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Canola growth, production and quality are influenced by seed size and seeding rate

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Canola (*Brassica napus* L.) is the most widespread profitable cash crop in Canada. In 2014 and 2015, direct-seeded experiments were conducted in sixteen western Canada environments.

“Small” canola seed (average 3.32 to 3.44 g 1000⁻¹) was compared to “large” canola seed (average 4.96 to 5.40 g 1000⁻¹) at five seeding rates (50, 75, 100, 125 or 150 seeds m⁻²). Large canola seeds increased crop density and crop biomass but decreased plant mortality, days to start of flowering, days to end of flowering, days to maturity and percent green seed. Seed size did not influence harvested seed weight, seed oil content or seed protein content. Increasing the seeding rate of small seeds improved canola yield, but the same response did not occur for large seeds. Increasing seeding rates also increased crop density, plant mortality, crop biomass and seed oil content but decreased days to start of flowering, days to end of flowering, days to maturity, percent green seed and seed protein content. Seeding rate had no impact on

harvested seed weights. Because higher seeding rates often provide some of the same benefits as large seed, canola growers and the seed industry should balance seed size and seeding rate to obtain the best agronomic performance from canola.

Key words: crop density, flowering period, input costs, integrated weed management, maturity, mortality, oil content, protein content, oilseed rape, yield

For Review Only

Canadian-grown canola generates one quarter of all Canadian farm cash receipts and contributes \$19.3 billion to the Canadian economy each year (CCC 2016a). The Canola Council of Canada aims to produce 26 million tonnes of canola by the year 2025 (CCC 2016b); current production averages just under 20 million tonnes. Canola production efficiency will need to be optimized to meet the new industry target.

High quality canola seed inputs are important to optimize yield. The only canola input more important than seed is nitrogen. The preeminent role of adequate nitrogen for high Canadian Prairie canola yields is evident in numerous studies (Blackshaw et al. 2011; Brandt et al. 2007; Cutforth et al. 2009; Harker et al. 2012b; Smith et al. 2010). In recent years, herbicide-resistant hybrids have played a major role in increased canola production (Harker et al. 2003; Morrison et al. 2016). High quality hybrid canola seed is relatively expensive and some growers lower their seeding rates in an attempt to minimize costs. Grower field surveys indicate that approximately half of all western Canada canola growers have crop densities < 40 plants m^{-2} ; optimal yields require a minimum of 40 plants m^{-2} (CCC 2013). The latter suggests that many growers may have sacrificed yield by reducing seeding rates too much, or production practices resulted in poor germination and seedling survival.

Previous studies on canola seeding rates and seed size suggest inconsistent results from both variables. For example, seeding rate influenced yield in some studies (Brandt et al. 2007; Hanson et al. 2008; Harker et al. 2012b) but not others (Harker et al. 2015; Kutcher et al. 2013). Similarly, while seed size did influence canola shoot biomass, days to flowering, days to end of flowering and 1000 seed weight (Harker et al. 2015), it did not influence canola density or yield (Clayton et al. 2009; Harker et al. 2015; Lamb and Johnson 2004). In contrast, using a range of

relatively small seed, Elliott et al. (2008) showed consistent increases in canola emergence and yield as seed size increased. It is clear that in addition to different environmental conditions in each study, results depended on the specific seed sizes and rates that were compared. In a recent study in Australia, Brill et al. (2016) observed a yield benefit from planting “larger” canola seed. Additional research with new canola hybrids in more environments would help to elucidate the influence of canola seed size and seeding rate on canola growth, production and quality.

A recently published 2013 study emphasized five canola seed size categories and two seeding rates (Harker et al. 2015). The current study emphasizes a wide range of seeding rates at only two different seed sizes. Given relatively high seed costs, growers often seed canola at rates that may compromise stand density, delay maturity, decrease yield and influence seed quality. The objective of this study was to compare small and large canola seeds from a single seed lot at five seeding rates to determine effects on crop emergence, growth, mortality, yield, seed size and quality in sixteen western Canadian environments in 2014 and 2015.

MATERIALS AND METHODS

Direct-seeded (no-till) experiments were conducted at sixteen western Canadian sites in Alberta, Saskatchewan and Manitoba in 2014 and 2015 (Table 1). All plots were established in fields previously sown to wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), or oat (*Avena sativa* L.). Prior to seeding, an application of glyphosate (900 g ae ha⁻¹) was applied to the entire plot area to control weeds. Soil samples were collected at each site before seeding and analyzed for available soil nutrients. On the basis of the soil analyses, fertilizer additions

were made to achieve 100% of the soil test recommendations for each site. Yield targets varied from 2800 to 3900 kg ha⁻¹ at different sites. Most fertilizer was side-banded 2 cm beside and 3- to 4-cm below the seed row with small amounts of nitrogen and phosphorus also placed in seed rows. At Scott, SK and Brandon, MB, most of the nitrogen fertilizer was applied in a mid-row band; at Saskatoon, SK, liquid 28-0-0 was applied when canola reached the two-leaf stage. Sulphur was broadcast at Brandon, MB. Canola was seeded at a target depth of 1- to 2-cm in 19- to 30-cm rows and in plots ranging from 2 by 6 m to 4 by 15 m on the dates specified in Table 1.

The experimental design was a randomized complete block design with four replications. A factorial arrangement of treatments (2x5) was imposed with two canola seed size treatments and five seeding rates (50, 75, 100, 125 or 150 seeds m⁻²). Commercial seed from the same genetic source (one seed-lot) was segregated into two size fractions using 1.79 mm screens. "Small" seed that passed through the screens averaged 3.32 and 3.44 g 1000 seeds⁻¹ in 2014 and 2015, respectively. "Large" seed that remained on the screens averaged 4.96 and 5.40 g 1000 seeds⁻¹ in 2014 and 2015, respectively. The seed was treated prior to seed size segregation. Preliminary germination tests indicated that germination exceeded 97% for all seed size classes. The canola cultivar planted was glyphosate-resistant '73-75' (Monsanto Canada Inc., Winnipeg, MB) at all 2014 and 2015 sites.

One or two in-crop applications of glyphosate at 450 g ae ha⁻¹ were applied as required to control weed populations. Fungicides and insecticides were applied as needed according to disease and pest insect infestations.

Data collection included crop emergence density (2 crop rows x 1 meter x 2 places), crop biomass at the 6-leaf stage (2 rows x 1 meter x 2 places), days to start and end of flowering, days to maturity, canola yield, and productive plant stubble density (same method and area as crop density). Environmental data for each site was retrieved from nearby weather stations. At the appropriate time, plots were either swathed or straight-combined with or without desiccation. Excessive mid-season flooding compromised the Saskatoon site in 2015 (Table 2). Therefore, of the eight 2014 and eight 2015 sites, fifteen were considered suitable for data analyses and presentation. Canola seed was cleaned, weighed and corrected for percent moisture (8.5%). Thousand seed weights, % green seed and seed oil and seed protein content are presented based on an 8.5% moisture adjustment. Percent green seed was determined by crushing three samples of 100 canola seeds from each harvested plot and visually determining distinctly green seed numbers. Canola seed oil and protein contents (8.5% moisture basis) were determined using a near infrared reflectance spectrometer (Foss Model 6500, FOSS NIRSystems Inc., Silver Spring, MD, USA).

Statistical Analyses

Data were initially subjected to the UNIVARIATE procedure in SAS (SAS Institute Inc., Cary, NC) to detect and remove data outliers. All data were then subjected to the MIXED procedure in SAS to determine the significance of seed size and seeding rate main effects and their interaction. Linear and quadratic contrasts for the five equally-spaced seeding rate treatments were included in the MIXED procedure to detect significant regressions for all dependent variables. Statistical significance was declared at $P < 0.05$.

Replications, environments (year-site combinations) and all environment by treatment interactions were treated as random effects. Seed size and seeding rate were treated as fixed effects. In agronomic experiments with limited replication, Type II errors (acceptance of the null hypothesis when it is false) are more common than Type I errors (rejection of the null hypothesis when it is true) (Carmer and Walker 1988). By treating fifteen environments as random effects we increased the likelihood of making appropriate inferences at untested locations (Yang et al. 2010) and also increased “replications” to enable us to detect differences that were not apparent when analyzing individual environments.

We also examined seed size and seeding rate effects at individual sites (*i.e.* we also treated environments as fixed effects). We used environment and environment by treatment variance estimates (from PROC MIXED) to determine the relative size of environment by treatment interactions. When the environment by treatment interaction variance was at least 10% of the total environment plus the environment by treatment interaction variance (Table 3), we compared and discussed treatment effects at individual sites to treatment effects across sites. Regardless of the relative size of environment by treatment interaction, the number of environments with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses compared to overall responses are shown in data figures for each dependent variable. For most dependent variables, the relevance of some of these environments without relatively large environment by treatment interactions were also briefly discussed.

RESULTS AND DISCUSSION

Weather Patterns

Weather patterns were generally normal at most environments with some notable exceptions (Table 2). In 2014, Brandon was wetter than normal in May and June, while just the opposite occurred in 2015. Substantially more than normal precipitation was experienced in April at Saskatoon in 2014, in June at Melfort in 2014 and in July at Scott in 2014. Substantially less than normal precipitation was experienced in July at Beaverlodge in 2015 and Carman in 2014 as well as in August at Beaverlodge in 2014 and Fahler in 2014. In 2015, the extra 77 mm of precipitation in Saskatoon during July and August flooded the plots and compromised the experiment; therefore, agronomic data from that environment was not reported.

April temperatures were more than 4 °C lower than normal at Brandon, Melfort and Saskatoon in 2014, and more than 4 °C higher than normal at Melfort in 2015. Fahler also experienced higher than normal temperatures in July and August in 2014. Average canola yields at Fahler in 2014 (2217 kg ha⁻¹) were lower than in 2015 (2484 kg ha⁻¹), but the difference did not suggest substantial high temperature-related yield reduction in 2014. In all environments, average temperatures were generally favourable for canola growth, development and yield.

Crop Density

Larger seed resulted in greater canola densities than small seed (Tables 3 and 4). This effect confirms some studies (Brill et al. 2016; Elliott et al. 2008), but contrasts others (Clayton et al. 2009; Harker et al. 2015; Lamb and Johnson 2004). Average canola emergence rates were 48%

and 59% for small and large seed, respectively. These canola emergence rates compare well with previous research (Harker et al. 2003, 2012a, 2015).

A significant seed size by seeding rate interaction revealed that seeding rate increases led to slightly greater canola densities with large versus small seed (Fig. 1). The interaction was also significant at three individual environments. Given current trends for increased seed size, and the fact that canola seed costs are based on weight rather than seed number, it is useful to know that larger seed can lead to higher canola densities than small seed. As expected, canola density at all fifteen sites had a positive linear relationship with seeding rate.

The relatively large environment by seeding rate interaction (11.5%, Table 3) was due to large variations in canola density among environments. For example, at Brandon canola density at the 50 seeds m^{-2} rate was 37 plants m^{-2} in 2014, but was only 21 plants m^{-2} in 2015. Relatively high spring precipitation in 2014 (153 mm more than average) contrasted with very low spring precipitation in 2015 (120 mm less than average) (Brandon, Table 2). Somewhat less dramatic differences in canola density and weather patterns were apparent in other contrasting environments.

Plant Mortality

From seedling emergence until crop maturity, canola density declined by 19% for small seeds and 16% for large seeds (Tables 3 and 4). As mentioned above, this is useful information given the fact that canola seed is sold on a weight basis. Harker et al. (2015) found slightly less productive plant mortality (8 to 10%). As seeding rate increased, there was a linear increase in plant mortality (Fig. 2). Canola plant mortality was also found to be greater when subjected to

greater intra-species competition at higher seeding densities (Yang et al. 2014) or in wider versus narrower row spacings (Christensen and Drabble 1984). Plant mortality rates are likely to be greatly influenced by growing season conditions in specific environments.

Six individual environments had a linear mortality response to seeding rate (Fig. 2). There was a quadratic response at one environment (Fahler 2014) where plant mortality was greatest at 100 seeds m⁻² (data not shown); we have no explanation for such a response. In the one environment where seeding rate interacted with seed size (Lacombe 2015), large seeds led to greater mortality at high seeding rates while there was no linear mortality response to seeding rate for small seeds (data not shown). A similar seed size effect was observed in subterranean clover (*Trifolium subterraneum* L.) (Black 1958). Harper (1977) suggests that the latter effect occurred because the more vigorous seedlings that arose from larger seeds caused greater density stress due to intra-species competition, and therefore experienced greater plant mortality.

Shoot Biomass

Canola shoot biomass at the 6-leaf stage from large seeds was 28% greater than from small seeds (Tables 3 and 4). This result supports other research (Brill et al. 2016; Elliott et al. 2008; Harker et al. 2015). Greater canola shoot biomass enhances crop competition with weeds (Zand and Beckie 2002) and reduces compensatory branching (Angadi et al. 2003; McGregor 1987), which could improve canola quality in environments subjected to early fall frosts by reducing chlorophyll content in seed.

Canola shoot biomass increased linearly with seeding rate (Fig. 3). Twelve environments responded linearly; one of those (Fahler 2015) also responded quadratically with biomass peaking at 125 seeds m⁻² (data not shown). Therefore, (with the exception of Fahler 2015), at the seeding rates employed in this experiment, intraspecific competition among canola plants was not strong enough to restrict early season (6-leaf stage) biomass as seeding rate increased. For the four environments with a seed size by seeding rate interaction, crop biomass usually increased more rapidly for large versus small seeds as seeding rate increased (data not shown). Whether greater crop biomass is achieved with large seeds or higher seeding rates, integrated weed management systems are facilitated by increased crop competition with weeds (Blackshaw et al. 2008); in such systems, herbicide resistance to weeds can be reduced or delayed (O'Donovan et al. 2007).

Flowering and Maturity

Large seed decreased the time from seeding to the start and end of flowering by 1 day and the time to maturity by 2 days compared to small seeds (Tables 3 and 4). Furthermore, as seeding rate increased, the time from seeding to the start and end of flowering and the time to maturity decreased linearly (Figs. 4 to 6). In western Canada, decreasing the time to start and end of flowering without decreasing flowering time, and decreasing days to maturity is advantageous for optimum canola yields because the likelihood of experiencing hot and dry conditions decreases as flowering and maturity are hastened (Harker et al. 2011, 2012b; Kutcher et al. 2010; Nuttall et al. 1992; Polowick and Sawhney 1988; Young et al. 2004).

Quadratic responses to seeding rate on days to maturity were significant in two environments (Fig. 6). In those environments (Lacombe 2015 and Melfort 2014), decreases in flowering times and days to maturity were less at higher seeding rates (data not shown). The greatest impacts for improved canola production were found when the lowest seeding rates were increased from the lowest level. For each of the dependent flowering or maturity variables (Figs. 4 to 6), one of 15 environments had a significant seed size by seeding rate interaction; no consistent effects were apparent in these interactions. .

Seed Yield

While large seed tended to result in greater yield than small seed at all locations, the differences were not significant ($P = 0.0861$, Table 3). However, the seeding rate by seed size interaction was significant ($P = 0.0229$). For large seed, yield did not increase as seeding rate increased ($P = 0.1715$), whereas for small seed, yield increased ($P = 0.0002$) with seeding rate (Fig 7). Yield benefits from planting “larger” canola seed have been observed in previous studies (Brill et al. 2016; Elliott et al. 2008). In the current study, most of the yield response to higher seeding rates of small seed occurred from the 50 to the 75 seeds m^{-2} rate. Indeed, even for small seeds, there was no linear yield response to seeding rate when the 50 ($P = 0.1037$) or the 50 and 75 ($P = 0.3632$) seeds m^{-2} rates were not included in the regression contrasts. At the lowest seeding rate (50 seeds m^{-2}), it was rather striking that average yields were 197 kg ha^{-1} greater (8%) for large versus small seed. The two environments with quadratic responses confirmed greater yield responses to seeding rate from the 50 to the 75 seeds m^{-2} rate compared to higher seeding rates (data not shown). As noted above, because canola seed is

sold on a weight basis, it is useful to know that yield responses to increasing seeding rates of small seeds are greater than those from larger seed.

Ten of 15 sites did not result in a significant yield response to seeding rate (Fig. 7). This confirmed some research (Harker et al. 2015; Kutcher et al. 2013), but contradicted other research (Brandt et al. 2007; Hanson et al. 2008; Harker et al. 2012b). Gan et al. (2016) reported that canola seed yield increased with increased plant density in 12 of 16 site-years. Rather than being a contradiction, the yield response or the lack of a response to seeding rates appeared to depend not only on environment, but on which seeding rates or plant densities were being compared. Relatively low seeding rates were more likely to show yield responses to increased seeding rates than were relatively high seeding rates. Planting small versus large seeds at 50 seeds m^{-2} led to 23 versus 31 plants m^{-2} , respectively (Fig. 1). Given the fact that optimal yields in western Canada usually come from canola stands with at least 40 plants m^{-2} (CCC 2013), seeding rate effects on yield found in this study were probable.

In Australia, Zhang and Flottmann (2016) showed that higher canola biomass explained higher canola yield. In the current study, early canola biomass from large seed was 28% higher than the biomass from smaller seeds across all seeding rates (Table 4), and although early-season crop biomass increased linearly with seeding rate for both seed sizes (Fig. 3), there was only a corresponding yield response to greater seeding rates for small seeds. In this study, biomass was collected earlier in the growing season and the canola grew in a relatively short summer season compared to a longer winter growing period in Australia. Comparisons between the two growing regions and seasons are not always valid.

1000 Seed Weights

Across environments, neither seed size nor seeding rate influenced canola seed weight (Tables 3 and 4, Fig. 8). In contrast, using a wider range of seed sizes and only two seed rates, Harker et al. (2015) reported that increased seed size and increased seeding rate led to greater canola seed weights. Planted seed size did not influence harvested seed weights in other studies (Clayton et al. 2009; Lamb and Johnson 2004).

Although eight environments had results similar to the across environment means, five environments demonstrated a linear increase in seed weight as seeding rates increased (Fig. 8). The two environments with a significant but different response (Diff) (Lacombe 2015, Melfort 2015) demonstrated a linear decrease in seed weight as seeding rates increased. From an intra-specific competition point of view, it seems reasonable to observe a decrease in harvested seed size as crop density and intra-specific competition increased with increasing seeding rate. In the current study, the latter effect was the exception rather than the rule.

Percent Green Seed

Percent green seed was lower when large versus small seeds were planted (Tables 3 and 4) and when seeding rate increased (Fig. 9). The linear decrease in green seed with increased seeding rate was only significant at three environments, but the additional statistical power gained by treating environments as a random effect prevented a Type II error (failing to detect a seed size or seeding rate effect). Across all sites, there was also a weak trend for a quadratic green seed response to seeding rate ($P = 0.0952$). A similar study across nine environments failed to detect a seed size or seeding rate effect on green seed (Harker et al. 2015). In contrast, in another

study, doubling the seeding rate from 75 to 150 seeds m^{-2} decreased green seed percentage (Harker et al. 2013). In the one environment with a seed size by seeding rate interaction (Melfort 2015), there was a linear decrease ($P = 0.0026$) in green seed with increased seeding rate for small seed and no linear effect ($P = 0.6261$) for large seed where all values were close to zero (data not shown).

From a grower and seed industry standpoint, it is important to understand that larger seeds may help to reduce green seed content since larger seeds are more expensive to purchase on a per seed basis. However, purchasing more seed for higher seeding rate is also more costly. Therefore, growers and the seed industry will do well to balance seed size and seed rate considerations and consequences.

Seed Oil and Protein Content

There were trends for seed size to influence oil ($P = 0.0610$) and protein content ($P = 0.0747$) (Table 3). A quadratic oil content response to seeding rate illustrated that most gains in oil content occurred before the seeding rate reached 100 seeds m^{-2} (Fig. 10). Linear increases in oil content with increasing seeding rate occurred in five environments. Increased oil content with increased seeding rate confirms some research (Brandt et al. 2007; Harker et al. 2012b), but contradicts other research (Harker et al. 2015). In the environment with a significant but different response (Fahler 2015), the quadratic effect as seeding rates increased revealed a peak in oil content at the 100 seeds m^{-2} seeding rate.

Protein decreased linearly as seeding rate increased (Fig. 11). There was a trend ($P = 0.0743$) for a quadratic response indicating more rapid decreasing in protein content from 50 to

75 seeds m⁻² seeding rates than for other intervals. As expected, protein content was inversely related to seed oil content.

CONCLUSIONS

Large canola seeds increased crop density and crop biomass and decreased plant mortality, days to start of flowering, days to end of flowering, days to maturity and percent green seed. Seed size did not influence harvested seed weight, seed oil content or seed protein content. Increasing the seeding rate of small seeds improved canola yield, but the same response did not occur for large seeds. Increasing seeding rates also increased crop density, plant mortality, crop biomass and seed oil content and decreased days to start of flowering, days to end of flowering, days to maturity, percent green seed and seed protein content. Seeding rate had no impact on harvested seed weights.

Given current trends for increased seed size, and the fact that canola seed costs are based on weight rather than seed number, it is useful to know that large versus small seed increases crop density and decreases plant mortality, days to flowering, days to end of flowering and days to maturity. In western Canada, earlier flowering and maturity are advantageous for optimum canola yields because high temperature yield reductions are less likely earlier in the growing season. Larger seed also increased shoot biomass which favours crop competition with weeds and less reliance on herbicides. Furthermore, planting large seed led to lower levels of green seed than small seed, and therefore creates opportunities for higher canola grades and profits. Higher seeding rates often provide some of the same benefits as large seed. Because yield responses to increasing seeding rates of small seeds are greater

than those from larger seed, canola growers and the seed industry will do well to balance seed size and seeding rate considerations and consequences.

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Table 1. Site, plot, and seeding details at 2014 and 2015 experiment sites.

Site	GPS Coordinates	Plot size (m)	Seeding date		Seeder	Opener	Row spacing
			2014	2015			(cm)
Beaverlodge, AB	55.2° N, 119.4° W	4 x 15	May 12	May 13	Conserva Pak air	1 cm knife	23
Brandon, MB	50.0° N, 99.9° W	2 x 8	May 28	May 20	Versatile zero till	1 cm knife	20
Carman, MB	49.5° N, 98.0° W	5 x 8	May 15	May 20	Double disc	Notched disc	19
Falher, AB	55.7° N, 117.2° W	2 x 6	May 23	May 18	Fabro cone	1.6 cm knife	28
Lacombe, AB	52.5° N, 113.7° W	4 x 15	May 9	May 9	Conserva Pak air	1 cm knife	30
Melfort, SK	52.8° N, 104.6° W	4 x 10	May 22	May 19	Edwards hoe air drill	1 cm knife	20
Saskatoon, SK	52.1° N, 106.3° W	2 x 6	May 23	May 14	Fabro cone	disc	20
Scott, SK	52.4° N, 108.8° W	2 x 10	May 14	May 13	R-Tech cone	1 cm knife	25

Table 2. Growing season precipitation and temperature deviance^a at 16 experiment environments.

Environment	Average precipitation deviance (mm)						Average temperature deviance (°C)					
	Apr	May	Jun	Jul	Aug	Sep	Apr	May	Jun	Jul	Aug	Sep
Beaverlodge 2014	18	-38	-5	7	<u>-55</u>	-5	-0.7	-0.1	-0.3	-0.2	-0.2	-0.1
Beaverlodge 2015	8	-19	29	<u>-50</u>	-8	-14	1.7	1.8	1.1	0.6	-0.2	-1.1
Brandon 2014	26	<u>62</u>	<u>65</u>	-39	6	5	<u>-4.9</u>	-0.5	-0.7	-1.2	-0.3	-0.8
Brandon 2015	-15	<u>-52</u>	<u>-53</u>	-2	10	-16	-0.7	<u>-2.2</u>	0.1	0.1	-0.3	<u>2.1</u>
Carman 2014	-17	-39	20	<u>-51</u>	48	-3	-0.9	-0.4	-0.6	-1.8	0.1	-0.4
Carman 2015	-12	29	-21	31	-28	-7	1.0	-0.9	0.3	0.5	-0.2	<u>2.4</u>
Fahler 2014	6	-21	-17	-40	<u>-54</u>	-1	-1.1	-0.9	0.4	<u>2.2</u>	<u>2.2</u>	0.4
Fahler 2015	9	-20	-41	16	-8	-2	<u>2.3</u>	<u>2.4</u>	1.9	0.8	0.4	-0.5
Lacombe 2014	1	-4	-7	-13	-37	-1	-1.0	-0.7	-0.1	1.4	1.5	0.6
Lacombe 2015	-16	-25	-2	39	-9	16	1.3	-0.1	1.5	0.9	0.8	-0.3
Melfort 2014	24	-16	<u>104</u>	-28	6	-33	<u>-5.7</u>	<u>3.2</u>	<u>-2.6</u>	-0.5	0.1	<u>3.3</u>
Melfort 2015	8	-33	-9	-26	6	22	<u>4.5</u>	0.9	1.6	0.0	0.6	1.9
Saskatoon 2014	<u>64</u>	39	40	12	-22	-24	<u>-4.6</u>	<u>-2.2</u>	-1.7	-0.9	0.1	0.3
Saskatoon 2015	-6	-24	-43	40	37	15	-0.2	-1.7	1.0	0.3	-0.9	0.0
Scott 2014	19	-13	-1	<u>56</u>	-16	-12	-1.5	-1.6	-1.5	0.3	0.1	0.8
Scott 2015	-7	-32	-42	-26	29	14	<u>2.0</u>	-1.5	0.8	1.0	0.3	0.5

^aDeviance is based on comparisons to long-term averages (30 yr, usually 1981-2010) for each month in each environment. Precipitation deviations ≥ 50 mm and temperature deviances ≥ 2 °C are underlined.

Table 3. Dependent variable seed size (S) and seed rate (R) main effect and S by R interaction P-values, environment (E), E by S and E by R variance estimates (from PROC MIXED) and the relative size of E by S and E by R interactions.

Dependent variable	P-values ^a			Variance estimates				
	S	R	S x R	E	E x S	E x R	% E x S ^b	% E x R ^b
Crop density (# m ⁻²)	<u><.0001</u>	<u><.0001</u>	<u>0.0207</u>	319.6	3.8	41.6	1.2	<u>11.5</u>
Plant mortality (%)	<u>0.0300</u>	<u><.0001</u>	0.2326	120.1	1.8	4.7	1.5	3.8
Crop biomass (kg ha ⁻¹)	<u><.0001</u>	<u><.0001</u>	0.2923	564164	3121	0	0.6	0.0
Start of flowering (d) ^c	<u>0.0034</u>	<u><.0001</u>	0.5138	28.2	0.5	0.1	1.7	0.4
End of flowering (d) ^c	<u>0.0004</u>	<u><.0001</u>	0.4387	57.1	0.2	0.1	0.3	0.2
Maturity (d) ^c	<u>0.0059</u>	<u><.0001</u>	0.0706	101.4	1.4	0.7	1.4	0.7
Yield (kg ha ⁻¹)	0.0861	<u>0.0101</u>	<u>0.0229</u>	482924	7020	11410	1.4	2.3
1000 seed weight (g)	0.1399	0.1968	0.4809	0.281	0.002	0.003	0.7	1.1
Green seed (%)	<u>0.0355</u>	<u>0.0172</u>	0.2637	5.76	0.28	0.2	4.6	3.4
Seed oil content (%)	0.0610	<u>0.0106</u>	0.8381	3.56	0.02	0.04	0.6	1.1
Seed protein content (%)	0.0747	0.1036	0.7083	4.900	0.005	0.042	0.1	0.8

^aUnderlined P-values for treatment effects are statistically significant (P < 0.05).

^bEnvironment (E) by seed size (S) interaction variance as a percent of the total E plus the E by S variance or E by seed rate (R) interaction variance as a percent of the total E plus the E by R variance. The underlined value is for an interaction percentage ≥ 10%.

^cDays after seeding.

Table 4. Dependent variable seed size^a main effect means.

Dependent variable	Small seed	Large seed ^b
Crop density (# m ⁻²)	48	<u>59</u>
Plant mortality (%)	19	<u>16</u>
Crop biomass (kg ha ⁻¹)	669	<u>855</u>
Start of flowering (d) ^c	48	<u>47</u>
End of flowering (d) ^c	65	<u>64</u>
Maturity (d) ^c	105	<u>103</u>
Yield (kg ha ⁻¹)	2498	2566
1000 seed weight (g)	3.72	3.75
Green seed (%)	2.1	<u>1.6</u>
Seed oil content (%)	45.6	45.8
Seed protein content (%)	21.4	21.3

^a“Small” seed averaged 3.32 and 3.44 g 1000 seeds⁻¹ in 2014 and 2015, respectively. “Large” seed averaged 4.96 and 5.40 g 1000 seeds⁻¹ in 2014 and 2015, respectively.

^bUnderlined large seed means are statistically different from small seed means ($P < 0.05$).

^cDays after seeding.

Fig. 1. The effect of canola seeding rate on canola density. Means are averaged over fifteen 2014 and 2015 site-years (environments). “Small” seed averaged 3.32 to 3.44 g 1000 seeds⁻¹ and “Large” seed averaged 4.96 to 5.40 g 1000 seeds⁻¹. The seed size by seeding rate interaction was significant across environments ($P = 0.0207$); the interaction was also significant at three of fifteen environments. At the latter environments, linear effects were significant for small and large seeds, but as in Figure 1, increasing the seeding rate of large seeds increased plant density more than the same seeding rate increases for small seed. For the linear equations “x” = seeding rate. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.

Fig. 2. The effect of canola seeding rate on canola plant mortality (from plant emergence until canola harvest). Means are averaged over fourteen 2014 and 2015 site-years (environments) and two seed sizes. A seed size by seeding rate interaction was significant at one of fourteen environments. For the linear equation “x” = seeding rate. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.

Fig. 3. The effect of canola seeding rate on canola plant biomass at the 6-leaf stage. Means are averaged over fifteen 2014 and 2015 site-years (environments) and two seed sizes. A seed size by seeding rate interaction was significant at four of fifteen environments. No consistent data patterns were apparent at the latter environments. For the linear equation “x” = seeding rate. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.

Fig. 4. The effect of canola seeding rate on days from seeding to start of canola flowering. Means are averaged over fifteen 2014 and 2015 site-years (environments) and two seed sizes. A seed size by seeding rate interaction was significant at one of fifteen environments. For the linear equation “x” = seeding rate. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.

Fig. 5. The effect of canola seeding rate on days from seeding to the end of canola flowering. Means are averaged over fifteen 2014 and 2015 site-years (environments) and two seed sizes. A seed size by seeding rate interaction was significant at one of fifteen environments. For the linear equation “x” = seeding rate. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.

Fig. 6. The effect of canola seeding rate on days from seeding to canola maturity. Means are averaged over fifteen 2014 and 2015 site-years (environments) and two seed sizes. A seed size by seeding rate interaction was significant at one of fifteen environments. For the linear equation “x” = seeding rate. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.

Fig. 7. The effect of canola seeding rate on canola seed yield. Means are averaged over fifteen 2014 and 2015 site-years (environments) and two seed sizes. “Small” seed averaged 3.32 to 3.44 g 1000 seeds⁻¹ and “Large” seed averaged 4.96 to 5.40 g 1000 seeds⁻¹. The seed size by seeding rate interaction was significant across environments ($P = 0.0229$); the interaction was also significant at three of fifteen environments. No consistent data patterns were apparent at the latter environments. For the linear equation “x” = seeding rate. The linear contrast was only significant for small seed. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.

Fig. 8. The effect of canola seeding rate on canola 1000 seed weights. Means are averaged over fifteen 2014 and 2015 site-years (environments) and two seed sizes. A seed size by seeding rate interaction was significant at one of fifteen environments. Across environments, neither linear nor quadratic contrasts were significant. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.

Fig. 9. The effect of canola seeding rate on percent green canola seed. Means are averaged over fifteen 2014 and 2015 site-years (environments) and two seed sizes. A seed size by seeding rate interaction was significant at one of fifteen environments. For the linear equation “x” = seeding rate. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.

Fig. 10. The effect of canola seeding rate on percent oil content in canola seed. Means are averaged over fifteen 2014 and 2015 site-years (environments) and two seed sizes. None of fifteen environments had a significant seed size by seeding rate interaction. For the quadratic equation “x” = seeding rate. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.

Fig. 11. The effect of canola seeding rate on percent protein content in canola seed. Means are averaged over fifteen 2014 and 2015 site-years (environments) and two seed sizes. A seed size by seeding rate interaction was significant at one of fifteen environments. For the linear equation “x” = seeding rate. In the black- and gray-shaded site compliance box, the # of sites with similar linear (L), quadratic (Q), nonsignificant (NS) or significant but different (Diff) seeding rate responses are indicated.