Row Spacing and Nitrogen Fertilizer Effect on No-Till Oat Production

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ABSTRACT

A major challenge in agriculture is to enhance crop production in an environmentally sustainable fashion to meet the needs of a growing population given the continual decline in the global arable land base. The objectives of the study were to study the interaction between row spacing and N rate in oat (*Avena sativa* L.) on plant establishment and development, biomass production, grain quality, and grain yield under a no-till production system. Four row spacing (25, 30, 35, and 40 cm) and five rates of N fertilizer were investigated for 3 yr. Plant density was not affected by N rate and there was no N rate by row spacing interaction. There was a 10% decrease in plant population going from 25 to 40 cm with some years showing no differences. Some differences on the origin and frequency of tillers were observed due to spacing. Grain yield was similar among 25, 30, and 35 cm row spacing with a 13% yield decrease at 40 cm. A row spacing by N rate interaction for grain yield was observed. Grain quality was not affected by spacing other than for a small increase in thin seed and seed weight at wider spacing. Grain N and P concentrations were not affected by row spacing. The results support the feasibility of wide row spacing up to 35 cm combined with placing all fertilizer requirements in a side-banded position.

The global arable land base is estimated at 1.351 billion hectares which amounts to about 0.19 ha per person based on a population of 7 billion (World Fact Book, 2012). With the projected population increase to 9 billion by 2050, the per capita arable land amount will be 0.15 ha per person but in actual fact much less because an extra 2 billion people will require additional land for infrastructure. Also, the fact that 93 to 99% of the food consumed by humans comes from the land (Pimentel and Pimentel, 2000; Smil, 2000) implies that food production per unit area will have to increase. However, 45% of global arable soils are affected by degradation (Lal, 2007). The Food and Agriculture Organization endorses conservation agriculture as the key step to meeting the long-term global demand for food, feed, and fiber for the projected 9 billion people by 2050 (Mackenzie, 2009). Irrigated land comprises about 7% of the total arable land area (World Fact Book, 2012) and land under irrigation will probably not increase to make up for short falls in food production because of competing fresh water needs by a growing population. Therefore dry land farming systems will need to become more productive which means more water efficient.

The positive benefits of no-till production systems on crop production (Lafond et al., 1996, 2006b), economic performance (Gray et al., 1996; Zentner et al., 2002; Holm et al., 2006) and energy use efficiency (Zentner et al., 2004) are well recognized in the Northern Great Plains. More recent no-till studies have demonstrated additional yield increases in spring wheat (*Triticum aestivum* L.) and canola (*Brassica napus* L.) as length of time under no-till increases (Lafond et al., 2011). Additional benefits from no-till can be obtained if crops are seeded into tall stubble. Increases in grain yield and water use efficiency have been observed for spring wheat (Cutforth and McConkey, 1997), canola (Cutforth et al., 2006), field pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medik.), and chickpea (*Cicer arietinum* L.) (Cutforth et al., 2002) when seeding into >30 cm tall stubble. Tall stubble reduces water loss from evaporation at the soil surface and increases water available for transpiration, thereby explaining the greater reported crop water use efficiencies and grain yields when compared to shorter or no stubble. Growing crops into tall stubble combined with long-term no-till represents an important approach to increasing crop production under semiarid dryland farming conditions.

Given the reported benefits of no-till production systems, seeding into standing stubble and through surface residues has challenges. One solution to reduce plugging is to increase the row spacing. The common accepted knowledge is that narrow row spacing gives greater grain yields in cereal crops (Austenson and Larter, 1969; Briggs, 1975; Bauder, 1990; Chen et al., 2008). However, other studies have shown that it is possible to use wider spacing without experiencing grain yield losses. Research with no-till winter wheat showed equivalent yields between 18 and 36 cm under semiarid conditions (McCleod et al., 1996) and among 10-, 20-, and 30-cm row spacing under subhumid conditions (Lafond and Gan, 1999). With spring wheat, no differences in yield were observed among 10-, 20-, and 30-cm row spacing under no-till (Lafond, 1994; Bailey et al., 1998) and conventional till systems (Lafond and Derksen, 1996) and between 23 and 30 cm with no-till (Johnston and Stevenson, 2001) under subhumid conditions. No grain yield differences were observed among 10-, 20-, and 30-cm spacing in barley with no-till (Lafond, 1994; Bailey et al., 1998) and conventional till (Lafond and Derksen, 1996) under subhumid

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Table 1. The average monthly air temperature and total monthly precipitation for the period 2009 to 2011 at the Indian Head Research Farm.

Year	Precipitation					Growing season (long-term)
	May	June	July	August	Growing season	
	mm					%
2009	20	57	42	105	224	100
2010	63	122	28	94	307	137
2011	69	139	42	42	292	235
Long-term mean	43	87	49	45	224	
	temperature, °C					
2009	8.1	14.0	14.4	15.3	12.9	81
2010	9.6	15.6	17.4	16.2	14.7	92
2011	9.5	15.3	19.0	18.0	15.5	97
Long-term mean	11.4	16.1	18.4	17.5	15.9	

conditions and no-till durum wheat yields were also similar among 10, 20, and 30 cm (Lafond, 1994) under similar growing conditions. Xie et al. (1998) found grain yields to be similar in spring wheat between 25 and 38 cm when combined with a paired-row configuration with the fertilizer applied in the middle of each pair but for canola, seed yields were greater with 38- vs. 25-cm row spacing. Grain yields in canola and spring wheat were lowest at 51 cm (Xie et al., 1998). Others have also explored different row configurations. Cutforth and Selles (1992) compared equidistant rows of 25 cm with paired rows (two rows 10 cm apart with 50 cm between the centers of each pair) and found no differences in grain yields or water use during the growing season between these configurations. Austenson and Larter (1969) reported no difference in oat grain yield between 15- and 30-cm row spacing.

Therefore, there is sufficient evidence to support the concept of wider row spacing in cereal for both semiarid and subhumid areas. This opens up the opportunity to more easily capitalize on the benefits of tall stubble, especially in the semiarid areas of the Canadian prairies and Northern Great Plains, by allowing for greater ease of seeding between the stubble rows lessening issues with surface residues and standing stubble.

The most common no-till fertilizer management practice on the Canadian prairies is to apply all of the crop's fertilizer requirements at the time of seeding using either a side-band or mid-row band placement method with a small amount of seed-placed fertilizer, usually limited to mono-ammonium phosphate and, in certain cases, ammonium sulfate or potassium chloride. With side-banding, fertilizer is banded alongside each crop row while with mid-row banding, the fertilizer bands are placed between every second row. However, as row spacing increases, the fertilizer bands become much more concentrated and, in the mid-row band configuration, further away from the crop rows. Any attempt at applying some seed-placed fertilizer will also become riskier because of increased salt and toxic effects from the inorganic fertilizer. No studies have been conducted to determine the effects of side-banded inorganic fertilizers at row spacing beyond 30 cm in oat.

The objective of the study was to investigate possible interactions between row spacing and varying rates of side-banded urea N fertilizer on plant establishment, plant development, biomass production, N and P uptake in grain, grain yield, and grain quality using a no-till production system and oat as the test crop.

MATERIALS AND METHODS

Site Description: A 3-yr study (2009–2011) was conducted at the Agriculture and Agri-Food Canada Research Farm at Indian Head, SK, Canada (50°32' N, 103°40' W). The soil type is Indian Head heavy clay, a Rego Black Chernozem (Udic Boroll) (Mitchell et al., 1944). The soil texture is 630 g kg^{-1} clay, 270 g kg^{-1} silt, and 100 g kg^{-1} sand.

Weather Information: A summary of the mean monthly temperatures and total monthly precipitation is provided in Table 1. Growing season air temperatures were average to below average and precipitation was average to above average during the 3-yr period of the study.

Description of Study: In all 3 yr, oat was seeded into field pea stubble using a no-till production system. The use of field pea stubble avoided potential confounding effects of standing stubble with row spacing due to increasing interference with standing stubble as row spacing was decreased. The plots were relocated to another site in the general area each year.

A specially modified plot seeder was used for the study. The seeder consisted of eight commercial no-till shank openers attached on two ranks (SeedMaster, 2012). The openers were physically moved on the two ranks to achieve the desired row spacing. The openers provided a lateral separation of 38 mm and a horizontal separation of 19 mm between the seed and the fertilizer band with the fertilizer band located to the side and below the seed. The seeding depth was set at 19 mm.

The treatments were four row spacing (25, 30, 35, and 40 cm) and five N rates (20, 40, 60, 80, and 120 kg N ha^{-1}). The N source was urea with an analysis of 46–0–0. One rate (143 kg ha^{-1}) of a fertilizer blend with an analysis of 14–20–10–10 was side-banded across all treatments. The rate used for the fertilizer blend provided the equivalent of 20 kg ha^{-1} of N, 12 kg ha^{-1} of P, 14 kg ha^{-1} of K, and 14 kg ha^{-1} of S. The amount of urea used for the various N rates was adjusted for 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} rate treatment or lowest N rate treatment. The target seeding density was 300 plants m^{-2}. A field mortality of 25% was assumed when calculating actual seeding rates. All plots were seeded at 6.4 km per hour. Other pertinent agronomic information related to this study can be found in Table 2. 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%.

Experimental Design: The study was arranged using a split-plot randomized complete block design with four replicates.

Table 2. Other pertinent agronomic information related to the row spacing by N rate study in oat.

	Year		
Agronomic variable	2009	2010	2011
Seeding date	13 May	14 May	16 May
Seeding rate, kg ha^{-1}	151	151	143
Cultivar	Pinnacle	Pinnacle	Pinnacle
Harvest date	14 Sept.	14 Sept.	7 Sept.
Date for plant counts	1 June	31 May	3 June
Date for panicle counts	20 Aug.	4 Aug.	19 Aug.
Date for plant development scoring	29 June	28 June	4 July
Date for biomass sampling	1 Sept.	12 Aug.	19 Aug.
Soil residual nitrate-N (0–60 cm) kg N ha^{-1}	17	11	17
Soil residual PO4-P (0–15 cm) kg P ha^{-1}	16	8	9
Pre-seed herbicide date of application	n/a†	12 May	9 Oct. 2010
Pre-seed herbicide product and rate	n/a	Florasulam 5 g a.i. ha^{-1} Glyphosate 446 g a.i. ha^{-1}	Glyphosate 845 g a.i. ha^{-1}
In-crop herbicide date of application	16 June	n/a	29 June
In-crop herbicide product and rate	Bromoxynil 280 g a.i. ha^{-1} MCPA 280 g a.i. ha^{-1}	n/a	Fluroxypyr 23 g a.i. ha^{-1} MCPA 168 g a.i. ha^{-1} Chlopyralid 30 g a.i. ha^{-1}

† n/a signifies that no application was required.

The main plots were row spacing and the subplots were rates of N fertilizer. The study was conducted over a 3-yr period (2009–2011). All three factors, row spacing, N rate, and year, were considered fixed effects. Plots were 10.7 m long and 2.0 m, 2.4 , 2.8, and 3.3 m wide for the 25-, 30-, 35-, and 40-cm row spacing, respectively.

Variables Measured

Plant Density: Plant density was measured approximately 3 wk after planting. For each plot, the number of plants present in two separate 1-m length of row was determined. The row spacing was taken into account when reporting average plant densities per plot.

Tiller Frequency, Seeding Depth, and Main Stem Haun Stage: Twenty oat plants per plot were collected at approximately 5.5 leaf stage. The 5.5 leaf stage means that the extension of the sixth is 50% the length of the fifth leaf. Each plant was scored for depth of seeding and main stem Haun stage (Haun, 1973). Main stem Haun stage is an indirect indicator of speed of emergence (Lafond and Baker, 1986). The depth of seeding was determined in each plant by measuring the distance from the seed to the appearance of chlorophyll on the crown, which corresponds to the soil surface. Each tiller on each plant was identified and scored for presence or absence using the method developed by Klepper et al. (1983). Tiller T0 refers to the presence of a coleoptilar tiller; Tiller T1 refers to the tiller in the axil of the first leaf on the main stem; Tiller T2 refers to the tiller in the axil of the second leaf of the main stem.

Panicle Density: Panicle density was measured approximately 3 to 4 wk after full panicle emergence. For each plot, the number of panicles present in two separate 1-m length of row was determined.

Estimated Panicle Density at the 5 to 6 Leaf Stage: Expected panicle density was calculated by summing tiller frequencies (including main stem) and then multiplying this sum by plant density m^{-2}. For this calculation, it was assumed that each tiller recorded at the 5.5 leaf stage produced a panicle.

Total Aboveground Biomass: Total aboveground biomass was measured at maturity by cutting 1 m of row per plot and drying the samples at 60°C for 48 h. Biomass yields were adjusted for row spacing.

Grain Nitrogen and Phosphorus: Total N in grain was determined by the Kjeldahl digestion method (Noel and Hambleton, 1976) after grinding a 50-g subsample in a Wiley–Thomas mill (Thomas Scientific, Swedes-6010, NJ) to <1 mm (AACC, 1976). Total P in the grain was determined following digestion of ground grain in H_2SO_4–H_2O_2 (Varley, 1966). The concentration of N and P was multiplied by grain yield to estimate the amount of total N and P present in the grain.

Grain Yield: Grain yields were determined by mechanically harvesting six rows from the 25- cm row spacing plots, five rows from the 30-cm row spacing plots and four rows from the 35- and 40-cm row spacing plots. The harvested samples were dried at 35°C for approximately 3 to 4 d, weighed, and the yields adjusted to 13.5% grain moisture. Approximately six samples were chosen at random after drying to determine the grain moisture content achieved after the drying process. Grain yield was determined taking into consideration the number of rows harvested and their respective row spacing. After recording the grain weights for each plot, a subsample of 500 g was retained for grain N analysis and other grain quality measurements.

Grain Quality: Thin seed was recorded as the portion of the grain sample mass that fell through a 1.98- by 19.05-mm slotted screen (5/64 by 3/4 in slotted sieve) and plump seed was the seed mass that stayed on top of a 2.18- by 19.05-mm screen (5.5/64 by 3/4 in slotted sieve). Test weight was measured as specified by the Canadian Grain Commission's Official Grain Grading Guide (Canadian Grain Commission, 2006). Groat percentage was determined using a compressed-air oat laboratory dehulling machine. A 50-g sample was used with a dehulling time of 60 s, an air pressure of 690 kPa and a blast gate aperture of 1.5 to 2.0 cm (Doehlert et al., 1999; Doehlert and McMullen, 2001). Groat percentage was recorded as the mass of the groat divided by the mass of the whole oat multiplied by 100. Seed weight was the average weight of 700 to 1000 seeds.

Table 3. Analysis of variance for the effects of year, row spacing, and N fertilizer rate on plant populations, main stem Haun stage, seeding depth, tiller development, actual and estimated panicles m^{-2}.

Effect/contrast	Plant density	Seeding depth	Main stem haun stage	T0†	T1†	T2†	Actual panicles m^{-2}	Estimated panicles m^{-2}
	p value‡						no. m^{-2}	
Row spacing (*R*)	0.001	<0.0001	ns	ns	ns	0.001	0.018	<0.0001
R linear	<0.0001	<0.0001	ns	0.033	ns	0.006	0.002	<0.0001
R quadratic	ns	0.013	ns	ns	ns	0.001	ns	ns
N fertilizer rate (N)	ns	0.010	0.012	ns	<0.0001	<0.0001	0.038	<0.0001
N linear	ns	ns	ns	ns	<0.0001	<0.0001	0.017	<0.0001
N quadratic	ns	ns	0.007	ns	ns	ns	ns	0.038
R × N	ns	ns	ns	ns	ns	ns	ns	ns
Year (Y)	0.003	0.019	<0.0001	ns	ns	0.021	<0.0001	<0.0001
Y × R	ns	ns	ns	ns	ns	<0.0001	0.006	ns
Y × N	ns	ns	0.012	ns	ns	ns	ns	0.023
Y × R × N	ns	ns	ns	ns	ns	ns	ns	ns

† T0, T1 and T2 refer to the origins of the tillers. T0 originates from the coleoptilar node, T1 from the axil of the first leaf on the main stem, and T2 from the axil of the second leaf on the main stem.

‡ *p* values represented by ns means that the values were >0.05.

Table 4. The effects of row spacing and rates of N fertilizers on plant densities, main stem Haun stage, seeding depth, tiller development, actual and estimated panicles m^{-2}.

Variable	Plant density	Seeding depth	Main stem Haun stage	T0†	T1†	T2†	Actual panicles	Estimated panicles
Row spacing, cm	no. m^{-2}	mm	leaf no.		%		no. m^{-2}	
25	370	40	5.5	3.6	13.5	3.8	427	486
30	357	33	5.5	3.0	11.2	1.9	416	465
35	330	32	5.5	1.3	12	3.3	406	435
40	335	31	5.4	1.0	9.0	6.3	400	438
LSD (0.05)‡	19	3	-	-	-	2.0	17	21
Nitrogen rate, kg N ha^{-1}								
20	341	30	5.4	1.1	5.2	1.5	406	416
40	353	32	5.5	1.6	10.6	2.6	399	455
60	351	31	5.5	2.7	9.5	2.1	422	461
80	343	30	5.5	2.8	16.5	7.2	411	474
120	351	32	5.4	2.4	14.8	5.7	424	473
LSD (0.05) ‡	-	2.6	0.09	-	4.4	2.9	18	28
Year								
2009	399	34	5.5	1.4	16.3	7.3	505	492
2010	345	38	5.1	0.4	6.2	0.8	370	523
2011	300	30	5.8	4.6	11.4	3.4	362	354

† T0, T1, and T2 refer to the origins of the tillers. T0 originates from the coleoptilar node, T1 from the axil of the first leaf on the main stem, and T2 from the axil of the second leaf on the main stem.

‡ Only the LSD (0.05) values corresponding to a significant *F* test are presented.

Statistical Analysis: Data were analyzed with the PROC MIXED procedure of SAS (Littell et al., 2006; SAS Institute, 2005). The analysis considered the effects of replicate as random, and the effect of row spacing, N fertilizer rate, and year as fixed. Contrasts were used to assess linear and quadratic effects of N fertilizer rate. Row spacing was considered a discrete variable and not analyzed as a quantitative variable. The interest was not in extrapolating row spacing effects in the 10- to 40-cm range used in the study but rather in understanding the effects of row spacing chosen. Treatment effects were declared significant at $p < 0.05$ and LSD were reported at $p = 0.05$.

RESULTS AND DISCUSSION

Effects on Plant Population and Plant Development: Plant density was affected by row spacing and year but not fertilizer N rate (Table 3). The effect of year is expected given that it is very difficult to attain the same plant population every year. In general, a decrease in plant numbers on the order of ~10% was noted when going from 25- to 40-cm row spacing (Table 4). This has also been reported in barley (*Hordeum vulgare* L.), durum (*T. durum* L.), and spring wheat with row spacing ranging from 10 to 30 cm (Lafond, 1994). The largest decrease in plant numbers with row spacing occurred between 30- and 35-cm row spacing with no difference between 35 and 40 cm (Table 4). The lack of differences between 35 and 40 cm was consistent for all years (data not presented). The plant densities achieved in this study were at or above the density required to optimize grain yield in oat (May et al., 2009). In the past, reductions in plant numbers have been observed in oat (May et al., 2004) and other crops with various side-banding fertilizer openers as the rate of N increases (Johnston et al., 1997, 2001); however, this was not observed in this study. Also, the lack of an N rate × row spacing interaction on plant density is an indication of the advances made with side-banding technology with regards to improved crop safety by ensuring consistent and adequate separation between seed and fertilizer. The 38 by 19 mm configuration used in this study is providing adequate separation between the seed and fertilizer band in terms of crop establishment, considering that the fertilizer band is 60% more concentrated when going from 25 to 40 cm, regardless of N rate.

Depth of seeding was influenced by row spacing, N rate, and year (Table 3). As row spacing increased, depth of planting decreased such that the largest differences occurred between 25 cm and the other row spacing and only small differences among 30, 35, and 40 cm (Table 4). The year effect is attributed to soil moisture differences. There was no distinct seeding depth pattern discernible with changes in N rate and the absolute differences due to N rate were very small (Table 4). Seeding depth differences among row spacing were attributed "soil stepping". This corresponds to the movement of soil from one rank of openers to the next, that is, the openers on the back rank moving soil onto the seeded area of the opener located on the rank ahead of it. This effect was most pronounced at 25 cm and the effect more or less disappeared once row spacing reached 30 cm or wider. This soil stepping effect was observed with seeding speeds used in this study of only 6.4 km h^{-1}. At greater seeding speeds, it is possible that some effect might be observed at 30-cm row spacing. This implies that wider row spacing can result in overall planting depths that are closer to the desired depths because soil stepping will not be a concern thereby allowing for greater travel speeds.

Main stem Haun stage is a quantitative measure of the appearance of leaves on the main stem (Haun, 1973) and also provides for an indirect measure of speed of emergence (Lafond and Baker,1986). Nitrogen rate and year had an effect on main stem Haun stage but not row spacing. The year effect is due to the fact that the plants were not sampled exactly at the same stage each year. Although an N effect was observed, there was no consistent pattern noted (i.e., increases or decreases in values as N rate increases or decreases). The lack of observed differences among row spacing provides important evidence that even though the number of seeds in a length of row increases with wider row spacing, the increased competition does not affect speed of emergence. Similar results have been reported for spring wheat (Lafond et al., 2006a; Chen et al., 2008).

There was interest in further quantifying potential competitive effects among seedlings as a function of row spacing and N rate by measuring the number of tillers present and their origin. Tiller T0 is commonly referred to as the coleoptile tiller because it originates at the coleoptilar node. This tiller is very sensitive to management, which means that high frequencies are a reflection of good seeding management or growing conditions. It is very sensitive to stresses like inadequate or excessive moisture, inadequate packing, excess planting depth, interplant competition, and/or inadequate separation between seed and N fertilizer (Peterson et al., 1982). In this study, tiller T0 was affected only by row spacing (Table 3). As row spacing increased, the number of T0s decreased. The largest decrease was observed when 40 cm was compared with 30-cm row spacing (Table 4). Although the overall incidence of tiller T0 is very low, the decrease with wider row spacing could be interpreted as reflecting an increase in interplant completion. The incidence of T0 were not different between 23- and 30-cm row spacing in spring wheat (Lafond et al., 2006a) which supports our observations of no difference between 25- and 30-cm row spacing in the current study. The incidence of tiller T1 was only affected by N rate (Table 3). As N rate increased, the presence of T1 increased (Table 4). The T1 tiller is an important contributor to final grain yield. With T2, an effect due to row spacing, N rate and year and a year × row spacing interaction were observed (Table 3). As row spacing and N rate increased, the presence of T2 increased with the highest recorded incidence observed at 40-cm row spacing and 80 kg N ha^{-1} (Table 4). Others have observed increases in panicles per plant with increasing rates of N fertilizer which supports our observation (May et al., 2004). The year effect was expected because the plants measured were not collected at exactly the same leaf stage each year. The year × row spacing interaction was due to an observed increase in the incidence of T2 going from 25 to 40 cm in 2009 with very little differences among row spacing in 2010 and 2011 (data not presented). Previous research in spring wheat showed no difference in the incidence and origin of tiller T2 between 23- and 30-cm row spacing (Lafond et al., 2006a). In this study, only small differences between 25- and 30-cm row spacing were observed.

The number of panicles were affected by row spacing, N rate, year and a year × row spacing interaction (Table 3). As row spacing increased from 25 to 40 cm, there was a 6% decrease in panicle numbers. Nitrogen rate had an opposite impact on panicle numbers and increased 4% with increasing N (Table 4). A 20% increase in panicles m^{-2} from 15 to 120 kg N ha^{-1} was observed by May et al. (2004). When comparing the actual number of panicles counted to the panicle counts estimated at the 5.5 leaf stage, the estimates were larger; however the effects of row spacing, N rate, and year were the same regardless of whether the number of panicles were measured or estimated (Table 3). The overall estimated value for panicle counts was 456 vs. 412 from the actual counts, a difference of ~10%. Similar work in spring wheat showed a difference of only 1% between estimated and actual spikes m^{-2} as a function of row spacing (23 vs. 30 cm) and N management (Lafond et al., 2006a).

Effects on Grain Quality: Studies quantifying the effects of row spacing on oat grain quality were not found in the scientific literature. In this study, row spacing had no effect on the grain quality parameters measured (Tables 5 and 6). A row spacing × year interaction was noted for seed weight. In 2009, seed weight increased going from 25 to 40 cm while in 2010 there was no effect and in 2011 there was an increase up to 35 cm and a decrease at 40 cm and no difference between 25 and 30 cm (data not presented). The only interaction observed with row spacing was with N rate on the proportion of thin seeds (Table 5). As a rule the proportion of thins increased with N rate but the increase was least at 30 cm, highest at 40 cm and intermediate for 25 and 35 cm (data not presented). The proportion of thin seeds in this study was less than values reported for the same location but with different cultivars in earlier studies, possibly a reflection of different growing conditions and genetic differences (May et al., 2004).

The largest effects on grain quality were due to year and N rate. A year effect was observed for all variables except grain N

Table 5. Analysis of variance for the effects of row spacing and rates of N fertilizer on grain protein concentration, groat yield, 1000 seed weight, test weight, and the proportion of plump and thin kernels.

Variable	Grain protein	Groat yield	1000 seed weight	Test weight	Plumps†	Thins†
	p values‡					
Row spacing (R)	ns	ns	ns	ns	ns	ns
R linear	ns	ns	ns	ns	ns	ns
R quadratic	ns	ns	0.014	ns	ns	ns
N fertilizer rate (N)	<0.0001	ns	<0.0001	<0.0001	<0.0001	<0.0001
N linear	<0.0001	ns	<0.0001	<0.0001	<0.0001	<0.0001
N quadratic	<0.0001	ns	ns	ns	0.036	<0.0001
R × N	ns	ns	ns	ns	ns	<0.0001
Year (Y)	ns	0.001	0.000	0.001	0.002	ns
Y × R	ns	ns	0.006	ns	ns	ns
Y × N	<0.0001	ns	<0.0001	<0.0001	<0.0001	<0.0001
Y × R × N	ns	ns	ns	ns	ns	ns

† Plumps refers the kernels that remain on top of a 2.18- by 19.05-mm slotted screen and thins refers to the kernels that fell through a 1.98- by 19.0- mm slotted screen

‡ *p* values represented by ns means that the values were >0.05.

Table 6. The effects of row spacing and rates of N fertilizers on grain protein concentration, groat yield, 1000 seed weight, test weight, and the proportion of plump and thin kernels.

Variable	Grain protein	Groat yield	1000 seed weight	Test weight	Plumps†	Thins†
	g kg^{-1}		g	kg m^{-3}	%	
Row spacing, cm						
25	84	725	35.0	486	94.5	1.3
30	84	718	35.5	486	94.9	1.1
35	84	723	35.6	486	94.8	1.3
40	85	722	35.1	482	94.6	1.5
LSD (0.05) ‡	-	–	0.5	-	-	-
N fertilizer rate, kg N ha^{-1}						
20	82	717	36.6	492	96.1	1.1
40	81	720	36.0	491	95.9	1.0
60	83	723	35.2	487	94.7	1.2
80	84	725	35.0	481	94.4	1.3
120	91	724	33.7	476	92.3	1.8
LSD (0.05) ‡	2	–	0.6	4	0.6	0.2
Year						
2009	84	722	38.4	497	95.5	1.1
2010	83	731	32.7	468	93.4	1.4
2011	85	712	34.8	490	95.2	1.4
LSD (0.05) ‡	-	7	1.0	13	1.0	-

† Plumps refers the kernels that remain on top of a 2.18- by 19.05-mm slotted screen and thins refers to the kernels that fell through a 1.98- by 19.05-mm slotted screen.

‡ Only the LSD (0.05) values corresponding to a significant *F* test are presented.

concentration and proportion of thin seeds (Tables 5 and 6). An N rate effect was observed on all variables except groat yield (Table 5). Nitrogen rate increased grain N protein as would be expected in a linear and quadratic fashion indicating that a linear trend was observed but at a reduced rate at the higher N rates based due to the quadratic nature of the response as well (Table 6) and as previously reported (May et al., 2004). Additionally, N rate caused a linear decrease in seed weight (Tables 5 and 6) and this was also previously observed (May et al., 2004). The year × N rate interaction for seed weight was because in 2009, N rate did not affect seed weight while in 2010 and 2011 a decrease occurred with increasing N rate with a larger decrease observed in 2010 than 2011 (data not presented). Increasing N rate caused an overall linear decrease in test weight and the decrease was greater at the higher N rates due to the quadratic nature of the response (Tables 5 and 6) which is in agreement with earlier observations (May et al., 2004). There was no row spacing × N rate interaction detected for test weight indicating that the response to N was not influenced by row spacing but there was a year × N rate interaction. In 2009, test weight decreased from 506 to 492 kg m^{-3} going from 20 to 120 kg N ha^{-1} while in 2010 it went from 486 to 436 kg m^{-3}, falling below 470 at rates of 40 kg N ha^{-1} or greater. In 2011 the test weights did not change with N rate and averaged 482 kg m^{-3}. The threshold for milling quality oat is 470 kg m^{-3} and oat samples with test weights <470 kg m^{-3} are downgraded to feed. This threshold was breached only in 2010 with N rates >40 kg ha^{-1}. With respect to kernel plumpness, there was an overall linear decrease with increasing N rate but the rate of decrease was greater at the intermediate N rates explaining also the quadratic nature which was also reported in other studies (May et al., 2004) (Tables 5 and 6). The year × N rate interaction was the result of there being no differences due to N rate in

Table 7. Analysis of variance for the effects of row spacing and rates of N fertilizer on total aboveground biomass at maturity, grain yield, grain N concentration, grain N yield, grain P concentration, and grain P yield.

Effect/Contrast	Biomass	Grain yield	Grain N	Grain N	Grain P	Grain P
	p values					
Row spacing (R)	<0.0001	<0.0001	ns†	0.001	ns	0.028
R linear	<0.0001	<0.0001	ns	<0.0001	ns	0.006
R quadratic	ns	ns	ns	ns	ns	ns
N fertilizer rate (N)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.005
N linear	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.051
N quadratic	<0.0001	<0.0001	<0.0001	0.001	<0.0001	0.011
R × N	ns	0.004	ns	0.023	ns	ns
Year (Y)	<0.0001	<0.0001	ns	0.001	ns	0.024
Y × R	0.012	0.002	ns	ns	ns	ns
Y × N	<0.0001	0.011	<0.0001	<0.0001	0.001	<0.0001
Y × R × N	ns	ns	ns	ns	ns	ns

† ns signifies that the *p* values were >0.05.

Table 8. The effects of row spacing and rates of N fertilizer on total aboveground biomass at maturity, grain yield, grain N concentration, grain N yield, grain P concentration, and grain P yield.

Variables	Biomass	Grain yield	Grain N	Grain N	Grain P	Grain P
	Mg ha^{-1}		g kg^{-1}	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
Row spacing, cm						
25	9.8	5.46	14.7	80.7	2.56	13.9
30	9.4	5.33	14.8	78.7	2.54	13.4
35	8.5	5.19	14.7	76.6	2.61	13.4
40	8.5	4.66	14.9	69.1	2.65	12.2
LSD (0.05)†	0.6	0.28	0.5	5.6	0.13	1.2
N fertilizer, kg ha^{-1}						
20	7.4	4.33	14.5	62.2	2.89	12.3
40	9.0	5.10	14.1	72.1	2.66	13.5
60	9.0	5.47	14.6	79.9	2.51	13.7
80	10.1	5.49	14.7	80.8	2.41	13.2
120	9.8	5.41	15.9	86.3	2.47	13.4
LSD (0.05)†	0.4	0.21	0.4	3.7	0.1	0.8
Year						
2009	9.8	6.02	14.8	89.7	2.40	14.6
2010	10.8	5.41	14.5	78.6	2.73	14.6
2011	6.5	4.05	15.0	60.5	2.64	10.5
LSD (0.05)†	1.1	0.54	-	11.9	-	3.1

† Only the LSD (0.05) values corresponding to a significant *F* test are presented.

2009 while in 2010 the percentage of plump kernels went from 97.0 to 88.3% and in 2011 from 95.4 to 93.3% with N rates going from 20 to 120 kg ha^{-1}.

Row spacing did not bring test weight below the threshold level of 470 kg m^{-3}. The overall lack of an N rate × row spacing interactions was a strong indicator that changes in row spacing will not impact grain quality. Producers need to be aware of the negative impact of high N rates on oat test weights to improve their likelihood of obtaining milling grades.

Effect on Biomass Production, Grain Yield, and Nitrogen and Phosphorus Uptake: There were row spacing, N rate, and year effects observed for total aboveground biomass at maturity along with a year × row spacing and year × N rate interaction but no row spacing × N rate interaction (Table 7). In general, as row spacing increased aboveground biomass production decreased with the largest differences occurring between 30 and 35 cm and no differences between 35 and 40 cm or between 25 and 30 cm (Table 8). Some reports claim larger accumulations of biomass at 15 cm than 30 cm in spring wheat (Chen et al., 2008) while others claim no differences in spring wheat biomass accumulation with row spacing ranging from 9, 18, 27 to 36 cm (Yunusa et al., 1993). In 2009, there was no difference in biomass accumulation among the row spacing investigated while in 2010 25 cm had the highest biomass accumulation but no differences between 30 and 40 cm with 35 cm being lower than 30 or 40 cm (Table 9). In 2011, no differences between 25 and 30 cm or between 35 and 40 cm were observed but 25- and 30-cm row spacing had greater biomass accumulations than 35 or 40 cm. As N rate increased, there was an overall linear increase in biomass and the increase was greater at 80 kg N ha^{-1} explaining also the quadratic nature of the response. The year × N rate interaction

Table 9. The interaction of row spacing and year on total biomass production (Mg ha^{-1}).

Row spacing	Year		
	2009	2010	2011
cm			
25	9.8	12.1	7.5
30	10.0	10.9	7.3
35	9.7	9.6	6.1
40	9.7	10.4	5.3
LSD (0.05)† = 1.0			

† Only the LSD (0.05) values corresponding to a significant *F* test are presented.

Table 10. The effects of row spacing and N fertilizer rate on oat grain yield.

	Row spacing, cm			
N Rate	25	30	35	40
kg ha^{-1}	Mg ha^{-1}			
20	4.45	4.42	4.31	4.13
40	5.50	5.16	4.93	4.80
60	5.61	5.67	5.74	4.90
80	5.81	5.65	5.41	5.09
120	5.93	5.73	5.56	4.41
LSD (0.05) = 0.42†				

† Only the LSD (0.05) values corresponding to a significant *F* test are presented. The LSD (0.05) is applicable only for mean differences among N fertilizer rates for each row spacing.

Table 11. The effects of row spacing and year on oat grain yield.

	Year		
Row spacing	2009	2010	2011
cm	Mg ha^{-1}		
25	5.93	5.85	4.60
30	5.91	5.62	4.44
35	6.27	5.30	3.99
40	5.96	4.86	3.17
LSD (0.05) = 0.48†			

† Only the LSD (0.05) values corresponding to a significant *F* test are presented.

Table 12. The effects of year and N fertilizer rates on oat grain yield.

N fertilizer rate	Year			Mean response
	2009	2010	2011	
kg ha^{-1}	Mg ha^{-1}			
20	5.32	4.27	3.39	4.33
40	5.80	5.38	4.12	5.10
60	6.19	5.92	4.33	5.48
80	6.31	5.89	4.27	5.49
120	6.48	5.60	4.15	5.41
LSD (0.05) = 0.36†				

† Only the LSD (0.05) values corresponding to a significant *F* test are presented.

was due to differences in the responses to N with year which was to be expected based on year to year growing conditions variations (Table 8).

Grain yield was affected by row spacing, N rate, year, row spacing × N rate and row spacing × year interactions (Table 7). The highest grain yields were recorded in 2009 with average yields of 6.02 t ha^{-1} vs. 5.41 and 4.05 in 2010 and 2011, respectively. Averaged across N rates and years, a yield reduction was observed at 40 cm but no differences were observed among the 25-, 30-, and 35-cm row spacing (Table 8). Austenson and Larter (1969) reported similar grain yields between 15- and 30-cm row spacing. Of greater interest is the row spacing × N rate interaction (Table 10). At the lowest N rate, no yield differences among the row spacing were observed but at 40 kg N ha^{-1}, yields were lower at 35 and 40 cm row spacing. For the remaining N rates, 40 cm gave the lowest grain yield although the difference was not significant at 80 kg N ha^{-1}. With the row spacing × year interaction, there were no differences among row spacing in 2009 which corresponds to the highest recorded yields for the study, but in 2010 and 2011, lower grain yields were observed with 35- and 40-cm row spacing (Table 11). We did not observe any lodging in the 3 yr of the study but we did observe stem breakage about one-third up the stem during the straw dry down period before harvest with N rates >60 kg ha^{-1} in both 2010 and 2011. The stem breakage created problems at harvest in 2010 and 2011 such that it was difficult to separate the rows to be harvested from those left behind especially at the 25-cm row spacing where some panicles from the unharvested rows were being picked up by the plot combine due to the proximity of the rows. This problem diminished as row spacing increased. In 2009, stem breakage was not observed and, in addition to having the highest overall grain yields, no differences among the row spacing were observed (Table 10). The grain yields at 60 kg N ha^{-1}, the optimum N rate based on the quadratic response (Tables 7 and 12) and where no stem breakage was observed, did not differ among 25, 30, and 35 cm but a reduction at 40 cm was still noted (Table 10).

Grain N concentration was affected by N rate but not row spacing and there was a year × N rate interaction but not a row spacing × N rate interaction, thereby indicating that row spacing did not modify the response to N fertilizer (Table 7). The lack of a row spacing effect indicated that the greater concentration of fertilizer in the bands by the seed row with wider row spacing did not increase the potential for greater grain N concentration from greater N uptake. The effect of N rate on grain N concentration showed an overall positive linear trend and the quadratic response simply means that the response was less at the higher N rates used (Tables 7 and 8). The year × N interaction is to be expected because of yearly variations in weather along with differences in soil fertility among actual test locations affecting the overall response to N.

Grain N yield is the product of grain yield and N concentration. Row spacing, N fertilizer rate, and year effects were observed (Tables 7 and 8). Since there was no effect of row spacing on grain N concentration, the differences observed in grain N yield are due to yield differences from row spacing which were previously discussed. The row spacing × N rate interaction was due to the same interaction on grain yield which was also previously discussed. The effects of N rate on grain N yield were due to the increase in grain N concentration and grain yield with N fertilizer and the year × N rate interaction was the result of a differential response to N rate as a result of varying environmental conditions.

Grain P concentration was affected by N rate and a year × N interaction but not row spacing (Table 7). As N rate increased, grain P concentration decreased in a quadratic fashion (Tables 7 and 8). The tendency was for grain P concentration to decrease with N rate but the magnitude of the decrease varied with years (data not presented). Grain P yield, the product of grain P concentration with grain yield, was affected by row spacing, N rate, and year (Table 7). Grain P yield was lowest at 40 cm reflecting the lower yields recorded at that row spacing and increased with N rate reflecting the greater yields with the addition of N fertilizer (Table 8). Grain P yield followed a similar trend as the yield increase with N rate explaining the year × N interaction (data not presented).

Achieving Greater Dryland Grain Production with Wider Row Spacing: The challenge is to find ways to increase total grain production under dryland farming conditions to meet the food, feed, and fiber needs of a growing world population combined with a dwindling arable land area. This can be accomplished by adapting dryland farming systems to allow for more efficient use of existing water resources by altering the crop water use balance. This can be achieved by reducing evaporative water losses at the soil surface thereby increasing water availability for transpiration. Conservation agriculture will be a key component to future production systems and this requires coping with crop residues at the soil surface (Mackenzie, 2009).

The results of this study have shown that it is possible to use row spacing from 25 to 35 cm without experiencing yield losses in oat and for other cereal crops as reported by others (Cutforth and Selles, 1992; Lafond, 1994; Lafond and Derksen, 1996; McCleod et al., 1996; Bailey et al., 1998; Xie et al., 1998; Lafond and Gan, 1999; Johnston and Stevenson, 2001). Adopting wider row spacing will permit the full microclimatic benefits of tall stubble to be fully exploited (Caprio et al., 1985). In addition, wider row spacing means that wider seeding implements can be pulled with the same amount of draft energy resulting in quicker seeding times (enhanced timeliness of seeding), less soil disturbance, and a reduction in overall fuel use. More recently, it has been shown that grain yields and water use efficiencies in canola, pulse crops, and spring wheat increased linearly with stubble heights ranging from 0 to 45 cm under dry conditions (Cutforth et al., 2011). Leaving tall stubble in the field also has important implications for the harvest operation. Taller stubble means less plant material to process at harvest which reduces overall energy requirements while accelerating the overall harvest operation, thereby helping to ensure greater grain quality. Tall stubble will also enhance the capacity to capture snow thereby increasing the opportunity to conserve more water and replenish soil moisture reserves.

One could argue that adopting wider row spacing may actually reduce crop water use efficiency by increasing water loss from evaporation because of the reduced ability of the crop to cover the ground. However this has not been observed based on field research comparing water use at different row spacing under both continental semiarid and dry Mediterranean growing conditions (Cutforth and Selles, 1992; Yunusa et al., 1993). In both studies the extent and pattern of crop water use was not affected by row spacing.

Another area of concern with the adoption of wider row spacing is fertilizer management. This study has shown that it is possible to side-band the entire fertilizer requirements of oat when seeded at wide row spacing. Applying all inorganic fertilizers at the time of seeding increases fertilizer use efficiency (Malhi et al., 2001).

Concerns were raised about wider row spacing and weed growth. The current thinking is that using wider row spacing will reduce ground shading and crop competition against weeds. Research in barley has shown that wild oat (*A. fatua* L.) seed production was not different between 20- and 30-cm row spacing (O'Donovan et al., 2001). Other work has shown that green foxtail (*Setaria viridis* L.) was reduced with no-till and that emerged weed seedlings of a large number of species in the spring were always less under no-till (O'Donovan and McAndrew, 2000). In another study, the effect of row spacing was inconsistent, and had little effect on Canada thistle shoot density or dry weight in a canola–barley rotation (O'Donovan et al., 2001). May et al. (2009) reported that greater seeding rates increase the competiveness of tame oat against wild oat. One can argue that when wide row spacing is combined with no-till, precision fertilizer placement (e.g., side-band), greater seeding rates and diversified cropping systems, factors such as reduced soil disturbance, presence of crop residues at the soil surface, use of in-crop herbicides, increased crop competition, and easy access to fertilizer nutrients by the crop all act together to reduce weed densities and competition against the growing crop. The concept of wider row spacing only makes the most sense if combined with no-till production systems. Together, they allow for the full benefits of tall stubble and surface crop residues to be expressed and provide for greater grain production.

CONCLUSIONS

The study investigated the possible interaction between row spacing and N fertilizer rates in oat. The results confirmed that wider row spacing up to 35 cm is feasible for oat production even when all the fertilizers are side-banded at seeding. The findings would also apply to other cereal crops. As row spacing increased, the number of coleoptilar tillers (T0) decreased. Row spacing did not influence the number of tillers in the first leaf axils of the main stem (T1), and increased tillers in the second leaf axils of the main stem (T2) indicating some inter-seedling competition. A 38 by 19 mm configuration between seed and fertilizer provided adequate safety in terms of crop establishment and nutrient uptake supporting the concept of side-banding inorganic fertilizer at wide row spacing. These results provide support to the opportunity of capturing the full benefits of tall stubble under no-till production systems by allowing greater ease of sowing between stubble rows.

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