3 yr as the row spacing increased from 25 to 51 cm in a year with 60% of the normal precipitation in May. It is important to remember that as the spacing between rows increases the seeds per linear meter of increase. Variability in the environmental conditions in the seed bed that affects germination and emergence may have a larger impact due to the increased concentration of seeds in the row attempting to germinate and emerge. Precipitation after seeding tends to remove a large portion of the variation caused by environmental conditions within a seed row and improving germination and emergence. A small decrease in plant density as row spacing increased from 25 to 45 cm was observed in oat (Lafond et al., 2013). If producers adopt an integrated approach to weed control to manage herbicide-resistant weeds, they will need to increase their seeding rate to maintain their target plant densities to control weeds as they increase their row spacing (May, Shirtliffe, McAndrew, Holzapfel, & Lafond, 2009; O'Donovan et al., 2001b). If a weed community shifts to difficult to control species that have a greater sensitivity to row spacing than plant density then the producer would probably not use a wide row spacing.

Unlike this study, other studies have found durum plant density to decrease with an increasing N rate, attributed to faults in side-banded seeding systems which can inadvertently expose seeds to toxic levels of fertilizer during seeding (May et al., 2008). The lack of effect on plant density by N rate or a N rate × row spacing interaction indicates that the separation of seed and fertilizer was maintained in this study even under the high N rates at wide row spacing.

Tiller number (tillers plant^{-1}) was affected by N rate, year, and the row spacing × year interaction (Table 2). In 2015, there was a quadratic increase in tiller number as the row spacing widened with the largest value of 2.3 tillers plant^{-1} occurring with a 30-cm row (Table 5). There was a linear decrease in tiller number as the row spacing widened in 2016, from 1.2 tillers plant^{-1} at 25 cm to 0.6 tillers plant^{-1} at 40 cm. It is interesting to note that in 1 of the 2 yr, 2013, when there was a linear decrease in plant density as the row spacing increased the crop compensated with a linear increase in tiller density. In 2015, plant density tended to be lower than the other years and tiller density responded by tending to be higher in 2015 than the other years and the curvi-linear response in tiller density tended to be the inverse of the plant density response to a wider row spacing. Overall, there was a linear increase in tiller number with an increasing N rate, this indicates that the yield potential was not maximized by just the plant density and the crop is continuing to respond to increasing rates of N through increased tillering (Table 4).

Head density (heads m^{-2}), a combination of plant density and tiller density, was affected by row spacing, N rate, and year, but was not affected by the interactions between factors (Table 2). There was a linear decrease from 321 to 259 heads m^{-2} as row spacing widened from 25 to 40 cm (Table 4). This indicates that tiller density alone could not completely compensate for the decrease in plant density that occurred in 2 out of 4 yr. Other studies have observed a similar decrease in head density as the row spacing increased in common wheat, durum wheat, and barley (Lafond, 1994; Lafond & Gan, 1999; Xie et al., 1998). This indicates that when plant density is decreased by a wider row spacing tillering alone does not completely compensate for this decrease. If it did then head density would not change as the row spacing widened. There was also a linear increase from 261 heads m^{-2} to 322 heads m^{-2} observed as the N rate increased. Similar results have been reported in durum (May et al., 2008) and in winter wheat (Brinkman, Deen, Lauzon, & Hooker, 2014). In 2015, head density was 368 heads m^{-2}, which was higher than head density in each of the other 3 yr of the study (Table 4).

TABLE 2 Analysis of variance for the effects of year, row spacing, and N fertilizer rate on plant density, head density, tiller number, seed number, seed density, kernel weight, test weight, grain yield, total aboveground biomass at maturity, straw biomass, and harvest index

Variable	Plant density	Head density	Tiller number	Seed no.	Seed density	Kernel weight	Test weight	Grain yield	Total biomass	Straw biomass	Harvest index
	plants m^{-2}	heads m^{-2}	tillers $plant^{-1}$	seeds $head^{-1}$	seeds m^{-2}	g 1000 K^{-1}	g 0.5 L^{-1}	kg ha^{-1}			%
	p-values[a]										
Row spacing (R)	<.0001	.0002	ns	.0375	.0004	ns	ns	.0001	<.0001	<.0001	.0021
N fertilizer rate (N)	ns	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	ns
R × N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Year (Y)	<.0001	.001	<.0001	.0004	.0001	<.0001	<.0001	.0001	.0032	.0069	.0009
R × Y	<.0001	ns	.0245	ns	.0032	.0186	ns	.0023	.0053	.0003	<.0001
N × Y	ns	ns	ns	ns	<.0001	ns	<.0001	<.0001	.0017	ns	ns
R × N × Y	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

[a]Note. ns, not significant.

[a]*p*-values represented by ns means that the values were > .05.

TABLE 3 The interaction of row spacing × year on plant density (plants m^{-2})

Row spacing	Plant density 2013	2014	2015	2016
cm	plants m^{-2}			
25	261	227	210	258
30	241	245	158	197
35	242	223	173	283
40	202	229	161	264
Linear	<0.0001	ns[a]	0.0006	0.0054
Quadratic	ns	ns	0.0152	0.0098

[a]ns, not significant.

TABLE 4 The effects of year, row spacing, and N fertilizer rate on plant density, head density, tiller number, seed number, kernel weight, test weight, straw biomass, and harvest index

Variable	Plant density	Head density	Tiller no.	Seed no.	Kernel weight	Test weight	Straw biomass	Harvest index
	plants m^{-2}	heads m^{-2}	tillers $plant^{-1}$	seeds $head^{-1}$	g 1000 K^{-1}	g 0.5 L^{-1}	kg ha^{-1}	%
Row spacing, cm								
25	239	321	1.4	35	35.20	382.5	5,702.3	36.5
30	210	289	1.5	39	35.08	382.0	4,668.1	41.1
35	230	295	1.4	36	35.10	381.8	4,863.6	39.6
40	214	259	1.3	38	34.93	381.8	4,484.6	39.0
Linear	0.0037	<0.0001	ns[a]	ns	ns	ns	<0.0001	ns
Quadratic	ns	ns	ns	ns	ns	ns	ns	0.0021
N fertilizer rate, kg N ha^{-1}								
20	224	261	1.2	33	34.62	380.7	3,813.0	40.1
40	227	276	1.3	36	35.06	381.0	4,640.7	38.4
80	225	295	1.4	38	35.28	382.4	5,316.8	38.2
120	221	301	1.4	39	35.33	383.2	5,425.1	39.3
160	221	322	1.6	38	35.10	382.8	5,452.6	39.2
Linear	ns	<0.0001	<0.0001	<0.0001	0.002	<0.0001	<0.0001	ns
Quadratic	ns	ns	ns	<0.0001	0.0002	0.0003	<0.0001	ns
Year								
2013	236	271b	1.2	42a	37.31	400.2	5,957.7	38.3
2014	231	256b	1.1	41a	34.32	374.4	4,227.9	43.0
2015	176	368a	2.2	24b	36.72	382.8	4,854.7	36.0
2016	251	267b	1.1	40a	31.96	370.7	4,678.3	38.9

[a]ns, not significant.

TABLE 5 The interaction of row spacing × year on tiller number (tillers $plant^{-1}$)

Row spacing	Tiller number 2013	2014	2015	2016
cm	tillers $plant^{-1}$			
25	1.2	1.1	1.9	1.2
30	1.2	1.1	2.3	1.2
35	1.2	1.2	2.2	1.0
40	1.0	1.1	2.2	0.9
Linear	ns[a]	ns	ns	0.003
Quadratic	ns	ns	0.013	ns

[a]ns, not significant.

TABLE 6 The interaction of row spacing × year and N rate × year on seed density (seeds m^{-2})

Row spacing	Seed density 2013	2014	2015	2016
cm	seeds m^{-2}			
25	11,216	10,859	8,791	9,820
30	12,637	10,582	8,677	10,065
35	10,520	10,653	8,200	10,645
40	9,439	10,030	8,157	9,744
Linear	<0.0001	ns[a]	ns	ns
Quadratic	ns	ns	ns	ns
N fertilizer rate, kg N ha^{-1}				
20	9,579	7,623	6,779	8,676
40	10,343	9,308	7,752	9,406
80	11,490	11,305	8,912	10,339
120	12,258	12,097	9,468	10,793
160	12,345	12,322	9,371	11,128
Linear	<0.0001	<0.0001	<0.0001	<0.0001
Quadratic	<0.0001	<0.0001	<0.0001	0.0043

[a]ns, not significant.

Seed number (seeds head^{-1}) was affected by row spacing, N rate, and year, but was not affected by the interactions between factors (Table 2). There was a curvilinear increase in seed number from 33 to 39 seeds head^{-1} as the N rate increased from 20 to 120 kg N ha^{-1} (Table 4). The largest proportion of this increase occurred between 20 and 40 kg N ha^{-1}. This indicates that the crop is continuing to respond to N rate by increasing the potential yield with this yield component. In 2015, the seed number was 24 seeds head^{-1}, which was significantly lower than the seed number in observed in 2013, 2014, and 2016, which ranged between 40–42 seeds head^{-1}. This indicates that in 2015, when seed number was set this crop was under a significant amount of stress compared to the other years. This may be due to the low rainfall in May and June in 2015, the higher average temperature in July for 2015 than other years or maybe both. Although seed number varied among the row spacings, there was no consistent change in seed number as row the spacing widened. This indicates that seed number was not a strong yield component for compensating for the initial decrease in plant density in this trial. Other research observed an increase in seed number of common wheat, and durum wheat as the row spacing increased from 20 to 30 cm in compensation for a decreased head density (Lafond, 1994; Lafond & Gan, 1999; Xie et al., 1998).

Seed density (seeds m^{-2}), the summation of all yield components except kernel weight was affected by row spacing, N rate, year, the row spacing × year interaction, and the N rate × year interaction (Table 2). There was a linear decrease in seed density from 11,216 to 9,439 seeds m^{-2} as row spacing widened in 2013 (Table 6). This indicates that the yield components, tiller number and seed number, could not compensate for the initial decrease in plant density that occurred in 2013. Row spacing had no effect in the other 3 yr. The lack of a similar response in 2015 compared to 2013 appears to be due to the environmental stress that reduced seed number at all row spacings having a bigger impact then the impact of row spacing on plant density. In each year (2013–2016) there was a curvilinear increase in seed density as the N rate increased, with the highest seed density occurring at an N rate of 160 kg N ha^{-1} in 2013, 2014, and 2016.

Kernel weight (g 1000 K^{-1}) was affected by N rate, year, and the row spacing × year interaction, but not by row spacing (Table 2). There was a slight curvilinear increase of 0.71 g 1000 K^{-1} as the N rate increased from 20 to 120 kg ha^{-1}, with the peak value occurring at 120 kg N ha^{-1} (Table 4). This indicates that the yield potential of the crop was still being increased by increasing N rates. Applications of N fertilizers with rates of 41.5, 80, and 140 kg N ha^{-1} did not affect kernel weight with durum (May et al., 2008), while rates from 100 to 170 resulted in a decrease in kernel weight in winter wheat and rates from 20 to 120 kg N ha^{-1} resulted in a linear decrease in kernel weight with oat (Brinkman et al., 2014; Lafond et al., 2013). In this study, there was also a quadratic response in kernel weight as row spacing increased in 2014, with a peak of 34.78 g 1000 K^{-1} occurring at a row spacing of 35 cm. While in 2016, there was a linear decrease from 32.38 to 31.72 g 1000 K^{-1} as row spacing widened (Table 7). Therefore, row spacing did not have a consistent affect on kernel weight.

TABLE 7 The interaction of row spacing × year on kernel weight (g 1000 K^{-1})

Row spacing	Kernel weight 2013	2014	2015	2016
cm	g 1000 K^{-1}			
25	37.70	33.98	36.85	32.28
30	37.15	34.33	36.65	32.18
35	37.10	34.78	36.86	31.67
40	37.30	34.19	36.51	31.72
Linear	ns[a]	ns	ns	0.0128
Quadratic	ns	0.0167	ns	ns

[a]ns, not significant.

TABLE 8 The interaction of row spacing × year and N rate × year on grain yield (kg ha^{-1})

Row spacing	Grain yield 2013	2014	2015	2016
cm	kg ha^{-1}			
25	4,603.8	3,696.8	3,246.8	3,172.9
30	4,705.8	3,643.0	3,186.9	3,235.4
35	3,900.0	3,716.9	3,028.6	3,375.7
40	3,525.9	3,430.6	2,968.7	3,092.8
Linear	<0.0001	ns[a]	ns	ns
Quadratic	ns	ns	ns	ns
N fertilizer rate, kg N ha^{-1}				
20	3,547.1	2,569.8	2,428.9	2,781.3
40	3,896.7	3,182.4	2,841.0	3,002.5
80	4,292.1	3,923.0	3,292.0	3,320.3
120	4,600.4	4,160.7	3,514.0	3,473.5
160	4,583.1	4,273.3	3,462.9	3,518.5
Linear	<0.0001	<0.0001	<0.0001	<0.0001
Quadratic	<0.0001	<0.0001	<0.0001	0.0037

[a]ns, not significant.

Similar inconsistent results have been reported in wheat with row spacings ranging from 25 to 51 cm (Xie et al., 1998), as well as durum and hard red spring wheat with spacings from 10 to 30 cm (Lafond, 1994).

3.3 | Grain yield and test weight

Grain yield (kg ha^{-1}) was affected by row spacing, N rate, year, the row spacing × year interaction, and the N rate × year interaction (Table 2). In 2013, there was a linear decrease in grain yield as row spacing increased from 25 to 40 cm. The largest proportion of the decrease occurred between row spacings of 30 and 35 cm, when grain yield dropped from 4,705.8 to 3,900.0 kg ha^{-1} (Table 8). This indicates that the initial decrease in plant density in 2013 as the row spacing increased could not be compensated for with the other yield components in that year. The grain yield in 2013 was better than the other years and plant density may have been the biggest restraint on increasing yield. The same response could have occurred in 2015 except the seed number was impacted by a stress that had a larger impact than plant density.

The results from other studies are variable. Xie et al. (1998) observed greater grain yield with 25- and 38-cm rows compared to 51-cm rows with 1 site-year of data and no difference between row spacings of 25 and 38 cm. In the semiarid region of Saskatchewan, widening the row spacing from 30 to 60 cm resulted in a yield decrease at 2 out of 4 site-years (Hu et al., 2015). As in our experiment, row spacing had its largest impact at the site with the highest yield potential. Lafond et al. (1994) did not observe a significant grain yield response in hard red spring wheat when row spacing increased from 10 to 30 cm, and there was an increase in durum wheat yield as the row spacing widened. In Mexico under irrigation similar results were found with a decrease occurring in 1 out of 3 site-years when the row spacing was increased from 20 to 40 cm (Fischer, Sayre, & Ortiz-Monasterio, 2005). It was also reported that the shorter dwarf wheat plants were more sensitive to row spacing than semi-dwarfs with heights similar to the cultivar used in this study (Fischer, Moreno Ramos, Ortiz Monasterio, & Sayre, 2019). These taller cultivars were not affected by row spacings up to 50 cm. In the Inland Pacific Northwest region of the United States winter wheat production has traditionally used a row spacing of 40 to 45 cm row to accommodate the use of deep-furrow drills (Schillinger & Wuest, 2014). They found that increasing the row spacing to greater than 50 cm resulted in a continuous decrease in grain yield in 1 out of 3 yr. The responsive site-year again had a greater yield potential than the other two sites. When they kept the seeds per meter of row constant as the row spacing widened thereby decreasing the plant density the decline in yield as the row spacing increased was very consistent (Schillinger & Wuest, 2014). The results from this study combined with this current study suggest that seeding rate and plant density have a larger impact on grain yield than row spacing. When weeds were incorporated into a study, Reinertsen et al. (1984) found in common wheat with wild oat (*A. fatua* L.) growing in the plots, that yield declined as the row spacing increased from 20 to 40 cm. In the current study, the decrease in grain yield past 30 cm occurred in 1 out of 4 yr. This decrease demonstrates a 25% probability of a negative response, though the limitations of just 4 site-years of data create uncertainty about a negative response to increasing seeding rate. Due to the sizable impact on economic returns, a 25% probability of a yield decrease is cause for concern.

In each test year (2013–2016), there was a curvilinear increase in grain yield as the N rate increased (Table 8). The significant N rate × year interaction indicates that the shape of grain yield response to N varied among the 4 yr. The largest increase occurred in 2014 when grain yield climbed from 2,569.8 to 4,273.3 kg ha^{-1}, while the smaller increase occurred in 2016, when grain yield increased from 2,781.3 to 3,518.5 kg ha^{-1}. Overall, grain yield increased by the greatest proportion each year when the N rate increased from 40 to 80 kg N ha^{-1}. This increase in grain yield was due to an increase in each individual yield component, tiller number, seed number, and kernel weight. It is interesting to note that 2013 the year most sensitive to row spacing was not more responsive to N rate than the other years despite its higher yield potential. Our study combined with the results from Hu et al. (2015) underscore the need when examining the effect of row spacing of having a range of locations with varying yield potential to fully understand the stability of a wider row spacing.

A general increase in wheat grain yield with higher N rates is expected and has been reported in several studies (Grant, Moulin, & Tremblay, 2016; Mooleki et al., 2010; St. Luce et al., 2015). A similar response curve with grain yield increase occurring between 40 and 85 kg N ha^{-1} was reported by May et al. (2008). The response curves for grain yield reported by St. Luce et al. (2015) were more varied across years and sites. When the N rate that maximized grain yield was estimated with a curvilinear response curve generated from the data in Table 8, grain yield was maximized at 144, 139, 131, and 148 kg N ha^{-1} in 2013, 2014, 2015, and 2016. These rates are fairly close together indicating that the same N rate is suitable across a range of environmental conditions. Due to maximum yield occurring on the plateau portion of the yield curve the best economic N rate would be lower since the current price of fertilizer per kilogram is greater than the income per kilogram of wheat.

The lack of an interaction between row spacing and N rate was also observed by Lafond et al. (1994) with just one interaction in barley for one test year, out of a possible 12 cases. However, Lafond et al. (2013) did find a significant row spacing and N rate interaction in a study with oat. The importance of not having a row spacing × N interaction for grain yield cannot be understated. Not only does the lack of an interaction indicate that the separation between seed and fertilizer was maintained it also indicates that each agronomic practice can be adjusted independently providing producers with greater flexibility as they select the row spacing and N rates to use on wheat in their cropping system.

Nitrogen rate, year, and the interaction between N rate × year affected test weight (g 0.5 L^{-1}), but row spacing did not (Table 2). In 2013, there was a linear decrease in test weight from 401.8 to 398.4 g 0.5 L^{-1} as the N rate increased from 20 to 160 kg N ha^{-1} (Table 9). In both 2014 and 2015 a curvilinear increase in test weight was observed as the N rate rose; however, only the increase in test weight in 2014 would be considered biologically significant as it rose from 369.4 to 378.7 g 0.5 L^{-1} compared to just 381.7 to 382.8 g 0.5 L^{-1} in 2015. In 2016, there was a small linear increase in test weight as the N rate increased, from 369.8 to 371.4 g 0.5 L^{-1}. Overall, the impact of N rate on test weight was small in 3 of the 4 yr, with the largest change occurring in 2014. This minimal effect has been echoed in a study with durum that found N rate to have an insignificant effect on test weight in wheat (May et al., 2008). The insignificant effect of row spacing on test weight in this study has also been observed in winter wheat (Schillinger & Wuest, 2014) and oat (Lafond et al., 2013).

TABLE 9 The interaction of N rate × year on test weight (g 0.5 L^{-1})

N fertilizer rate	Test weight 2013	2014	2015	2016
kg N ha^{-1}	g 0.5 L^{-1}			
20	401.8	369.4	381.7	369.8
40	401.0	370.8	382.1	370.1
80	400.1	375.2	383.5	370.7
120	399.5	377.9	383.8	371.5
160	398.4	378.7	382.8	371.4
Linear	<0.0001	<0.0001	0.0111	0.0011
Quadratic	ns[a]	<0.0001	0.0062	ns

[a]ns, not significant.

TABLE 10 The interaction of row spacing × year and N rate × year on total biomass (kg ha^{-1})

Row spacing	Total biomass 2013	2014	2015	2016
cm	kg ha^{-1}			
25	10,568.0	7,305.1	8,385.8	9,209.6
30	9,333.2	7,540.2	7,758.4	6,743.7
35	10,190.0	7,403.7	7,261.7	6,657.5
40	8,132.4	7,121.7	6,584.0	7,176.4
Linear	0.0006	ns[a]	0.0014	0.0009
Quadratic	ns	ns	ns	0.0004
N fertilizer rate, kg N ha^{-1}				
20	7,776.1	4,967.2	5,990.2	6,263.1
40	9,258.5	6,525.2	6,718.8	7,173.6
80	10,167.0	8,015.9	7,828.1	8,007.9
120	10,432.0	8,371.9	8,433.7	7,917.9
160	10,146.0	8,836.1	8,516.7	7,871.6
Linear	<0.0001	<0.0001	<0.0001	<0.0001
Quadratic	<0.0001	<0.0001	0.0045	0.0007

[a]ns, not significant.

3.4 | Biomass

Total biomass (kg ha^{-1}) was affected by row spacing, N rate, year, the interaction between row spacing × year, and the interaction between N rate × year (Table 2). As row spacing widened, there was a linear decrease in total biomass in 2013 and 2015, with the greater decrease occurring in 2013 when total biomass dropped from 10,568 to 8,132.4 kg ha^{-1} (Table 10). Widening the row spacing also brought a curvilinear decrease in total biomass in 2016, with the lowest value occurring at a row spacing of 35 cm. This general pattern of a decrease in biomass as the row spacing widens has also been observed in both wheat (Liu, Wang, & Cai, 2016; Reinertsen et al., 1984) and oat (Lafond et al., 2013). It is interesting that the biomass decrease is very consistent compared to grain yield. This indicates that wheat tends to produce more biomass than required to maximize grain yield in a weed-free environment. In the presence of weeds the higher biomass would probably help to protect grain yield. Each year (2013–2016) experienced a curvilinear increase in total biomass as the N rate increased (Table 10). The greatest increase in total biomass in three of the four test years (2013, 2014, and 2016) occurred when the N rate rose from 20 to 80 kg N ha^{-1}. It is interesting to note that the year with the greatest biomass also experienced the highest grain yield. However, this trend does not carry through to the year with the next highest yields (2014), as biomass was observed to be the lowest of the 4 yr. The lack of an interaction between N rate and row spacing indicates that regardless of the row spacing, N rate increased biomass and grain yield. In the presence of weeds it would be interesting to determine if the

TABLE 11 The interaction of row spacing × year on straw biomass (kg ha^{-1}) and harvest index (%)

Row spacing	Straw biomass			
	2013	2014	2015	2016
cm	kg ha^{-1}			
25	6,608.7	4,125.9	5,593.6	6,481.0
30	5,286.2	4,407.2	5,017.6	3,961.3
35	6,835.9	4,207.1	4,657.1	3,754.4
40	5,100.1	4,171.4	4,150.3	4,516.6
Linear	0.0497	ns[a]	0.0045	0.0002
Quadratic	ns	ns	ns	<0.0001
Row spacing	**Harvest index**			
cm	%			
25	37.8	44.3	33.7	30.2
30	43.7	42.1	35.6	42.9
35	33.3	43.7	36.4	45.1
40	38.2	41.8	38.3	37.6
Linear	ns	ns	ns	0.0015
Quadratic	ns	ns	ns	<0.0001

[a]ns, not significant.

importance of crop biomass might grow to the level where the response to N fertilizer at wide row spacings would be increased enough compared to narrow rows to be detected in an interaction. It might be possible that high N rates at wide row spacings might be more important in the presence of weeds than in the current weed-free environment of this study.

Straw biomass (kg ha^{-1}) was affected by row spacing, N rate, year, and the interaction between row spacing × year (Table 2). There was a linear decrease in straw biomass as row spacing widened in 2013 and 2015 (Table 11). The larger drop occurred in 2013, when straw biomass decreased from 6,608.7 to 5,100.1 kg ha^{-1} when row spacing increased from 25 to 40 cm. In 2016, there was a curvilinear decrease in straw biomass as row spacing increased (Table 11), with the lowest value occurring at a row spacing of 35 cm. Straw biomass saw a curvilinear increase as the N rate increased, rising from 3,813.0 to 5,452.6 kg N ha^{-1}. A similar response with straw biomass increasing as the N fertilizer rate increased was observed in spring wheat across Saskatchewan at 6 out of 12 site-years (Mooleki et al., 2010). If a producer is intending to harvest the straw off the field then a narrow row spacing may be most appropriate to maximize the straw that can be removed from the field.

Harvest index (%) was affected by row spacing, year, and the row spacing × year interaction, but was not affected by N rate (Table 2). In 2016, there was a curvilinear increase in harvest index from 30.2 to 37.6% as row spacing increased, however, values higher than 42% occurred with row spacings of 30 and 35 cm (Table 11). There were no significant interactions observed with row spacing in other test years.

3.5 | Nitrogen content

Nitrogen rate and year affected straw N content (%), but row spacing and the interactions between factors did not (Table 12). There was a curvilinear increase in straw N content from 0.38 to 0.50% as the N rate increased from 20 to 160 kg N ha^{-1}, with the largest proportion of the increase occurring between 80 and 120 kg N ha^{-1} (Table 13). The greatest straw N content occurred in 2016 with a value of 0.62%, while 2013 saw the lowest value at 0.28%. In both 2013 and 2014, straw N content was significantly lower than in 2015 and 2016.

Straw N yield (kg N ha^{-1}) was affected by N rate, year, and the row spacing × year interaction (Table 12). As the N rate increased from 20 to 160 kg N ha^{-1}, straw N yield had a linear increase from 15.4 to 27.3 kg ha^{-1} (Table 13). These results are supported by Mooleki et al. (2010) which found a linear increase in straw N yield as the N fertilizer rate increased. The row spacing × year interaction showed no clear trend in 2013, 2014, and 2015 while in 2016 there was a quadratic response with the narrowest and widest row spacings being higher in the middle two row spacings (data not show) and there does not appear to be any biological relevance to this response. Straw N yield was highest in 2016 at 29.5 kg ha^{-1} and was higher than straw N yield in 2013 and 2014 (Table 13).

TABLE 12 Analysis of Variance for the effects of year, row spacing and N fertilizer rate on straw N uptake, grain protein concentration, and grain N uptake, and grain P uptake

Variable	Straw N	Straw N yield	Grain protein	Grain N	Harvested grain N	Grain P	Harvested grain P
	%	kg ha^{-1}	——%——		kg ha^{-1}	%	kg ha^{-1}
	p-values[a]						
Row spacing (R)	ns[a]	ns	ns	ns	ns	ns	0.0136
N fertilizer rate (N)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	ns	<0.0001
R × N	ns	ns	ns	ns	ns	ns	ns
Year (Y)	0.0007	0.0059	0.0082	0.0064	0.0157	0.0002	ns
R × Y	ns	0.0238	ns	ns	ns	ns	0.0343
N × Y	ns	ns	0.0028	0.0026	0.0078	<0.0001	<0.0001
R × N × Y	ns	ns	ns	ns	ns	ns	ns

[a]*p*-values represented by ns means that the values were > .05.
[b]ns, not significant.

TABLE 13 The effects of year, row spacing, and N fertilizer rate on straw N uptake, grain protein concentration, and grain N and P uptake

Variable	Straw N	Straw N yield	Grain protein	Harvested grain N	Grain P
	%	kg ha^{-1}	%	kg ha^{-1}	%
Row spacing, cm					
25	0.40	23.8	13.4	87.0	0.38
30	0.41	19.3	13.1	85.5	0.37
35	0.45	21.9	13.8	85.4	0.38
40	0.44	20.6	13.5	77.1	0.38
Linear	ns[a]	ns	ns	ns	ns
Quadratic	ns	ns	ns	ns	ns
N fertilizer rate, kg N ha^{-1}					
20	0.38	15.4	12.3	62.1	0.38
40	0.39	18.1	12.9	73.1	0.38
80	0.39	20.6	13.4	86.2	0.38
120	0.46	25.7	14.3	98.1	0.38
160	0.50	27.3	14.4	99.2	0.38
Linear	<0.0001	<0.0001	<0.0001	<0.0001	ns
Quadratic	0.0435	ns	ns	<0.0001	ns
Year					
2013	0.28c	17.6bc	13.3	99.5	0.35
2014	0.30c	13.0c	11.7	74.4	0.34
2015	0.50b	25.4ab	14.9	81.6	0.42
2016	0.62a	29.5a	13.9	79.6	0.41

[a]ns, not significant.

Grain protein (%) was affected by N rate, year, and the interaction between N rate × year, but was not affected by row spacing (Table 12). There was a linear increase in grain protein as the N rate increased in 2013 and 2016, with 2013 experiencing the greatest increase when grain protein rose from 11.7% at an N rate of 20 kg N ha^{-1} to 15.4% at an N rate of 160 kg N ha^{-1} (Table 14). In 2015, there was a curvilinear increase in grain protein with an increased N rate, with the highest value of 15.8% occurring at an N rate of 120 kg N ha^{-1}. Grain protein in durum has also been observed to increase as the N rate rises, with the highest protein value occurring at 140 kg N ha^{-1} in one study (May et al., 2008). It was observed in 2013 and 2015 that as grain yield plateaued at 120 kg N ha^{-1}, grain protein continued to

TABLE 14 The interaction of N rate × year on harvested grain N (kg ha^{-1}) and grain protein (%)

N fertilizer rate	Harvested grain N 2013	2014	2015	2016
kg N ha^{-1}	kg ha^{-1}			
20	75.9	50.4	57.7	64.5
40	84.1	63.5	74.9	69.9
80	96.6	81.8	86.4	80.2
120	116.7	88.2	97.8	89.5
160	124.0	87.8	91.1	94.0
Linear	<0.0001	<0.0001	<0.0001	<0.0001
Quadratic	ns[a]	<0.0001	<0.0001	ns
N fertilizer rate, kg N ha^{-1}	Grain protein, %			
20	11.7	11.1	13.5	12.9
40	12.0	11.5	15.0	13.1
80	12.8	12.0	15.0	13.7
120	14.4	12.2	15.8	14.7
160	15.4	11.8	15.2	15.2
Linear	<0.0001	ns	0.0033	<0.0001
Quadratic	ns	ns	0.245	ns

[a]ns, not significant.

increase as N rate rose to 160 kg ha^{-1}. Rial-Lovera, Davies, Cannon, and Conway (2016) observed a similar response in spring wheat in the United Kingdom with grain protein increasing as the N rate increased when yield was increasing and the protein increase continued as the N rate increased after grain yield reached a plateau. Mooleki et al. (2010) observed a similar response at some site-years and at other site-years a curvilinear response was observed with grain protein not increasing as the N level increased from 0 to 40 kg N ha^{-1} and then the protein increase as the N rates increase to 80 and 120 kg N ha^{-1}. In 2014, grain yield did not follow this same plateauing pattern, and grain protein remained low and stable. With row spacing not affecting grain protein, producers when managing their N fertilizer to reach their target protein level do not have to account for the row spacing they are using in their production system.

Harvested grain N (kg ha^{-1}) was affected by N rate, year, and the interaction between N rate × year, but was not affected by row spacing (Table 12). There was a linear increase in harvested grain N as the N rate increased in both 2013 and 2016 (Table 14). The greater increase occurred in 2013 when harvested grain N rose from 75.9 kg ha^{-1} at an N rate of 20 kg N ha^{-1} to 124.0 kg ha^{-1} at an N rate of 160 kg N ha^{-1}. In 2014 and 2015, there was a curvilinear increase in harvested grain N as the N rate increased. The largest increase for 2014 occurred between N rates of 40 and 80 kg N ha^{-1}, while in 2015 this jump occurred when N rate rose from 20 to 40 kg N ha^{-1}. Similar results were observed by Mooleki et al. (2010)) with a curvilinear increase in harvested grain N as the N fertilizer rate increased. Although row spacing did not affect grain N uptake in this study, other research with spring wheat has found N uptake to decrease as row spacing increased from 20 to 30 cm (Reinertsen et al., 1984).

3.6 | Phosphorus content

Grain P concentration (%) was affected by year and the N rate × year interaction but row spacing and N rate had no effect (Table 12). Grain P content remained at 0.38% for all row spacings, with the exception of the 30-cm row spacing, when it was 0.37% (Supplemental Table S2). There was a linear decrease observed in grain P content in 2013 from 0.38 to 0.35%, while a linear increase from 0.40 to 0.43% was observed in 2015. Nitrogen had no consistent effect on grain P concentration.

Harvested grain P (kg ha^{-1}) was affected by row spacing, N rate, the row spacing × year interaction, and the N rate × year interaction (Table 12). Harvested grain P was not affected by year (Table 12). There was a linear decrease from 16.57 to 12.45 kg ha^{-1} in harvested grain P as row spacing increased in 2013 (Supplemental Table S2). This is consistent with the grain yield decrease that occurred in that year as the row spacing increased. In each year (2013–2016), there was a curvilinear increase in harvested grain P as the N rate increased, with the highest grain P value occurring at an N rate of 160 kg N ha^{-1} in 2014, 2015, and 2016. The harvested grain P was higher in this study than in a long-term study conducted at Indian Head which measure a long-term average of 9 kg ha^{-1} of P in the harvested grain (Lafond et al., 2009).

4 | CONCLUSIONS

This study was carried out to explore the potential impacts and interactions of varying row spacing and N fertilizer rates on plant development, grain quality, and yield potential of no-till spring wheat, and to determine whether wider row spacings are feasible for addressing seeding issues in no-till cropping systems without limiting yield potential. As anticipated, higher N rates improve the establishment, development, quality, and yield of spring wheat. Increasing the row spacing did not have a large negative impact on plant development and seed quality, except in 2013 when a decrease in plant density as the row spacing increased could not be completely compensated for by the other yield components resulting in a decrease in grain yield. As evidenced by the lack of decrease in plant density as the N rate increased the separation of seed and fertilizer can be maintained with higher levels of N fertilizer. The lack of interaction between N and row spacing indicates that the reduced plant density observed as the row spacing increased two out of four times is due to factors other than N fertilizer rate. Perhaps interplant competition especially under stressful environmental conditions in the seed row. An important item to note is that when a wider row spacing is used, producers will need to monitor their plant density to ensure they are reaching an adequate density especially since all seeding equipment may not maintain the separation of seed and fertilizer. Also the fact that in this study the site sensitive to a wider row spacing had the highest yield potential combined with similar observations in several other studies indicates that the yield potential of a region must be taken into account when studying appropriate row spacings (Hu et al., 2015; Schillinger & Wuest, 2014). In addition, the difference among wheat cultivars in sensitivity to row spacing observed at CIMMYT indicates that a wider range of genotypes need to be used over western Canada to determine the variation among cultivars grown in this region to wider row spacings (Fischer et al., 2019).

A grain yield decrease was observed in 1 yr as row spacing increased beyond 30 cm, creating concern about possible loss of profit for wheat producers. Further research encompassing a larger geographic area with varying yield potential, a wide range of genotypes, and varying weed pressure will be required to provide producers with a better estimate of the likelihood of a grain yield decrease in common wheat once the row spacing is increased past 30 cm. In conclusion, wider row spacings beyond 30 cm are feasible, though producers need to weigh the risk of a potential yield decrease against the cost savings derived by increasing the row spacing.

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CONFLICT OF INTEREST

The authors declare that they have no conflict 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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