PROJECT DETAILS

- **Title**: Reducing toxicity of seed-placed phosphorus fertilizer in canola
- **Funders:** Alberta Canola and SaskCanola
- **Research program:** Canola Agronomic Research Program
- **Principal investigator:** Patrick Mooleki
- **Collaborators/additional investigators:** Manjula Bandara, Jeff Schoenau, Alick Mulenga, Kim Stonehouse, Brett Mollison, Brian Beres
- **Year completed:** 2021

Final report

Introduction

Phosphorus (P) recommendations range from 30 to 50 lb P_2O_5 ac^{-1} (33.6 to 56.0 kg ha^{-1}) for most crops. However, with the exception of cereals, these rates are too toxic and can cause damage to seed and seedlings if placed with the seed at the time of seeding. The option is to sideband or mid-row band high rates of P. Unfortunately, many producers do not have these options and use openers which place the seed and the fertilizer in the same space or near each other. Current maximum safe rate of seed-placed P recommendations are based only on one configuration (1" opener and 9" row spacing. Secondly, the recommendations are also based on having reached the maximum safe rate of seed-placed urea and Sulphur fertilizers. At this configuration, the safe rates of seed-placed P (in lb P_2O_5/ac) for canola (*Brassica napus* L.) are 15, 20 and 25 for Alberta, Manitoba and Saskatchewan, respectively. However, these rates are not adequate to meet P requirements of canola. As a result, one of the most frequently asked questions from producers and crop advisors, is: how much P fertilizer can they apply with the seed if they are using a wider (2", 3" or 4") opener? Hence, the objectives of this project were to determine the maximum safe rate of seed-placed P fertilizer with different opener widths and row spacing, and to develop guidelines for producers and crop advisors to use.

Methodology

Experimental design and plot layout
We conducted a two-year field study at five locations: Saskatoon, Melfort and Scott in Saskatchewan, and Brooks and Lethbridge in Alberta. The study was conducted as a three-way factorial design with the following treatments: Row Spacing (RS) at 9" and 12"; Opener Width (OW) at 1", 2" & 4"; and phosphorus rate (PR) at 20, 35, 50 and 65 lb P_2O_5 ac^{-1} (22.4, 39.2, 56.0 and 72.8 kg ha^{-1}). The 24 treatment combinations were arranged in a randomized complete block design (RCBD) with four replications at each location. The study conducted over two cropping years (2018 and 2019) at the same locations, but in different fields.

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Seeding and fertilizer application,

Treatment application was performed using a custom-built drill fitted with Morris Contour 1 shanks and rollers and Dutch Universal openers with the flexibility of changing opener width and type as well as row spacing easily (Figs. 1 and 2).

Dutch Universal openers with 1", 2" and 4" widths were used to place the seed at 6 lb ac^{-1} (6.7 kg ha^{-1}) and the P fertilizer [monoammonium phosphate (11-52-0)] at the appropriate rate for each treatment. The fertilizer and seed hoppers of the plot drill were fitted with Valmar metering components that allowed the operator to change rates easily. In 2018 plot size was 3 m x 10 m. In 2019, plot size used was 1.2 m x 15 m. The change in plot size is explained below.

Fig. 1. Custom-made plot drill used to apply all treatments and seeding at all locations.

In Year 1 (2018) a blend of urea (46-0-0) and ammonium sulphate (21-0-0-24) was banded to a depth of three inches (7.5 cm) at a rate of 140 lb N ac^{-1} (156.8 kg N ha^{-1}) and 20 lb S ac^{-1} (22.4 kg S ha^{-1}) using 1" knife openers on the plot drill, running from one end of the rep to the other end, perpendicular to the length of the plots. It was observed that the perpendicular pre-banding of fertilizer caused significant track compaction in the plots, creating uneven seeding and seedling emergence. To avoid this problem, changes were made in 2019, whereby the plot width was reduced to 1.2 m so that the entire plot width fitted between the tire tracks. Single disk openers were fitted on the front bar of the plot drill as mid-row openers. Hence, the blend of urea and ammonium sulphate was banded to a depth of 3.0 " (7.5 cm) at a rate of 140 lb N ac^{-1} (156.8 kg N ha^{-1}) and 20 lb S ac^{-1} (22.4 kg S ha^{-1}) and mid-row-banded during the seeding operation. Only the P fertilizer at the treatment rate was seed-placed.

Fig. 2. Dutch Universal openers used in the study and how they are changed.

In Year 1 (2018), a treatment with 0 kg P_2O_5 ac^{-1} was not included. Hence, in Year 1, a factorial combination of the three factors was used: row spacing (RS) at 9" and 12"; opener width (OW) at 1", 2" and 4"; and P rate (PR) at 20, 35, 50 and 65 lb P_2O_5 ac^{-1}, resulting in 24 plots per replicate. In Year 2 (2019), a treatment with 0 kg P_2O_5 ha^{-1} was included, making the total number of treatments 30. In both cases, the treatment combinations were

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arranged in a randomized complete block design (RCBD) with four replications at each location. Randomization was different at each location. The application of the treatments involved adjusting row spacing to either 9" or 12" setting on the tool bar. This was followed by placing 1" openers on the shanks and adjusting the fertilizer hopper containing MAP to the desired rate. The setting of the three factors at each level represented a treatment. Once set, the treatment was applied to all four reps. After the fourth rep, the drill returned to the first rep for the next P rate. Once all the P rates were done on the same setting of row spacing and opener width, the openers were changed to the next, with row spacing remaining the same. After seeding all the 9" row spacing treatments, seeding of the 12" row spacing treatments was done in the same manner. To ensure that there was no clogging of tubes, the seed and fertilizer distribution system was checked at the start of each P rate treatment application, ensuring that fertilizer and seed were flowing smoothly.

General crop husbandry

Except for the treatments described above, all the other agronomic and crop management (weed, insect and disease control) practices were carried out as needed at each location. Fall rye or winter wheat was seeded in the pathways and surrounding areas to protect the soil from erosion, and mowed to keep weeds down.

Soil sampling

Prior to seeding, soil samples were taken at 0-15, 15-30 and 30-60 cm soil depths to background soil characteristics at the selected locations. Soil samples were taken every 20 m along the length of each replication to determine within and among replicate variation, which could interfere with treatment effects. Consequently, 16 soil cores were taken in the spring at each location. The soil samples for each depth were placed into separate plastic bags and tightly secured for shipping and handling.

Data collection

Plots were examined four days after seeding to evaluate germination and assess toxicity damage by looking at the health of the emerging seedlings both above and below the soil surface. This process was repeated at three- to four- day intervals to ensure that no toxicity damage was missed. However, no visual toxicity damage was convincingly observed in both 2018 and 2019. In both seasons, the field conditions at and following seeding were very dry resulting in an uneven germination and emergence. Therefore, toxicity due to seed-placed fertilizer was measured only by counting the number of seedlings that survived and emerged in each treatment. This was captured at 14, 21 and 28 days after seeding (DAS), at which times plant population density were estimated using randomly selected three quadrats in each plot. In 2019, to assess changes in plant counts caused by the staggered germination, plastic markers were placed in one reference corner of each quadrant. These quadrants were placed in the inner part of each plot that would be included at harvest time (Figure 3).

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Other measurements included, days to first flower, days to full bloom, days to physiological maturity and plant height. Two 1-m^2 quadrants of aboveground biomass were taken from each plot prior to start of senesces to determine aboveground biomass yield.

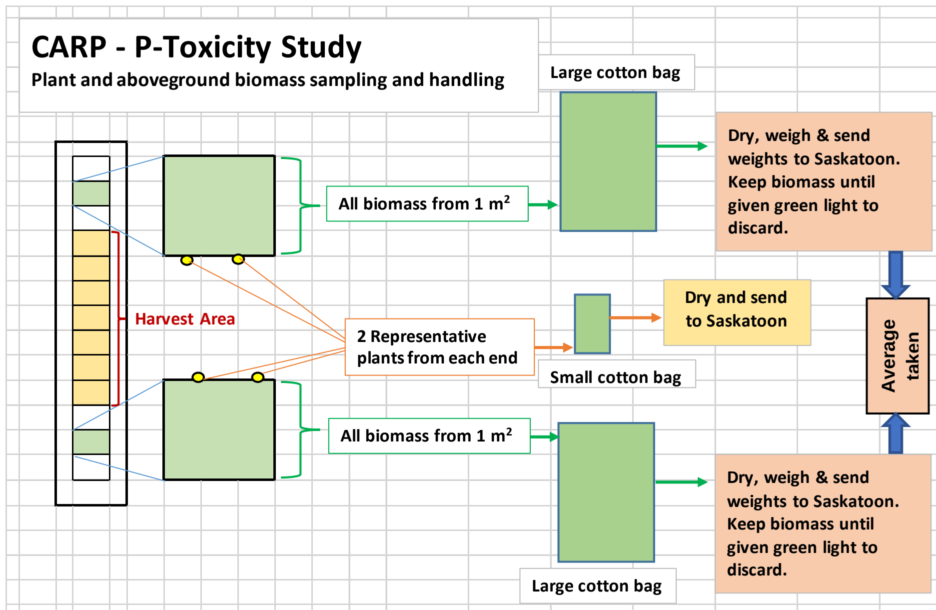

Fig. 3. Plot area designation for plant and biomass sampling and handling procedure. Harvest area designates where plant counts at all dates, plant height and grain yield would be taken at the designated times.

Due to different plot sizes, aboveground biomass was sampled differently in the two seasons. In 2018 when plot size was 3 m x 10 m, there was enough width such that the biomass was taken on one side of the plot while grain yield was taken from the other side of the plot. In 2019, plot size was changed to 1.2 m x 15 m with no sufficient room on the sides, aboveground biomass was taken from both ends of the plots, 1 m inside to avoid border effect as shown in Fig 3. These aboveground biomass sampling points were taken away from the area where grain yield would be taken, thus allowing a minimum of 9 m of plot length for grain harvesting. In addition, two representative plants were take on the inner side of each quadrant for further processing to determine nutrient (P) concentration in the aboveground biomass. This was not done in 2018.

At physiological maturity, the canola was desiccated using Reglone®, and when the crop was dry, it was straight cut using a plot combine. The canola seed was further dried, cleaned and weighed for the determination of grain yield, adjusted to grain moisture content. The final number of plants m^{-2} was determined by taking counts of stubble stocks of canola in three 1 m^2 quadrants along the combined path in each plot as guided by the plastic markers placed at 14 DAS. Grain quality parameters were determined, which included green seed content, protein content, oil content, test weight and TKW.

The M.Sc. level thesis training component of this project was initiated with the recruitment of Mingxuan Shao in Year 1 and the title of his thesis was '<u>Effect of seed row spread, row spacing, and fertilizer form on phosphorus uptake and recovery by canola (*B. napus*)</u>'. This post-graduate training component included data collections from the field studies and also a controlled environment study. The student's work has been completed and his thesis is appended to this final report as Appendix 2. Phosphorus uptake determined from the field study formed part of the MSc student's thesis.

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Statistical design and analysis

Statistical analysis was conducted on data collected using a mixed model for each year and for the two years combined. Replication was considered as a random factor. Because there were five sites in different ecological zones; site was considered a fixed factor. As well, year was considered a fixed factor as there were only two years of data.

Results

Climatic conditions:

In 2018, the soil moisture conditions at the time of seeding were satisfactory at normal seeding depth at all locations. However, due to lack of precipitation for two weeks following seeding, top soil dried rapidly leaving some seeds stranded near the soil surface. In 2019, except at Lethbridge, the soil moisture conditions were not sufficient at normal seeding depth at all locations at seeding time. However, due to lack of precipitation for two to three weeks following seeding, top soil dried rapidly leaving some seeds stranded near the soil surface. At Saskatoon, there was a delay in setting up the supplemental irrigation. Very little germination occurred until the plots were irrigated 10 days later. But once this was done, germination was good. Occasional supplemental irrigation kept the crop from moisture stress, resulting in good crop growth. The crop was irrigated four times during the season for a total of 40 mm. At Melfort, soil moisture was very low at the time of seeding and remained dry due to lack of precipitation for a while. No irrigation was set up. As a result, germination was very poor. Full emergence only occurred when it rained in the middle of June. Once the canola was up and growing, sufficient amount and distribution of rain allowed the crop to make up for late emergence. At Scott, no irrigation was set up. Soil conditions at seeding were quite dry resulting in delayed and sporadic emergence of canola. As precipitation improved, the crop picked up and grew well. At Brooks, where an irrigation system was already in place, the plots were irrigated the following day after seeding, resulting in good germination and crop establishment. The crop was irrigated five times during the growing season as precipitation remained low for most of the growing season. A total of 32 mm of irrigation was applied to keep the crop from moisture stress as the station received only 107 mm of rain from April to end of August. At Lethbridge, soil moisture was sufficient at the time of seeding and occasional rainfall kept the crop growing without moisture stress. Hence, germination was not impacted.

Soil characteristics

Soil samples were taken just prior to seeding. Table 2 and Fig 4 show the background characteristics of the soil at the various locations in 2018 and 2019. At Saskatoon, Scott, Brooks and Lethbridge, the study was conducted in a different area of the same field in 2018 and 2019. At Melfort, the study was conducted in fields almost a mile apart between the two years. The results of the soil analysis show that at Saskatoon, Melfort and Lethbridge, the study was conducted on clay soil while at Scott and Brooks, the study was conducted on loam soil. Exception was that in 2018 at Melfort, the study was conducted on a silty clay soil.

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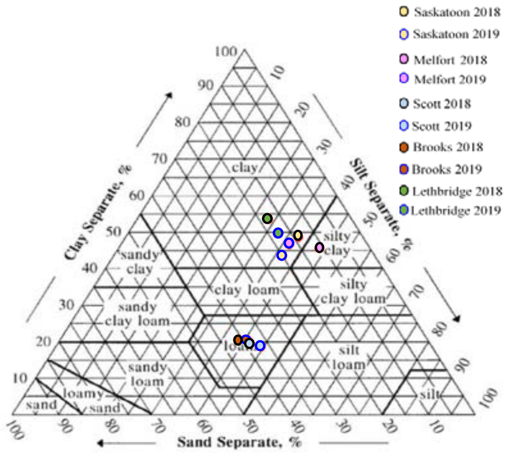
Nutrient composition

Location	Year	NO_3-N 0-30	NO_3-N 30-60	PO_4-P 0-15	K 0-15	SO_4-S 0-60	Ca 0-15	Mg 0-15	Na 0-15	Cl 0-60	B 0-15	Cu 0-15	Fe 0-15	Mn 0-15	Zn 0-15
Depth (cm) >>						- - - - - - -	- - - - -	-mg/kg -	- - - - - -						
Saskatoon	2018	10.7	4.8	38.1	716	128.3	6,163	783	24.8	98.3	1.6	2.2	28.6	7.4	0.8
	2019	25.2	4.6	37.2	652	37.3	6,493	734	21.6	32.3	1.6	2.0	26.4	5.5	0.7
Melfort	2018	16.2	2.1	56.4	683	38.1	4,472	1,074	27.5	22.1	1.3	1.6	192.5	14.0	5.7
	2019	11.0	0.7	7.9	342	11.0	4,451	863	14.3	10.1	0.6	1.2	105.7	24.8	3.0
Scott	2018	18.7	2.3	23.6	294	25.5	1,743	284	17.2	7.3	0.6	1.0	94.7	34.1	2.0
	2019	11.4	3.9	25.0	357	20.4	1,634	263	11.9	6.6	0.5	0.9	103.6	32.8	2.9
Brooks	2018	7.2	4.1	29.0	374	41.8	2,238	397	22.4	6.7	0.6	1.0	18.1	13.7	0.8
	2019	16.3	15.3	21.1	185	73.8	2,878	405	21.5	10.5	0.5	1.4	14.6	16.4	3.1
Lethbridge	2018	8.3	2.3	10.4	557	20.2	6,080	1,191	35.4	10.4	1.2	1.9	23.3	8.2	0.8
	2019	35.5	10.6	14.3	494	26.7	4,811	925	26.7	9.4	0.9	1.9	25.7	15.8	3.0

Other Soil charecteristica

Location	Year	pH	EC 1:2	OM	Clay	Sand	Silt	Texture
Depth (cm) >>		0-30	0-30	0-15	0-30	0-30	0-30	0-30
			dS/m	%	%	%	%	
Saskatoon	2018	8.1	0.4	3.9	48.4	15.1	36.5	Clay
	2019	8.0	0.4	4.0	43.3	20.8	35.9	Clay
Melfort	2018	7.2	0.3	9.9	44.7	11.6	43.6	Silty clay
	2019	7.1	0.2	8.3	46.0	17.7	37.2	Clay
Scott	2018	7.1	0.2	3.5	19.1	39.6	41.3	Loam
	2019	6.8	0.2	4.4	17.8	37.8	44.4	Loam
Brooks	2018	7.7	0.2	2.1	19.6	42.4	38.1	Loam
	2019	7.8	0.2	1.9	19.6	40.3	40.2	Loam
Lethbridge	2018	8.2	0.3	3.9	53.0	18.6	28.5	Clay
	2019	7.9	0.4	4.3	48.7	19.2	32.1	Clay



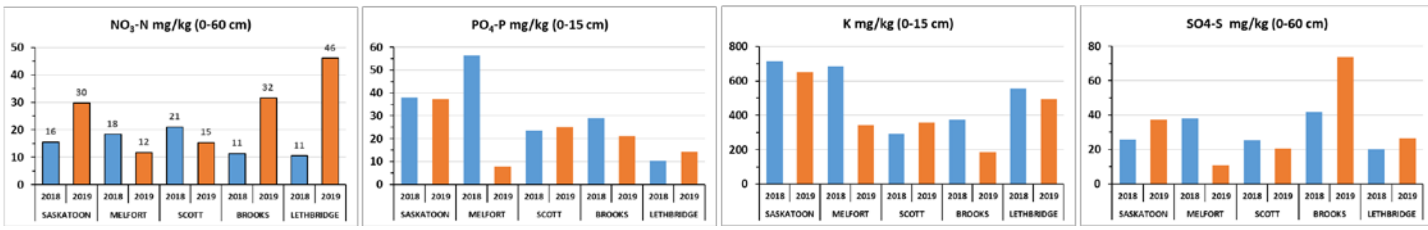


Fig. 4. Concentration of soil available N, P, K and S at Saskatoon, Melfort, Scott, Brooks and Lethbridge in 2018 and 2019.

Table 2: Background soil characteristics of the fields at the five locations in 2018 and 2019

Crop performance

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Year 1

Table 3 summarizes the results of statistical analysis of the data collected in Year 1, showing P-values (⍰ = 5%) of different sources of variation. Statistical analysis of Year 1 data showed that significant differences were observed among locations for all the measured crop parameters. The effects of row spacing (RS), opener width (OW) and phosphorus rate (PR) on plant density and plant height were significant at all sampling dates. There were more plants per square meter at 9" row spacing than at 12" row spacing (Fig. 5). As well, plant density increased with opener width. However, plant density decreased with increasing P rate. On the other hand, the effects of row spacing, opener width and P rate on plant height was the opposite to that on plant density. Plants tended to be shorter at 9" row spacing than at 12" row spacing; shorter with increasing opener width, but taller with increasing P rate. No significant effect on grain yield and grain quality characteristics were observed for all the three factors.

A number of interaction effects on plant density, plant height, grain yield and some quality parameters were observed (Table 3). These interactions were examined further, and the results are shown in the next few charts.

Table 3. Analysis of variance result showing p-values of measured canola variables in response to treatments

		Plants per m^2			Post Harvest	Plant height	Biomass Yield	Grain Yield	Harvest Index	Green Seed Count	Thousand Kernel Weight	Test Weight	Oil Content	Protein Content
		Days After Seeding												
Source	DF	14	21	28*	Plants/m^2									
LO	4	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.044**	**0.000**	**0.000**	**0.002**	**0.012**
Rep(LO)	15													
RS	1	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.126	0.320	0.125	0.813	0.971	0.439	0.889	0.986
OW	2	**0.000**	**0.000**	**0.000**	**0.011**	**0.000**	0.390	0.285	0.691	0.069	0.590	0.438	0.605	0.464
PR	3	**0.000**	**0.000**	**0.000**	**0.000**	**0.002**	0.171	0.110	0.546	0.432	0.874	0.723	0.484	0.411
RS*OW	2	0.549	0.506	**0.000**	**0.000**	0.649	0.636	**0.030**	**0.012**	0.088	0.779	0.219	0.870	0.838
RS*PR	3	0.891	0.984	0.153	0.648	0.356	0.662	0.956	0.417	0.286	0.319	0.828	0.776	0.844
OW*PR	6	**0.024**	**0.005**	**0.008**	0.483	**0.040**	0.937	0.675	0.132	0.851	0.171	0.382	0.332	0.469
RS*OW*PR	6	0.189	0.615	0.773	0.376	0.784	0.539	0.608	0.195	0.196	0.172	0.154	**0.023**	**0.030**
LO*RS	4	**0.000**	**0.000**	**0.000**	**0.000**	**0.024**	**0.000**	0.217	0.349	0.818	0.435	0.274	0.257	0.320
LO*OW	8	**0.000**	**0.000**	**0.001**	**0.026**	0.128	0.890	0.296	0.472	0.552	**0.029**	0.398	0.077	0.057
LO*PR	12	**0.048**	**0.028**	**0.000**	**0.005**	0.582	0.913	0.362	0.654	0.522	0.938	0.440	0.892	0.935
LO*RS*OW	8	0.089	**0.004**	0.108	0.431	0.660	0.590	0.974	0.423	0.194	0.412	0.989	0.418	0.464
LO*RS*PR	12	0.897	0.844	0.201	0.557	0.859	0.992	0.520	0.324	0.861	0.795	0.976	0.590	0.560
LO*OW*PR	24	0.716	0.818	0.571	0.251	0.249	0.985	0.563	**0.029**	0.815	0.398	0.627	0.428	0.496
LO*RS*OW*PR	24	0.857	0.667	0.640	0.424	0.799	0.763	0.681	0.363	0.819	0.486	0.851	0.373	0.207
Error	345													

Key: **LO** = Location; **RS** = Row Spacing; **OW** = Opener Width; **PR** = Phosphorus Rate

* Plant counts at 28 DAS not done at Lethbridge. Hence, P-values are from 4 locations only.

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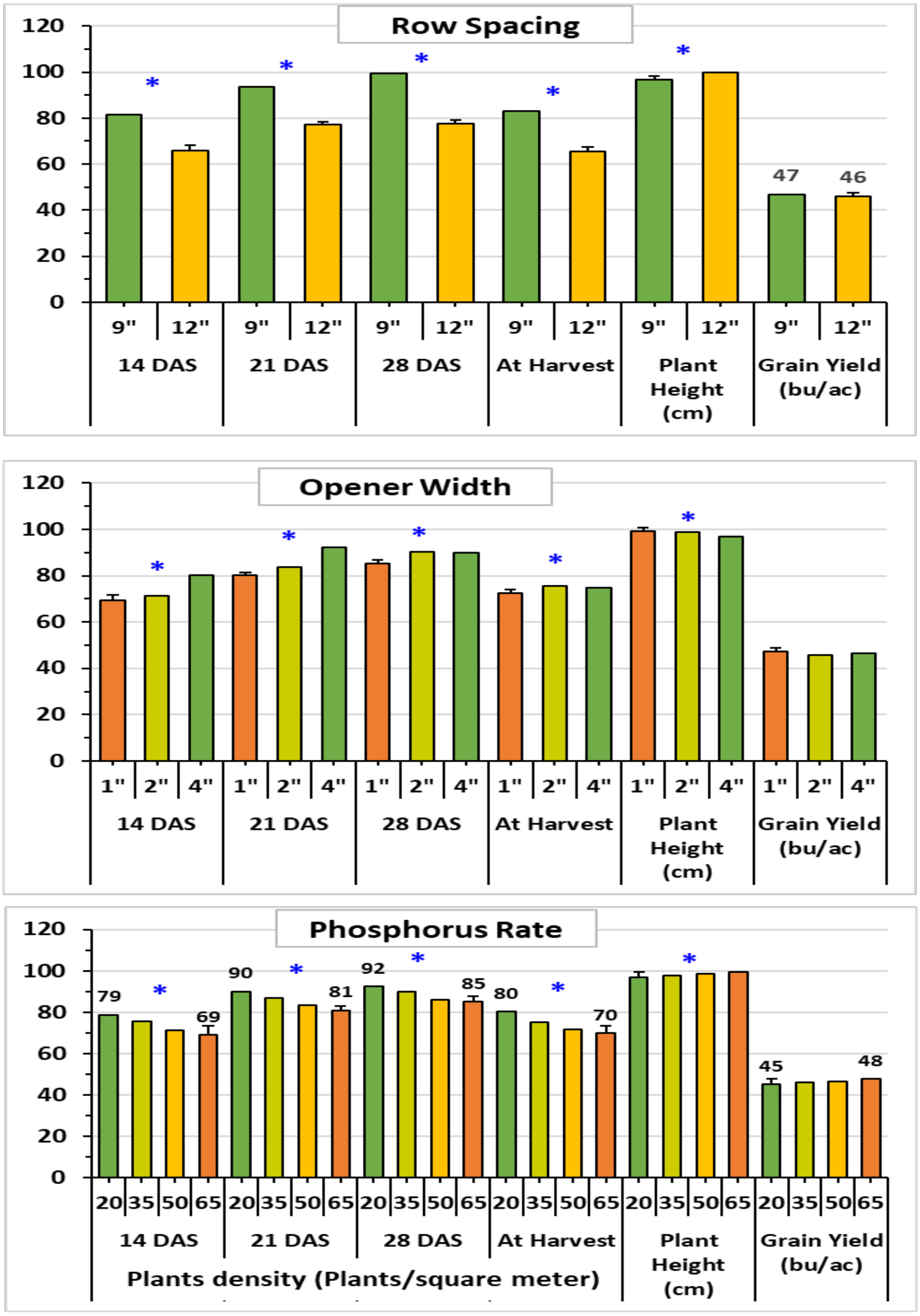

Fig. 5. Effect of row spacing, opener width and P rate on plant density, plant height and grain yield of canola. Error bars denote Tukey's HSD at α = 0.05

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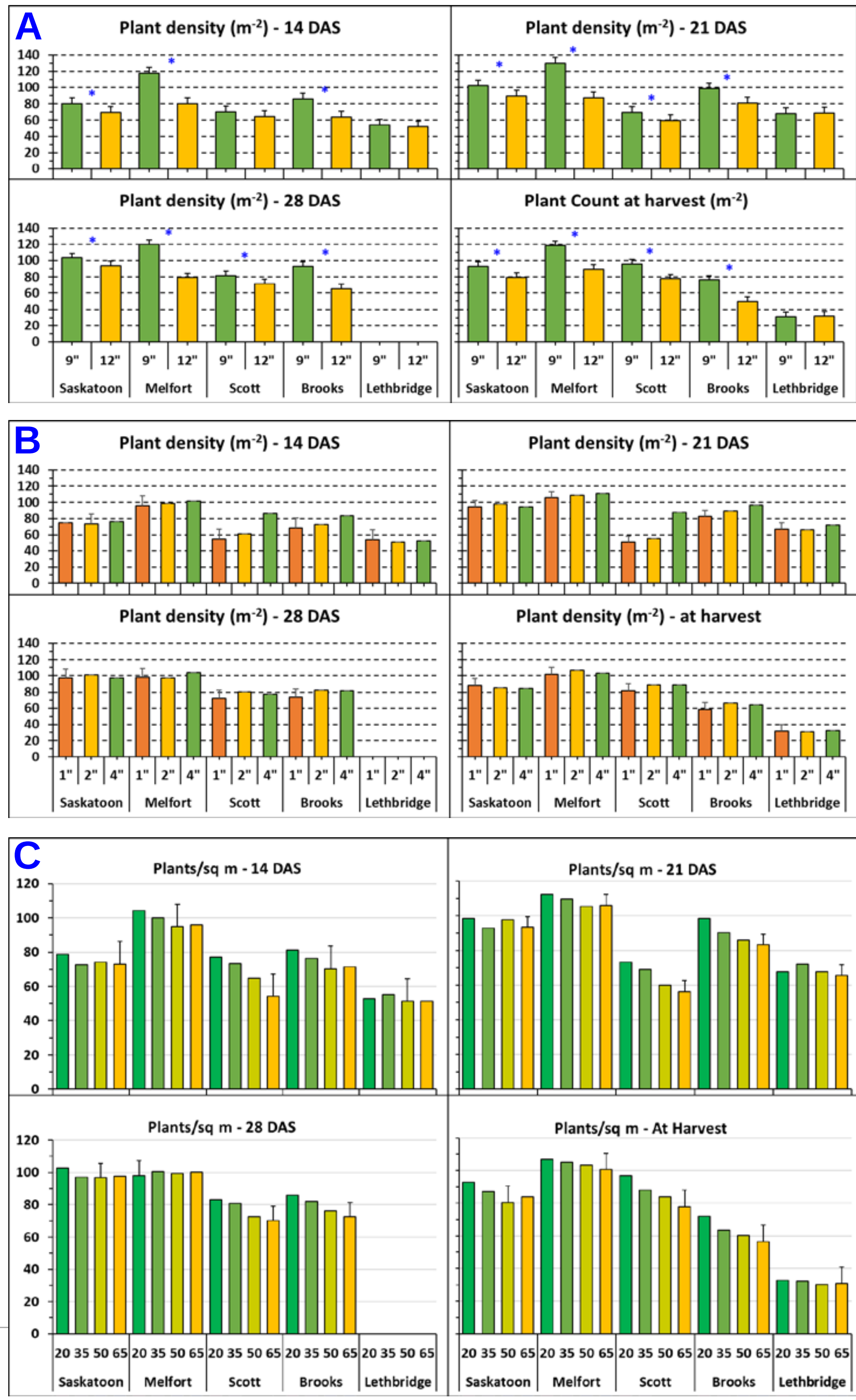

Fig. 6. Effect of row spacing (**A**), opener width (**B**) and P rate (**C**) on plant density of canola at Saskatoon, Melfort, Scott, Brooks and Lethbridge in 2018. Error bars denote Tukey's HSD at α = 0.05 level of significance.

The location (LO) x RS interaction for plant density was significant. However, a look at the response of plant density to RS at different locations showed that the effect was similar at all locations in that plant density was higher at 9" RS than at 12" RS (Fig. 5 A) as observed when averaged over locations (Fig. 5). The differences in plant density were significant at Saskatoon, Melfort, Scott and Brooks. The exceptions were that the differences were not significant at 14 DAS at Scott and at all sampling dates at Lethbridge. Thus, the LOxRS interaction for plant density was significant mainly as a matter of magnitude in difference. For instance the difference at Saskatoon was smaller than the difference at Melfort, although both differences in plant density were significant.

The LOxOW interaction effect on plant density was significant. At most locations, plant density was significantly lower at 1" OW than at 2" and/or 4" (Fig. 6 B) as observed when averaged over locations (Fig. 4). Significant differences in plant density among OWs were observed mainly at Scott and Brooks. At Saskatoon and Lethbridge, no significant differences in plant density among OWs were observed at all sampling dates. The exceptions were that the differences were not significant at 14 DAS at Scott and at all sampling dates at Lethbridge.

Plant density decreased with increasing phosphorus rate (PR) at Scott and Brooks at all sampling dates (Fig. 6. C). At Saskatoon, significant decrease in plant density as PR increased was only observed at harvest. At Melfort, significant effects were only observed at 21 DAS. At Lethbridge, significant decrease in plant density with increasing PR was also at 21 DAS. With the exception of Lethbridge, where differences were not significant, increasing PR resulted in significant decrease in plant density as observed at harvest time.

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The location by row spacing (LOxRS) interaction effect was significant for plant height and aboveground biomass yield (Table 2). It was noted that while plant height was generally higher at 12" RS, the difference was significant only at Saskatoon and Melfort (Fig. 7). Aboveground biomass yield at senescence was significantly higher at 12" RS than at 9" RS at Saskatoon and Scott, but lower at 12" RS than at 9" RS at Melfort, resulting in the significant LOxRS interaction effect. No differences in aboveground biomass yield between RSs were observed at Brooks and Lethbridge. No differences in grain yield between RSs were observed at all locations.

The increase in plant density with increasing opener width was more pronounced at 12" than at 9" row spacing at all sampling dates (Fig. 8).

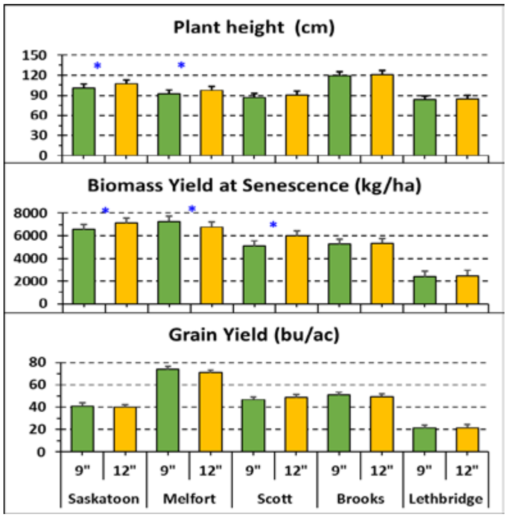

Fig. 7. Effect of row spacing on plant density of canola at Saskatoon, Melfort, Scott, Brooks and Lethbridge in 2018. Error bars denote Tukey's HSD at α = 0.05 level of significance.

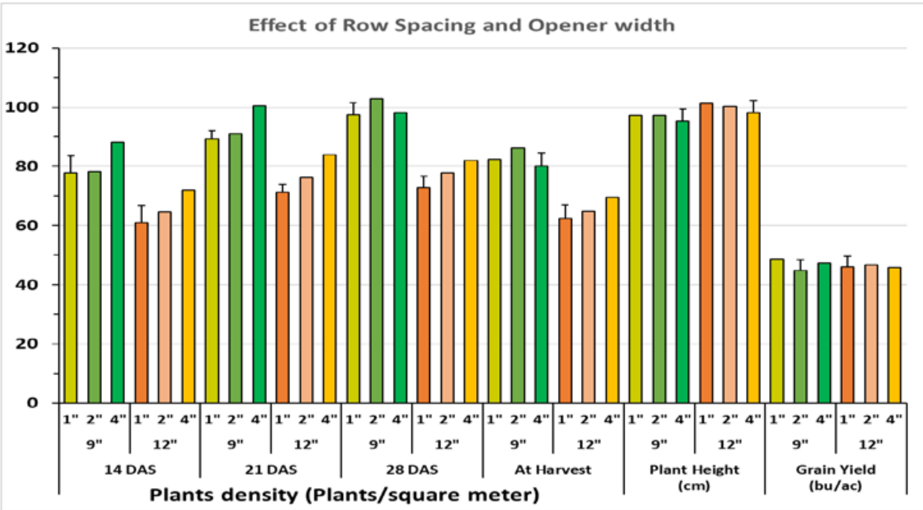

Fig. 8. Interaction effect of row spacing and opener width on plant density, plant height and grain yield of canola at combined over locations in 2018. Error bars denote Tukey's HSD at α = 0.05 level of significance.

There were no significant effects of RS, OW and PR on grain quality of canola (Table 3) in 2018. However, significant differences in grain quality parameters were observed among locations (Table 4). Green count per thousand seeds was low at all locations at less than two per thousand seeds. As a straight cut crop, the seed was allowed to mature and change colour prior to desiccation and harvesting.

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Table 4. Effect of Location on grain quality and harvest index of canola at in 2018. Means followed by the same letter are not significantly different based on Tukey's HSD at α = 0.05 level of significance.

Location	Green Seed Count/1000	TKW g	TW kg/hL	Oil Content %	Protein %	HI %
Saskatoon	1.3 a	3.3 b	66.6 c	46.3 b	26.2 c	33.9 c
Melfort	0.5 b	4.4 a	63.1 e	48.1 a	24.6 d	58.5 a
Scott	0.5 b	3.1 c	68.1 a	44.4 d	27.8 a	52.1 b
Brooks	0.6 b	3.2 bc	63.6 d	45.5 c	27.1 b	53.4 b
Lethbridge	0.4 b	2.5 d	67.2 b	45.0 cd	26.8 bc	50.5 b

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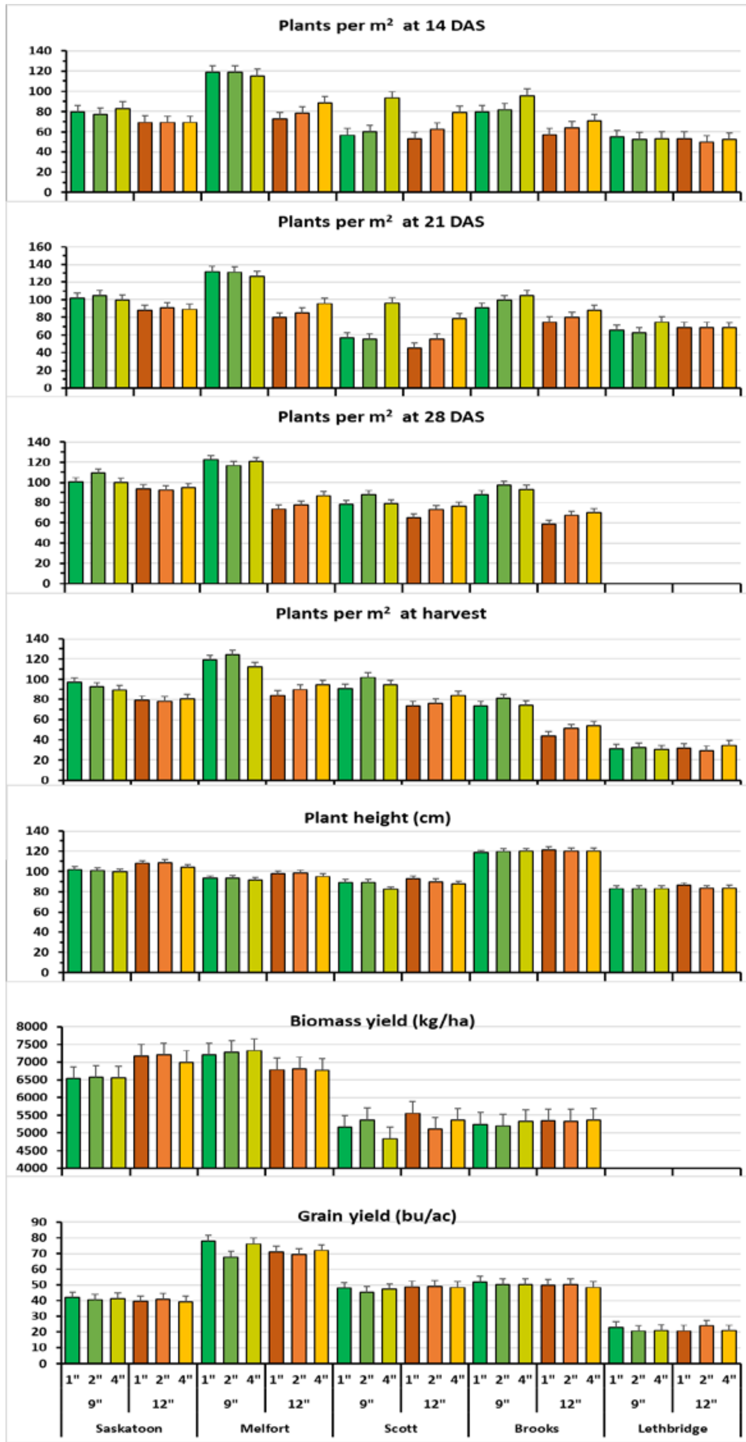

Fig. 9 . Interaction effect of row spacing and opener width on plant density, plant height and grain yield of canola at combined over locations in 2018. Error bars denote Tukey's HSD at α = 0.05 level of significance.

As SBU is determined by the combination RS and OW and may be affected by soil type, the effect of LOxRSxOW on canola was also assessed. The 2018 results showed that the effect of opener width varied with row spacing and location (Fig. 9). At 14 DAS, while at some locations increasing opener width resulted in subtle differences among opener sizes with row spacing (e.g. at Saskatoon and Lethbridge for 9" and 12" RS; increasing opener width resulted in increasing plant density at both 9" and 12" RS. However, a different pattern started to emerge as time went by, such that plant density was lower at 4" than at 2" opener width with 9" row spacing. At the 12" row spacing, the pattern of increasing plant density with increasing opener size, remained the same from 14 DAS to harvest time at all locations.

Marginal differences were observed in plant height. Except at Scott, biomass yield did not differ among opener sizes within row spacing. At Scott a significant decrease in biomass yield was observed at 4" OW and 9" RS. As well, a significant decrease in biomass yield was observed at 2" OW and 12" RS. No significant differences in grain yield were observed among opener sizes within row spacing. The exception was at Melfort where grain yield at 2" openers was significantly lower than that with 1" or 4" openers at 9" row spacing.

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Year 2 Results

Table 5 summarizes the results of statistical analysis of the data collected in 2019, showing P-values of different sources of variation. Significant differences were observed among locations for all the measured crop parameters. The effects of row spacing (RS), opener width (OW) and phosphorus rate (PR) on canola are given in Table 5. Overall, RS had a significant effect on plant density at 14 and 21 days after seeding (DAS), grain yield, thousand kernel weight (TKW) and protein content. Initially, plant density at 14 and 21 DAS was higher at 12" RS than at 9" RS. This was attributed to the covering of front openers in rows by rear openers especially at 4" OW. The extra soil on top of the rows inhibited emergence of most seedling in these rows. This was more serious at Lethbridge where at 4" OW, only four rows could be seen at the 9" RS (Appendix A). However, as more seedlings emerged with time, there was no difference in plant density between 9" and 12" RS as observed at 28 DAS and at harvest. Grain yield was significantly higher at 9" RS than at 12" RS. However, TKW was higher at 12" RS than at 9" RS.

Overall, OW significantly affected plant density, start of flowering, biomass and grain yield, and TKW. Plant density was higher at 2" than at 1" OW (Table 5). However, plant density at 4" OW dropped due to soil being thrown over the front rows, such that plant density at 4" OW was not different that at 1" OW at all stages. As well, start of flowering at 4" OW was delayed by a day compared to plots seeded at 1" and 2" OW. Despite reduction in plant density at 4" OW, grain yield and TKW were significantly higher at 4" than at 1" OW, but not different from that at 2" OW.

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Increasing rate of seed-placed P resulted in significant impact on all parameters except TW and oil content (Table 5). Plant density, number of days to start of flowering, full bloom and maturity, green seed content, and protein content decreased with increasing phosphorus rate (PR). Plant height, biomass yield, grain yield and TKW increased with increasing PR.

A number of interaction effects on various canola plant characteristics were observed (Table 5). These interactions were examined further and the results are shown in the next few charts. Significant interactions between location (LO) and RS, OW or PR were observed. Significant LOxRS interaction effect was observed for plant density at all stages (Fig. 10). This was due to the fact that at Saskatoon, Melfort, Scott and Brooks, plant density at 9" RS was higher or equal to that at 12" RS, while at Lethbridge, plant density at 12" RS was higher than that at 9" RS at all crop stages.

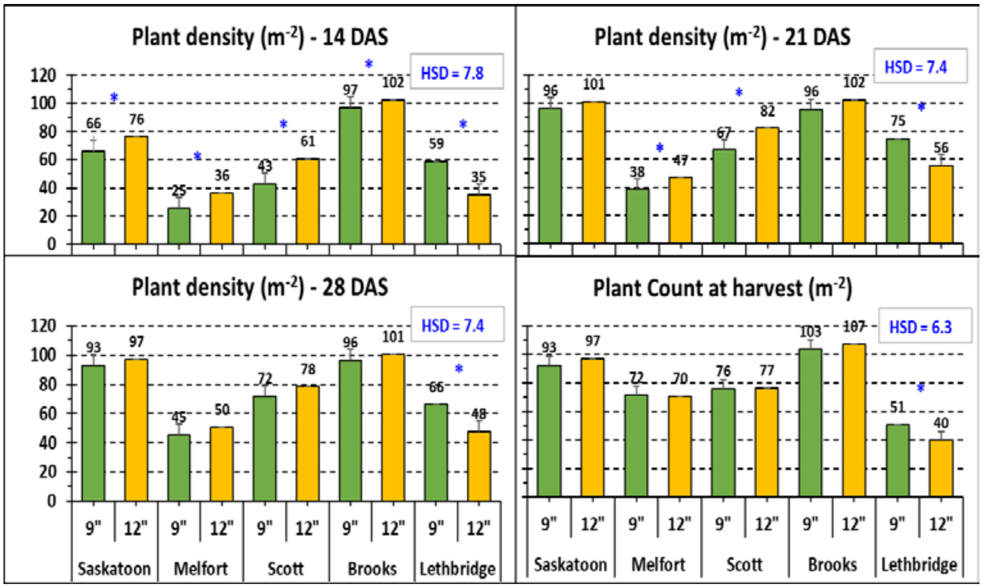

Fig. 10. Effect of row spacing (RS) on plant density of canola at Saskatoon, Melfort, Scott, Brooks and Lethbridge in 2019. Error bars denote Tukey's HSD at α = 0.05 level of significance.

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Analysis of variance result showing p-values of measured canola variables in response to treatments

		Plants per m^2 Days After Seeding			Post Harvest	Days to			Plant height	Biomass Yield	Grain Yield	Green Seed Content	Thousand Kernel Weight	Test Weight	Oil Content	Protein Content
	df	14	21	28		Start of Flowering	Full Bloom	Maturity								
	4	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
	15															
	1	**0.000**	**0.001**	0.763	0.480	0.199	0.160	0.434	0.721	0.852	**0.000**	0.519	**0.004**	0.132	0.058	**0.008**
	2	**0.012**	**0.011**	**0.015**	**0.004**	**0.000**	0.559	0.155	0.217	**0.001**	**0.008**	0.223	**0.047**	0.094	0.301	0.301
	3	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.022**	0.145	0.350	**0.022**
	2	0.130	**0.000**	**0.009**	**0.000**	0.940	0.305	**0.000**	0.088	**0.000**	**0.000**	0.066	0.532	0.150	0.274	0.675
	3	0.196	0.202	0.166	0.228	0.109	0.409	0.379	0.488	**0.036**	0.094	0.585	0.099	0.277	0.882	0.869
	6	**0.056**	0.331	0.802	**0.007**	**0.035**	0.194	0.150	0.372	0.065	0.421	0.839	0.567	0.144	0.615	0.499
	6	0.493	0.576	0.879	0.821	0.126	0.567	0.618	0.489	**0.001**	0.097	0.901	0.907	**0.007**	0.096	0.092
	4	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.009**	0.854	0.172	**0.000**	**0.000**	0.474	**0.000**	**0.003**	**0.044**	**0.048**
	8	**0.000**	**0.000**	**0.001**	**0.006**	**0.000**	**0.000**	0.100	0.398	**0.001**	**0.001**	0.238	**0.000**	0.147	0.063	0.076
	12	**0.001**	**0.018**	**0.004**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.008**	**0.016**	**0.000**	0.105	**0.005**	**0.002**	**0.004**
	8	0.008	**0.010**	0.797	0.424	0.187	0.242	**0.000**	**0.003**	**0.000**	**0.000**	**0.003**	0.244	0.512	0.625	0.716
	12	0.857	0.557	0.092	0.057	**0.003**	0.065	0.362	0.936	0.778	**0.009**	0.071	0.474	0.121	0.235	0.155
R	24	0.730	0.511	0.496	0.759	0.418	0.799	0.227	0.588	**0.022**	0.057	0.954	0.885	**0.000**	0.088	**0.024**
*PR	24	0.979	0.504	0.787	0.538	0.984	0.202	0.817	0.938	0.328	0.227	0.843	0.566	**0.000**	0.602	0.813
	345															

cation; **RS** = Row Spacing; **OW** = Opener Width; **PR** = Phosphorus Rate

ffect of row spacing, opener width and P rate on plant density, plant height and grain yield of canola

	Plants per m^2 Days After Seeding			Post Harvest	Days to			Plant height	Biomass Yield	Grain Yield		Green Seed Content	Thousand Kernel Weight	Test Weight	Oil Content	Protein Content
	14	21	28		Start of Flowering	Full Bloom	Maturity	(cm)	(kg/ha)	(kg/ha)	(bu/ac)	(%)	(g)	(kg/hL)	(%)	(%)
ng																
	58 b	74 b	75 a	79 a	48.0 a	64.1 b	105.9 a	105.7 a	7996 a	3264 a	48.7 a	0.15 a	3.26 b	66.1 a	47.5 a	24.67 b
	62 a	78 a	75 a	78 a	48.1 a	64.2 a	105.9 a	105.5 a	8014 a	2828 b	42.2 b	0.15 a	3.29 a	65.9 a	47.3 a	24.87 a
g	***	**	ns	ns	ns	ns	ns	ns	ns	***	***	ns	**	ns	ns	**
D	2	2	3	3	0.2	0.2	0.2	1.0	290	69	1.0	0.02	0.02	0.2	0.15	0.14
dth																
	58 b	74 b	73 b	78 ab	47.9 b	64.2 a	106.1 a	106.0 a	7741 b	2970 ab	44.4 b	0.15 a	3.26 b	65.9 a	47.5 a	24.69 a
	62 a	78 a	77 a	81 a	47.9 b	64.1 a	105.8 a	105.8 a	8102 a	3068 a	45.8 ab	0.16 a	3.28 ab	66.0 a	47.4 a	24.78 a
	60 ab	76 ab	75 ab	77 b	48.3 a	64.2 a	105.8 a	105.0 a	8172 a	3100 a	46.3 a	0.14 a	3.30 a	66.1 a	47.3 a	24.83 a
g	*	*	*	**	***	ns	ns	ns	**	**	**	ns	*	ns	ns	ns
D	3	3	4	4	0.2	0.3	0.3	1.5	135	100	1.5	0.04	0.03	0.3	0.22	0.21
P_2O_5/ac)																
	63 a	79 a	78 a	84 a	49.3 a	64.9 a	107.0 a	99.4 c	7237 c	2849 c	42.6 c	0.24 a	3.26 b	65.8 a	47.3 a	25.00 a
	62 ab	79 a	77 ab	82 ab	47.8 b	64.2 b	105.4 b	105.7 b	7795 b	2968 bc	44.3 bc	0.13 b	3.26 b	66.1 a	47.4 a	24.77 ab
	62 ab	76 ab	74 abc	78 bc	47.7 b	63.9 bc	105.4 b	107.0 ab	8254 ab	3083 ab	46.0 ab	0.14 b	3.29 ab	65.9 a	47.4 a	24.75 ab
	58 bc	74 b	73 bc	75 c	47.6 b	63.8 c	105.8 ab	107.7 ab	8294 a	3171 a	47.4 a	0.11 b	3.30 a	66.1 a	47.5 a	24.62 b
	56 c	73 b	71 c	74 c	47.8 b	64.0 bc	105.8 ab	108.3 a	8445 a	3159 a	47.2 a	0.13 b	3.29 ab	66.1 a	47.4 a	24.70 b
g	***	***	***	***	***	***	***	***	***	***	***	***	**	ns	ns	*
D	5	5	5	4	0.3	0.4	0.5	2.2	498	151	2.3	0.05	0.04	0.4	0.3	0.30

olumn and main factor, means followed by the same letter are not significantly different at $\alpha = 0.05$.

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When averaged over RS and PR, no significant effect of opener width on plant density was observed at all LO, except at Saskatoon where plant density was significantly reduced at 4" OW at all stages (Fig. 11 A). Except at Saskatoon where increasing PR tended to increase plant density, at the other locations plant density tended to decrease with increasing PR, and this trend was significant at Scott and Brooks at all crop stages (Fig. 11 B). At Melfort decrease in plant density with increasing PR was also significant at harvest.

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Row spacing had no effect on start of flowering and full bloom at all locations except at Lethbridge where it was

Fig. 11. Effect of row spacing on plant density of canola at Saskatoon, Melfort, Scott, Brooks and Lethbridge in 2019. Error bars denote Tukey's HSD at α = 0.05 level of significance.

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delayed by one day at 12" RS (Fig. 12). Row spacing had no significant effect on days to maturity and plant height at all locations. Biomass yield was significantly lower at 9" RS than at 12" RS at Saskatoon and Brooks, but the opposite was the case at Lethbridge. In contrast, grain yield was higher at 9" than 12" RS at all locations, although not significantly so at Melfort.

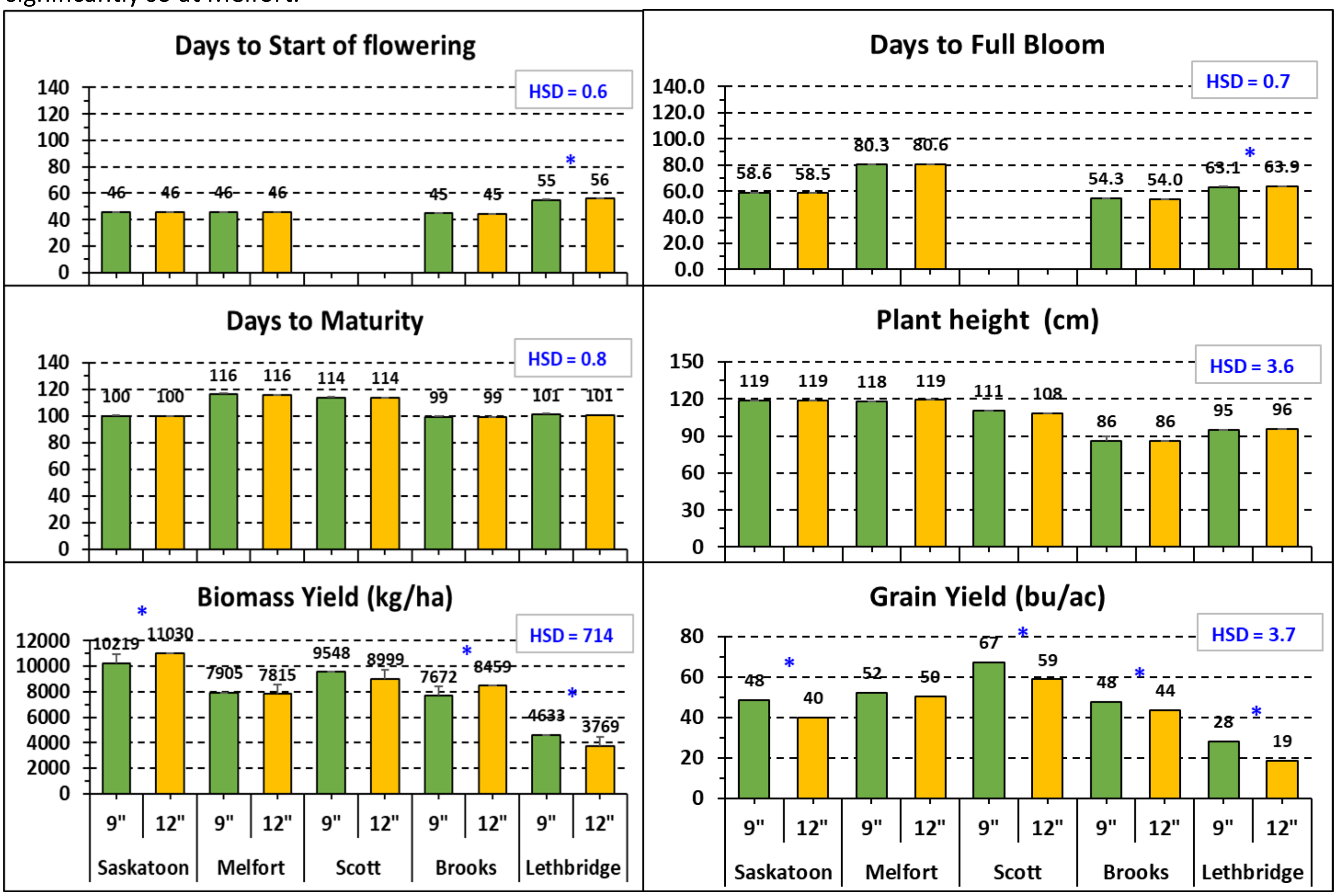

Fig. 12. Effect of row spacing on plant density of canola at Saskatoon, Melfort, Scott, Brooks and Lethbridge in 2019. Error bars denote Tukey's HSD at $\alpha = 0.05$ level of significance.

The interaction effect of LO, RS and OW was significant on plant density, maturity, plant height, biomass yield, grain yield and green seed content (Table 5). At the 9" RS, widening OW from 1" to 2" resulted in an increase in plant density though not significantly so at most locations except at Saskatoon (Fig. 13). At 12" RS, plant density tended to increase with increasing OW, at all locations except Saskatoon and Lethbridge where plant density tended to decline at the 4" OW, but not significantly so. At Scott and Brooks, Biomass yield and grain yield were

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higher at 4” OW than at 1" and 2” OW at the 9" RS. At the 12" RS at Scott and Brooks, biomass yield and grain yield declined at the 4" OW.

By and large, plant density decreased with increasing PR at all locations except Saskatoon (Fig. 14). However, the effect depended on the combination of RS and OW. At Saskatoon, increasing PR resulted in increased plant density at 1" and 2" OW at 9" RS, as well as at 4" OW with 12" RS. At Melfort, no significant effect was observed at 28 DAS, but significant reduction in plant density was observed at harvest with 1" and 4" openers. At Scott, increasing PR resulted in decreased plant density, particularly at 1" and 2" openers. At Brooks, significant decrease in plant density with increasing PR was observed in all combinations of RS and OW. At Lethbridge, no significant decrease in plant population was observed in all combinations of RS and OW, except with 4" openers.

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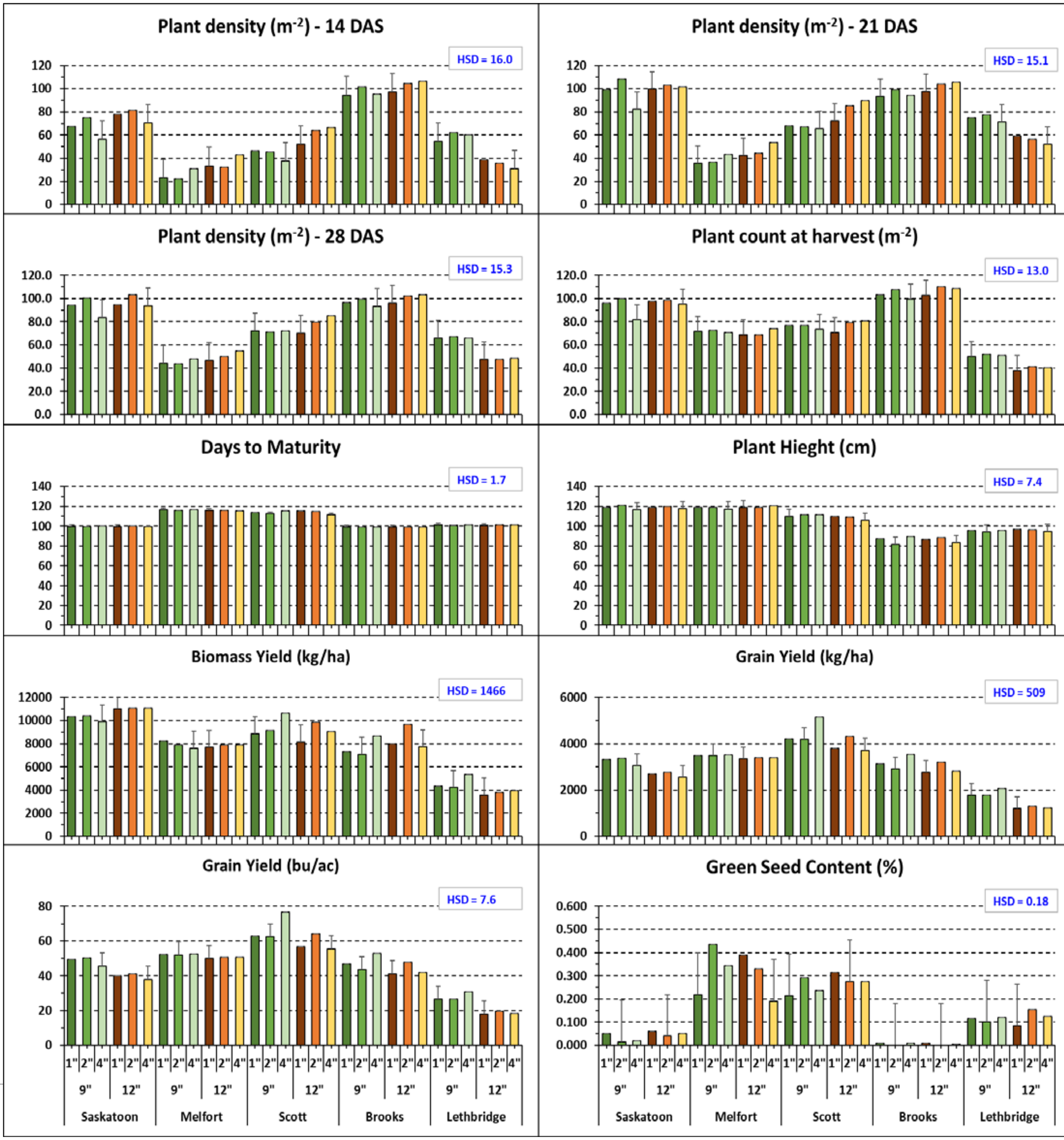

Fig. 13. Interaction effect of row spacing and opener width on plant density, plant height and grain yield of canola at combined over locations in 2019. Error bars denote Tukey's HSD at α = 0.05 level of significance.

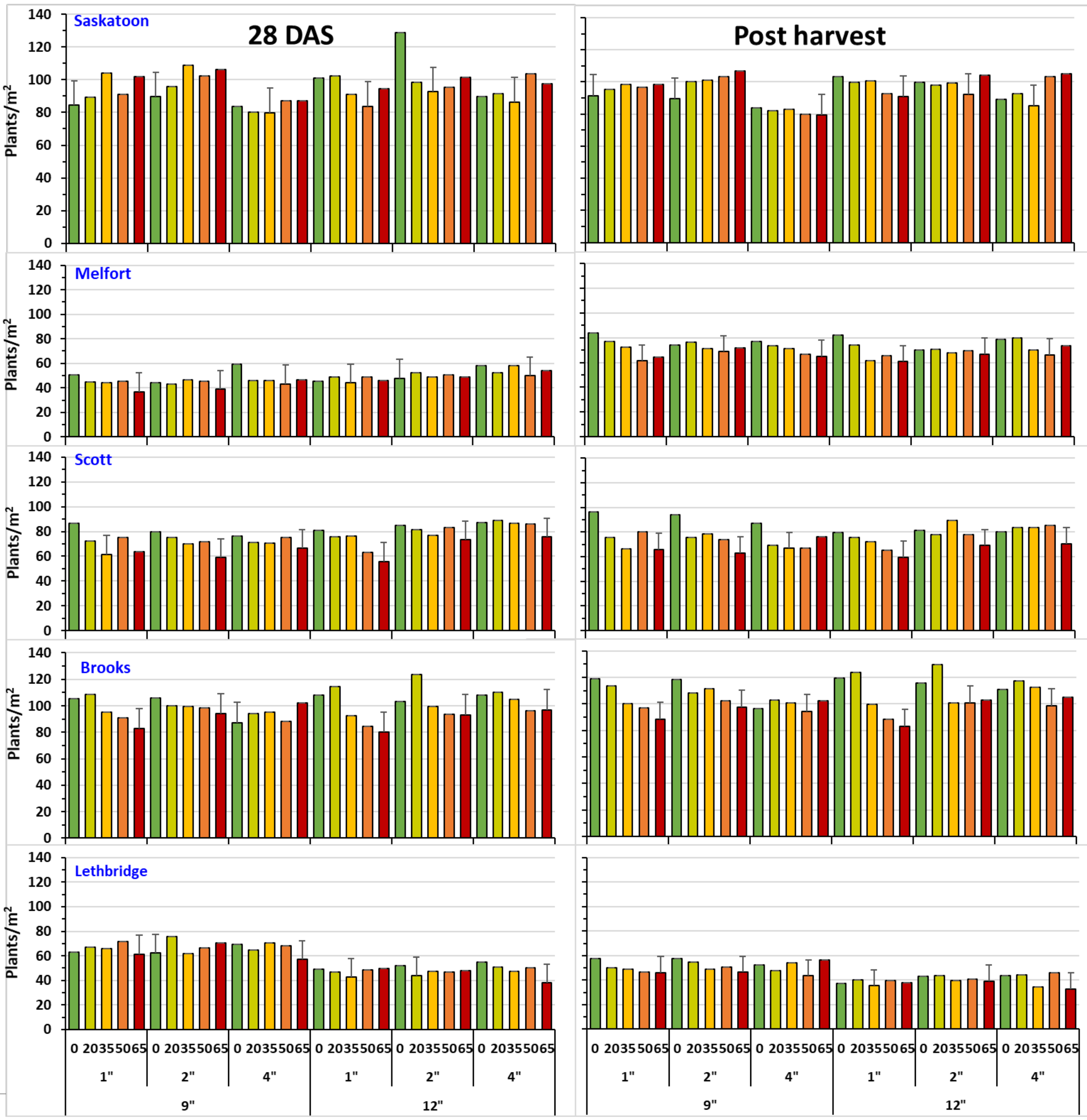

Fig. 14. Interaction effect of row spacing, opener width and rate of phosphorus on plant density at 28 days after seeding (DAS) and post-harvest in 2019. Error bars denote Tukey's HSD at α = 0.05 level of significance.

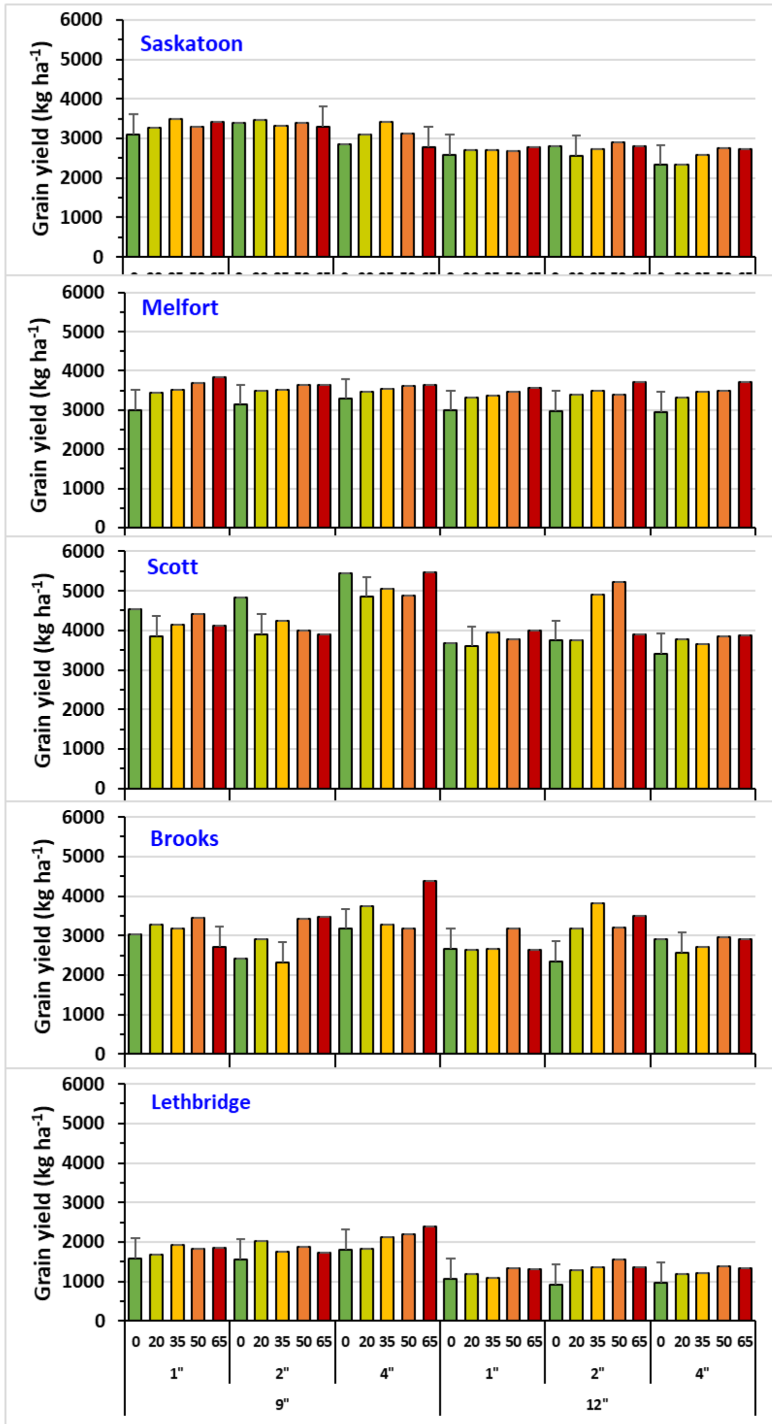

Fig. 15. Interaction effect of row spacing, opener width and rate of phosphorus on grain yield of canola in 2019. Error bars denote Tukey's HSD at α = 0.05 level of significance.

A linear to quadratic effect was observed at Saskatoon for grain yield in response to increasing PR at all combinations of RS and OW (Fig. 15). At Melfort, a significant linear trend to increasing PR was observed at all combinations of RS and OW. At Scott, addition of P resulted in decreased yield, except with the combination of 12" RS and 2" OW. At Brooks, no clear trend was observed in response to PR. At 9" RS and 1" openers, grain yield was not affected except for a significant reduction at 65 lb P_2O_5/ac. With 2" OW, increasing PR resulted in increasing grain yield. With 4” OW, increasing PR did not have a significant impact on grain yield except for a significant increase in grain yield at 65 lb P_2O_5/ac. At the 12" RS, no significant increase in grain yield was observed with 1" and 4" openers. However, with 2" openers, increasing PR resulted in increasing grain yield. At Lethbridge, no significant increase in grain yield with increasing PR was observed, except at 9" RS with 4" openers, and at 12" RS with 2" openers.

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Year 1 & 2 Combined Analysis Results

Due to minor changes in treatments (4 vs 5 P rates) and some missed data collections (e.g. no plant counts at 28 DAS at Lethbridge in 2018), not all data was used for the combined analysis. Hence, it should be noted for instance that means for the combined results in Year 2 are not exactly the same as those reported in Year 2 above. This is because, in the combined analysis, only four levels of P are used (20, 35, 50, and 65 lb P_2O_5/ac), while in 2019 report five rates of P were used (0, 20, 35, 50, and 65 lb P_2O_5/ac). The purpose of a combined results is to give the total overview effects of the treatments across the 10 site-years.

Table 7. Analysis of variance result showing p-values of measured canola variables in response to treatments

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		Plants per m^2			Plant height	Biomass Yield	Grain Yield	Harvest Index	Green Seed Content	1,000 Kernel Weight	Test Weight	Oil Content	Protein Content
		DAS		Post Harvest									
Source	df	14	21										
Y	1	**0.000**	**0.000**	0.083	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.620	**0.000**	**0.000**	**0.000**
L	4	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.001**	**0.000**	**0.000**	**0.000**	**0.000**
Y*L	4	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
R	1	**0.000**	**0.000**	**0.000**	**0.002**	**0.000**	**0.000**	**0.000**	0.925	0.076	0.421	0.265	0.121
O	2	**0.000**	**0.000**	**0.024**	**0.000**	0.822	0.249	0.774	0.057	0.291	0.344	0.243	0.161
P	3	**0.000**	**0.000**	**0.000**	**0.000**	**0.001**	**0.000**	0.891	0.541	0.259	0.204	0.608	0.459
R*O	2	**0.019**	**0.000**	**0.000**	0.128	0.625	**0.040**	0.093	**0.026**	0.983	0.483	0.477	0.607
R*P	3	0.584	0.337	0.893	0.963	0.542	0.614	0.389	0.732	0.065	0.699	0.990	0.971
O*P	6	**0.010**	**0.014**	**0.028**	0.485	0.466	0.608	0.067	0.905	0.566	0.928	0.186	0.291
R*O*P	6	0.208	0.221	0.709	0.776	0.058	0.393	0.555	0.360	0.675	0.095	0.064	0.095
Y*R	1	**0.000**	**0.000**	**0.000**	**0.000**	**0.014**	**0.000**	**0.001**	0.830	0.067	0.994	0.189	0.115
Y*O	2	**0.000**	**0.000**	**0.019**	0.644	0.618	0.527	0.595	0.357	0.923	0.143	0.716	0.746
Y*P	3	0.384	0.383	0.300	0.991	0.176	0.690	0.407	0.386	0.659	0.554	0.627	0.609
Y*R*O	2	**0.001**	**0.000**	**0.028**	0.180	0.173	0.319	**0.020**	0.102	0.599	0.207	0.879	0.952
Y*R*P	3	0.353	0.351	0.125	0.398	0.526	0.931	0.744	0.370	0.955	0.960	0.683	0.760
Y*O*P	6	0.445	0.274	0.711	0.339	0.600	0.957	0.617	0.616	0.226	0.673	0.962	0.923
Y*R*O*P	6	0.651	0.895	0.306	0.902	0.431	0.659	0.267	0.541	0.234	0.062	**0.045**	**0.040**
L*R	4	**0.000**	**0.000**	**0.000**	0.131	**0.000**	**0.000**	**0.007**	**0.021**	**0.001**	0.544	0.837	0.741
L*O	8	**0.000**	**0.000**	**0.002**	0.206	0.641	0.163	0.608	0.485	0.082	**0.049**	0.141	0.202
L*P	12	**0.000**	**0.001**	**0.000**	0.537	0.507	0.726	0.269	0.317	0.992	0.122	0.770	0.702
L*R*O	8	**0.035**	**0.000**	**0.001**	0.315	0.511	0.902	0.338	**0.006**	0.485	0.625	0.614	0.738
L*R*P	12	0.634	0.711	0.401	0.908	0.979	0.590	0.464	0.916	0.910	0.933	0.548	0.516
L*O*P	24	0.301	0.923	0.361	0.616	0.980	0.650	0.447	0.782	0.817	0.944	0.814	0.737
L*R*O*P	24	0.902	0.795	0.926	0.970	0.367	0.767	0.568	0.668	0.749	0.778	0.967	0.981
Y*L*R	4	**0.000**	**0.000**	**0.000**	0.205	0.778	**0.004**	0.940	**0.046**	0.125	**0.041**	**0.047**	0.062
Y*L*O	8	**0.000**	**0.000**	**0.000**	0.930	0.341	0.248	0.377	0.256	**0.043**	0.544	0.171	0.154
Y*L*P	12	0.581	0.911	0.083	0.950	0.425	0.262	0.539	0.729	0.625	0.173	0.539	0.650
Y*L*R*O	8	**0.000**	**0.000**	**0.000**	0.101	0.804	0.977	0.794	**0.022**	0.153	0.599	0.403	0.493
Y*L*R*P	12	0.948	0.960	0.482	0.919	0.987	0.353	0.585	0.981	0.523	0.601	0.418	0.329
Y*L*O*P	24	0.985	0.817	0.892	0.605	0.904	0.589	0.097	0.680	0.719	0.211	0.212	0.222
Y*L*R*O*P	24	0.955	0.650	0.117	0.915	0.298	0.503	0.519	0.960	0.761	0.720	0.227	0.144

Key: **Y** = Year; **L** = Location; **R** = Row Spacing; **O** = Opener Width; **P** = Phosphorus Rate; **DAS** = Days After Seeding

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w spacing, opener width and P rate on plant density, plant height, biomass yield, grain yield, HI, green seed content, TKW, test
nd protein content of canola

Plants per m² ys After eeding 21	Plants per m² Post Harvest	Plant height (cm)	Biomass Yield (kg/ha)	Grain Yield (kg/ha)	Grain Yield (bu/ac)	Harvest Index (%)	Green Seed Content (%)	Thousand Kernel Weight (g)	Test Weight (kg/hL)	Oil Content (%)	Protein Content (%)
81 a	77 a	102.0 b	6426 b	2830 a	50.7 a	45.89 a	0.96 a	3.27 a	65.9 a	46.7 a	25.6 a
75 b	70 b	103.4 a	6682 a	2688 b	48.2 b	42.63 b	0.97 a	3.29 a	65.9 a	46.6 a	25.7 a
***	***	**	***	***	***	***	ns	ns	ns	ns	ns
2	1	0.9	126	52	0.9	1.08	0.16	0.02	0.1	0.14	0.1
75 c	73 b	103.4 a	6559 a	2790 a	50.0 a	44.49 a	1.06 a	3.27 a	65.9 a	46.7 a	25.6 a
78 b	75 a	103.2 a	6576 a	2741 a	49.1 a	44.01 a	1.00 a	3.28 a	65.8 a	46.7 a	25.6 a
81 a	73 b	101.4 b	6527 a	2746 a	49.2 a	44.29 a	0.83 a	3.29 a	65.9 a	46.6 a	25.7 a
***	***	***	ns	ns	ns	ns	ns	ns	ns	ns	ns
2	2	1.3	185	76	1.4	1.59	0.23	0.03	0.2	0.20	0.2
c)											
82 a	79 a	101.2 c	6349 b	2676 b	48.0 b	43.91 a	0.97 a	3.26 a	65.9 a	46.6 a	25.7 a
79 b	74 a	102.4 bc	6524 ab	2736 ab	49.0 ab	44.24 a	0.98 a	3.29 a	65.8 a	46.7 a	25.6 a
76 bc	71 b	103.2 ab	6644 a	2798 a	50.1 a	44.45 a	0.88 a	3.29 a	65.9 a	46.7 a	25.5 a
75 c	70 b	104.0 a	6699 a	2827 a	50.7 a	44.45 a	1.05 a	3.28 a	66.0 a	46.6 a	25.6 a
***	***	***	***	***	***	ns	ns	ns	ns	ns	ns
3	2	1.6	234	96	1.7	2.01	0.29	0.04	0.2	0.3	0.3

nd main factor, means followed by the same letter are not significantly different at α = 0.05.

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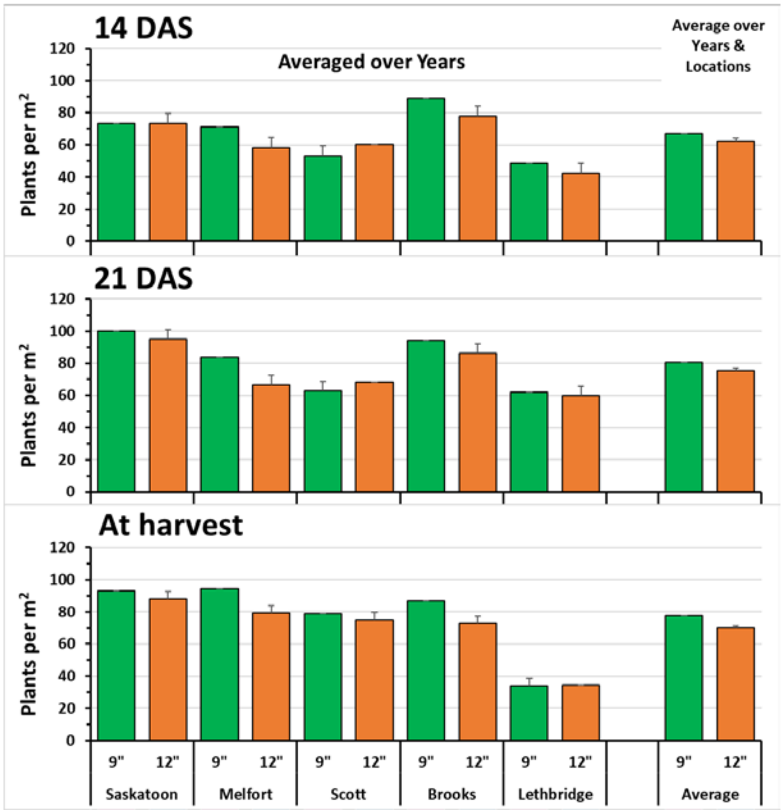
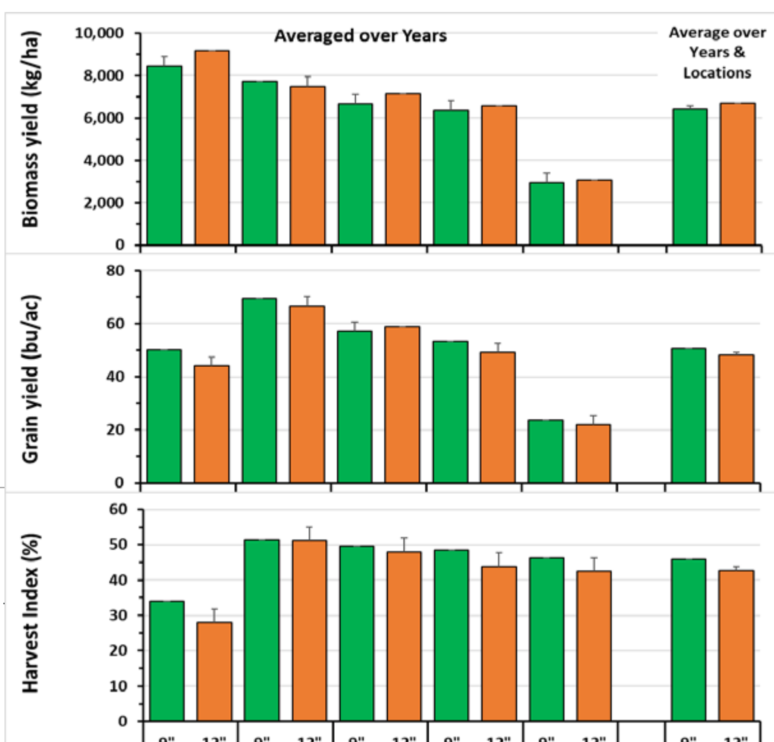


Fig. 16. Effect of row spacing on plant density at 14 DAS, 21 DAS and at harvest at various locations. Error bars denote Tukey's HSD at α = 0.05 level of significance.



Analysis of the combined data from 2018 and 2019 show significant treatment effect of RS, OW and PR (Tables 7 & 8). Despite several interaction effects observed, all three main factors had significant effects on plant density (Table 7, Fig. 16). Plant counts taken 14 DAS showed that plant density was higher at 9" RS than at 12" RS when averaged across locations (Table 8).

Twenty one DAS and at harvest, plant density at 9" RS was higher than at 12" RS at all locations except Lethbridge where no difference in plant density between 9" and 12" RS was observed. At these two sampling dates, averaged over locations, plant density remained higher at 9" RS than at 12" RS.

Row spacing had a significant effect on plant height, biomass yield, grain yield and harvest index. At all locations, except Melfort, aboveground biomass yield was higher at 12" RS than at 9" RS, and was significantly so at Saskatoon and Scott. At Melfort, biomass yield was higher but not significantly so at 9" RS than at 12" RS. When averaged over locations, biomass yield was higher at 12" than at 9" RS.

Grain yield was higher at 9" than at 12" RS at all locations except Scott. However, differences in grain yield were significant only at Saskatoon, Melfort, and Brooks. Averaged over locations and years, grain yield was higher at 9" than at 12" RS.

Harvest index was higher at 9" than at 12" at all locations, and the differences were found significant at Saskatoon, Brooks and Lethbridge; as well as when averaged over locations and years.

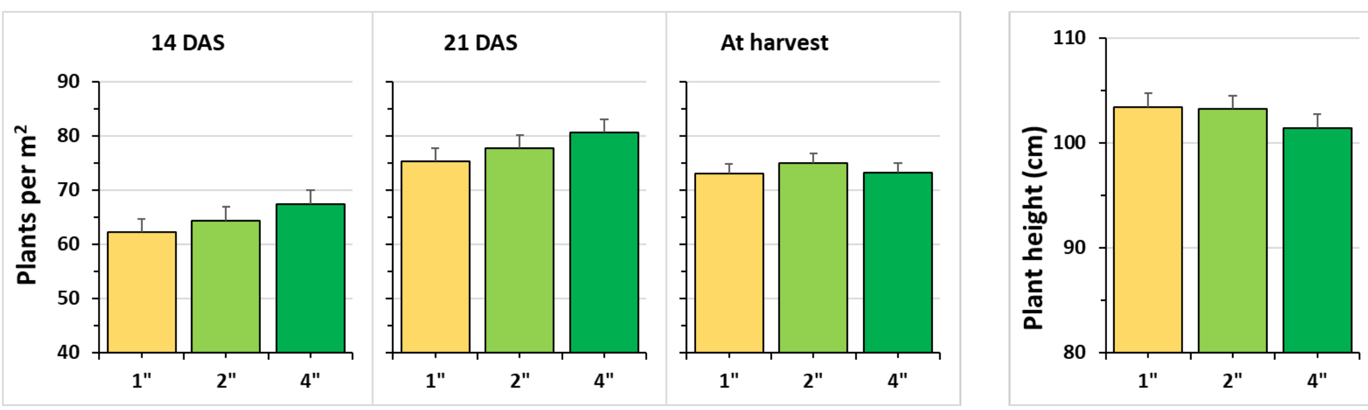


Fig. 18. Effect of opener width on plant density at 14 DAS, 21 DAS and at harvest, and plant height averaged over locations. Error bars denote Tukey's HSD at α = 0.05 level of significance.

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As a main factor, and combined over the two years, RS had significant effect only on plant density and plant height (Table 7, Fig. 18). Plant density at 14 and 21 DAS increased with increasing OW. However, plant density at harvest time showed that the increase was only at 2" OW and declined to the plant density observed at 1" OW. Plant height was lower at 4" OW than at 1" and 2" OW.

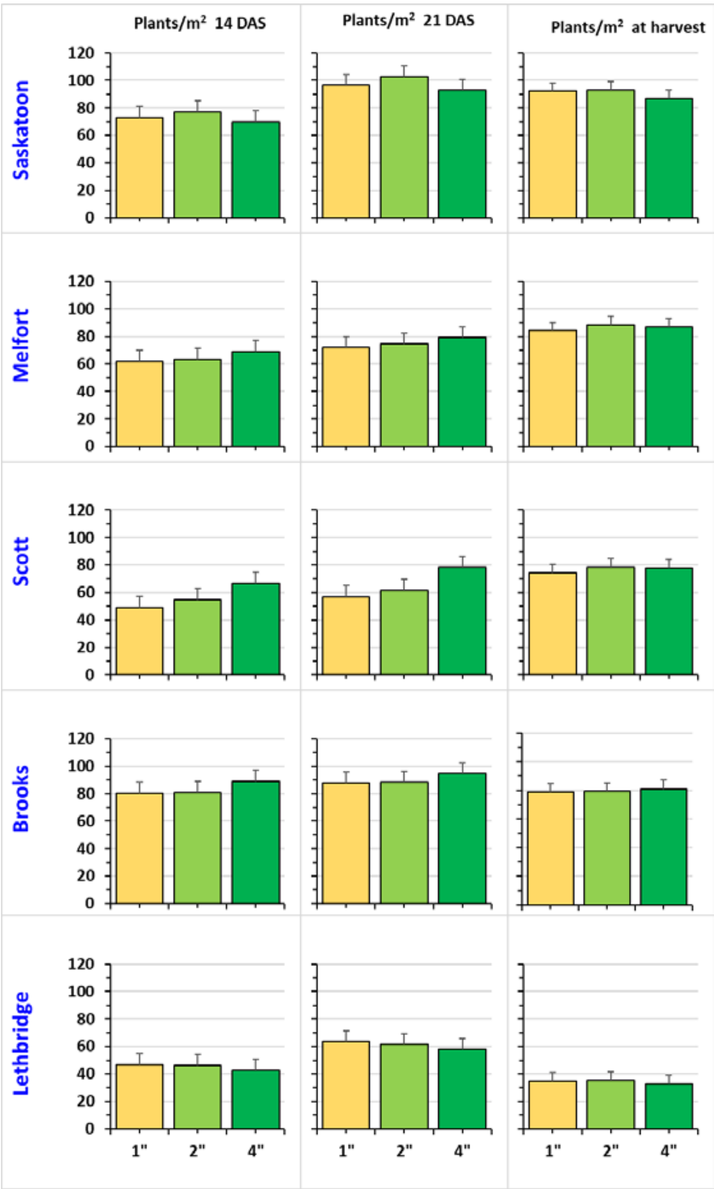

Fig. 19. Effect of row spacing on plant density at 14 DAS, 21 DAS and at harvest at various locations. Error bars denote Tukey's HSD at α = 0.05 level of significance.

Significant LOxOW interaction effects were observed for plant density (Table 7, Fig. 19). At 14 and 21 DAS, increasing OW resulted in increasing plant density at Melfort, Scott and Brooks. At Saskatoon and Lethbridge, plant density declined at 4" OW and significantly so at 21 DAS. By harvest time, very subtle differences in plant density were observed among the OWs.

Significant interaction effects of year, location, RS and OW was observed for plant density (Table 7). Figure 20 below puts this information together to show the nature of interaction effects observed. The effect of OW varied with RS, location and year. The most outstanding difference was the drop in plant density at 4" OW and 9" RS in 2019 as compared to 2018 at most locations. This drop was significant at Saskatoon, Scott, Brooks and Lethbridge at all sampling dates.

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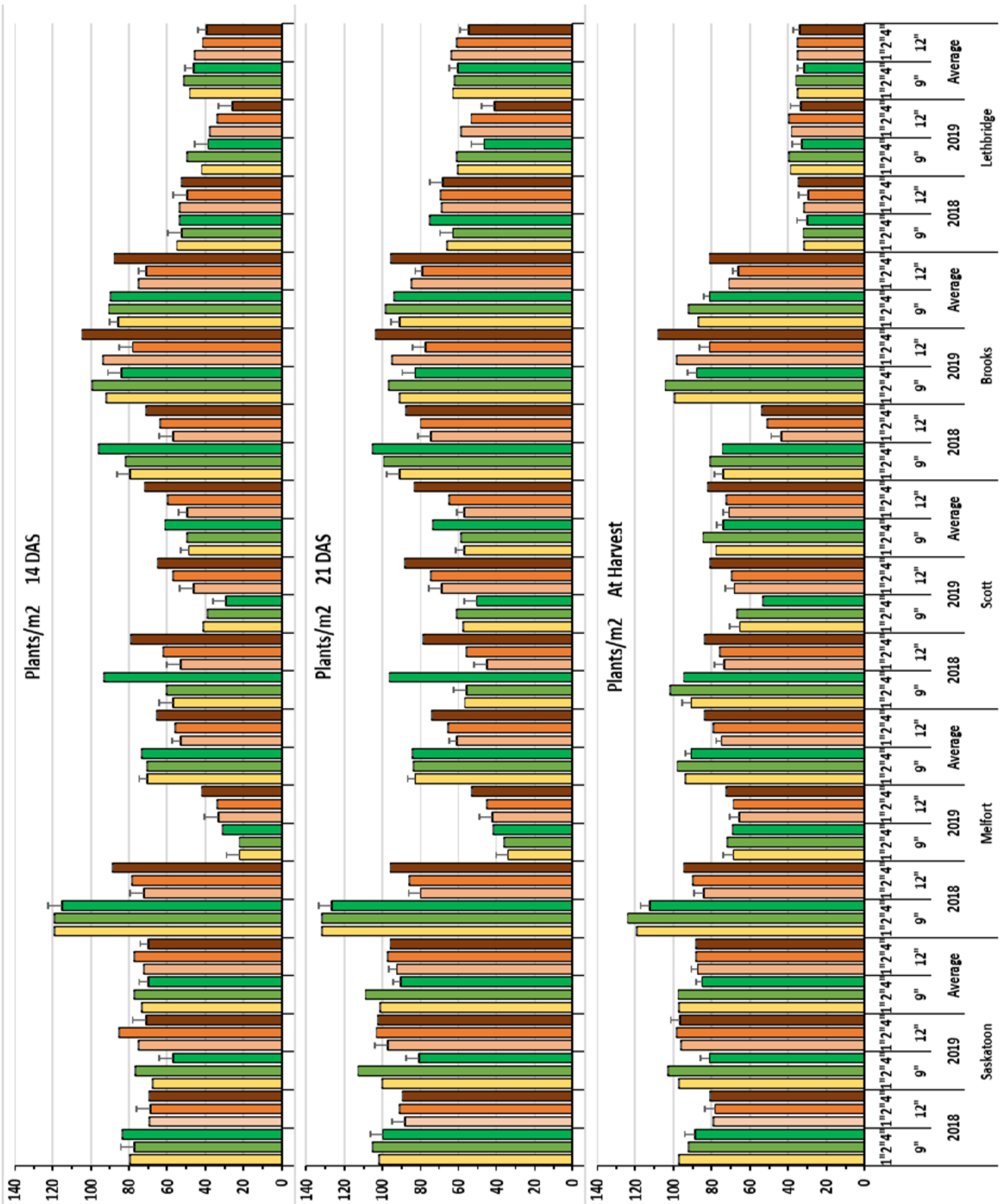

Fig. 20. Interaction effects of year, row spacing and opener width on plant density at various locations. Error bars denote Tukey's HSD at $\alpha = 0.05$ level of significance.

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Averaged over the two years, the drop in plant density at 4" OW and 9" RS was significant (at harvest) at all five locations. Except at Lethbridge, plant density at 4" OW tended to be higher than at 1" and 2" OW at all locations. At Lethbridge, plant density at 4" OW and 9" RS was lower than at 1" and 2" OW, particularly at 14 and 21 DAS. No differences in plant density were observed at harvest time at Lethbridge.
Averaged over locations, years, RS and OW, the effect of increasing the rate of seed-placed phosphorus was a significant decrease in plant density, as observed at all stages of sampling (Fig. 21). Although statistically significant, the absolute decrease in plant density was not huge. We are talking about a difference of eight, seven and nine plants per square meter at 14 DAS, 21 DAS and at harvest, respectively. Similarly, averaged over all factors, increasing P rate also increased plant height, biomass yield and grain yield, although the increases were not huge.

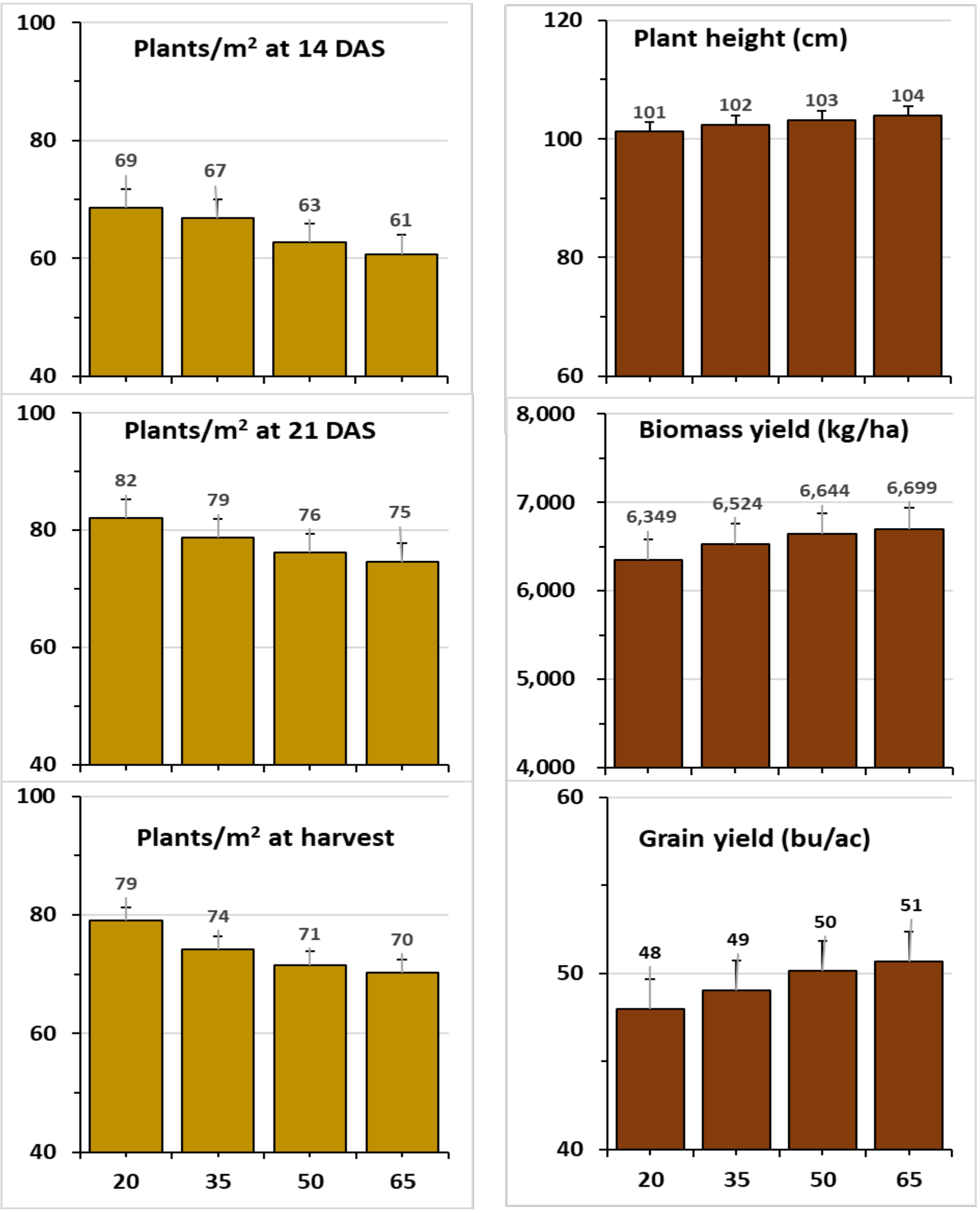

Fig. 21. Effect of seed-placed phosphorus rate on plant density, plant height, biomass yield and grain yield. Error bars denote Tukey's HSD at α = 0.05 level of significance.

Figures 22 and 23 below, show the effect of increasing seed-placed P fertilizer on plant density, biomass yield and grain yield at the six OW and RS

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combinations, and at various locations. Across the different combinations of OW and RS, generally, plant density decreased with increasing rate of seed-placed P fertilizer. This was observed for both 9" and 12" RS. Strong response to seed-placed P fertilizer was observed at Melfort, Scott and Brooks.

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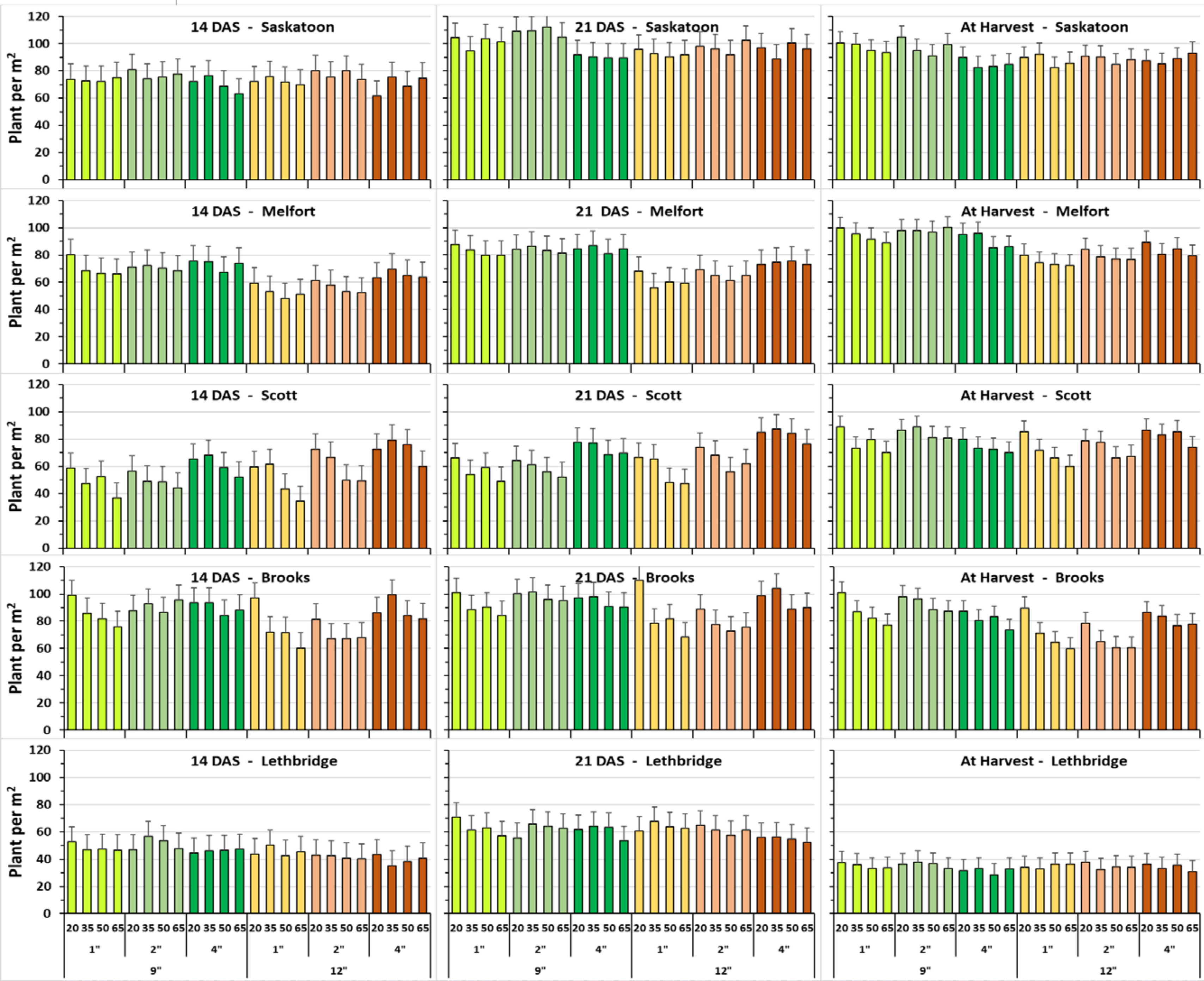

Fig. 22. Effect of increasing rate of seed-placed P fertilizer at various row spacing and opener width on plant density at various locations averaged over 2018 and 2019 seasons. Error bars denote Tukey's HSD at α = 0.05 level of significance.

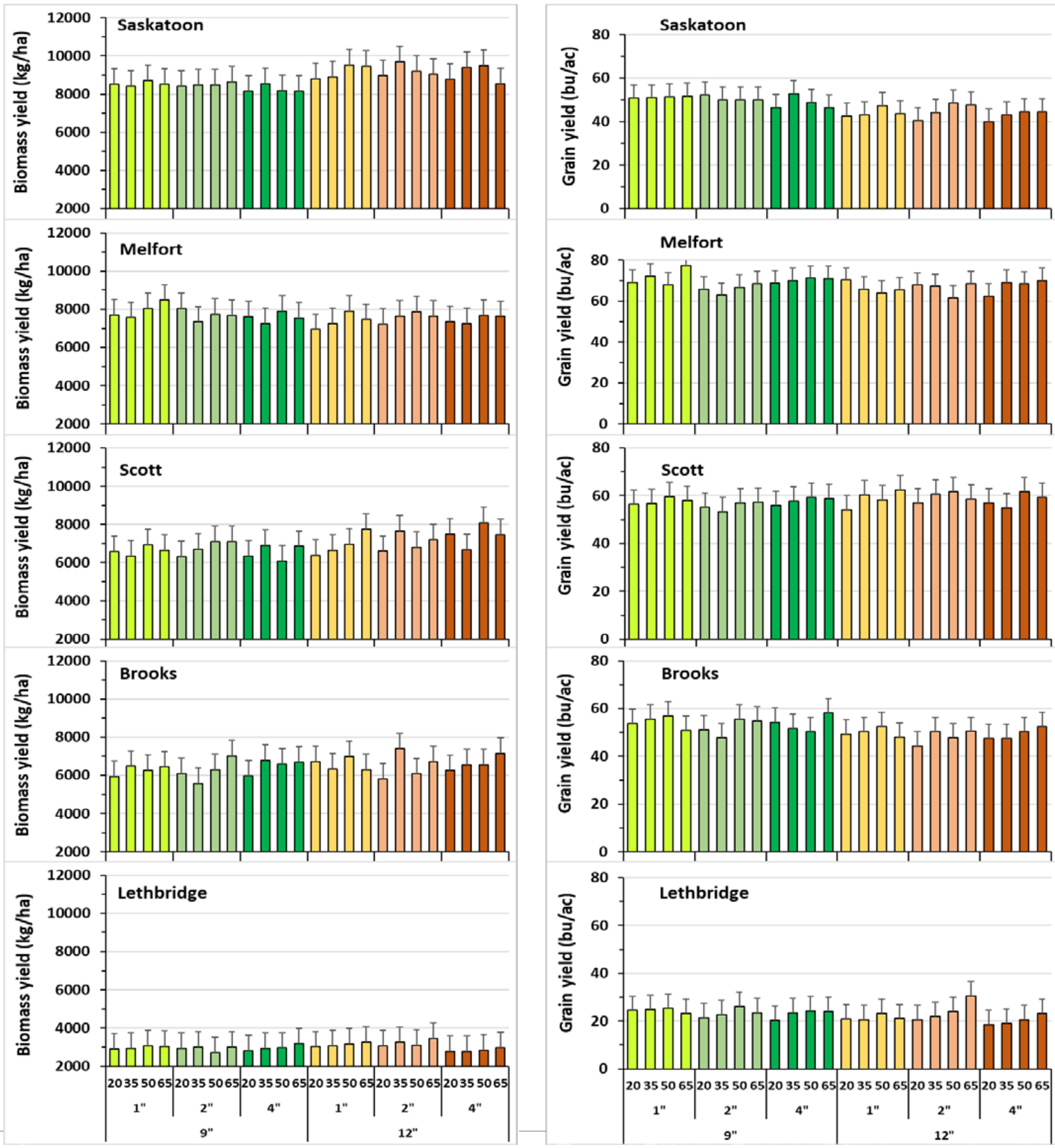

Fig. 23. Effect of increasing rate of seed-placed P fertilizer at various row spacing and opener width on biomass yield and grain yield at various locations averaged over 2018 and 2019 seasons. Error bars denote Tukey's HSD at α = 0.05 level of significance.

Each combination of RS and OW represents seed-bed utilization (SBU) level. It's against this configuration that our focus of the impact of increasing rate of seed-placed P fertilizer was placed. Averaging over PR gives us an overview of the effect of the six configurations on various canola crop parameters. Increasing OW resulted in increasing plant density at all three sampling dates at 12" RS (Fig. 24). At 9" RS, no significant increase in plant density was observed at 14 and 21 DAS. At harvest time, plant density was significantly lower with 4" openers than with 1" and 2" openers. Within RS no differences in biomass yield were observed with different openers. However, biomass yields with 2" and 4" openers at 9" RS were lower than those with 12" RS. Grain yield was higher at 9" RS than with 12" RS with 1" or 4" openers. Similarly, harvest index was higher at 9" RS with 1" and 4" openers than with the corresponding openers at 12" RS. Plant height at 12" RS with 1" and 2" openers were significantly higher than with the other four configurations. No differences in green seed content were observed except for a lower green seed content with 9" RS and 4" openers than that with 12" RS and 1" openers. Row spacing and OW configuration had no effect on any other canola characteristic such as oil and protein content, TKW, and test weight.

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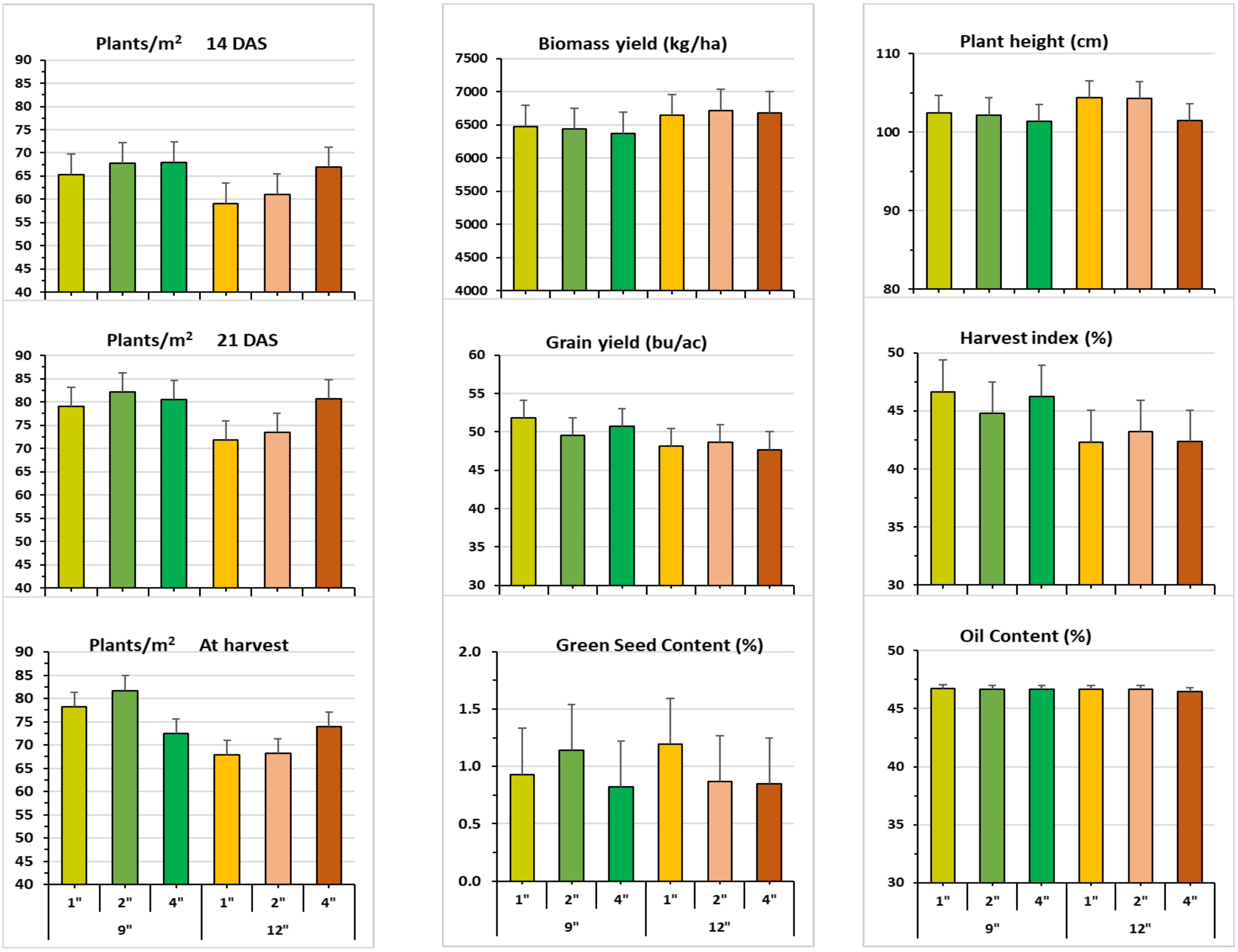

Fig. 24. Interaction effect of row spacing and opener width on plant density, biomass yield, grain yield, green seed content, plant height, harvest index and oil content of canola averaged over locations and years. Error bars denote Tukey's HSD at α = 0.05 level of significance.

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The effect of rate of seed-placed P fertilizer on canola was measured within the six SBU levels. Results of data combined over locations and years, show significant response to increasing rate of seed-placed P fertilizer on plant density, biomass yield and grain yield (Fig. 25). Increasing rate of seed-placed P fertilizer resulted in decreased plant density with all six configurations at all three sampling dates. Increasing rate of seed-placed P fertilizer had no effect on plant height within the same configuration of row spacing and opener width.

Biomass yield and grain yield increased with increasing rate of seed-placed P fertilizer with all configuration of row spacing and opener width. The strongest increase in grain yield was observed with 12" RS, and 2" and 4" openers.

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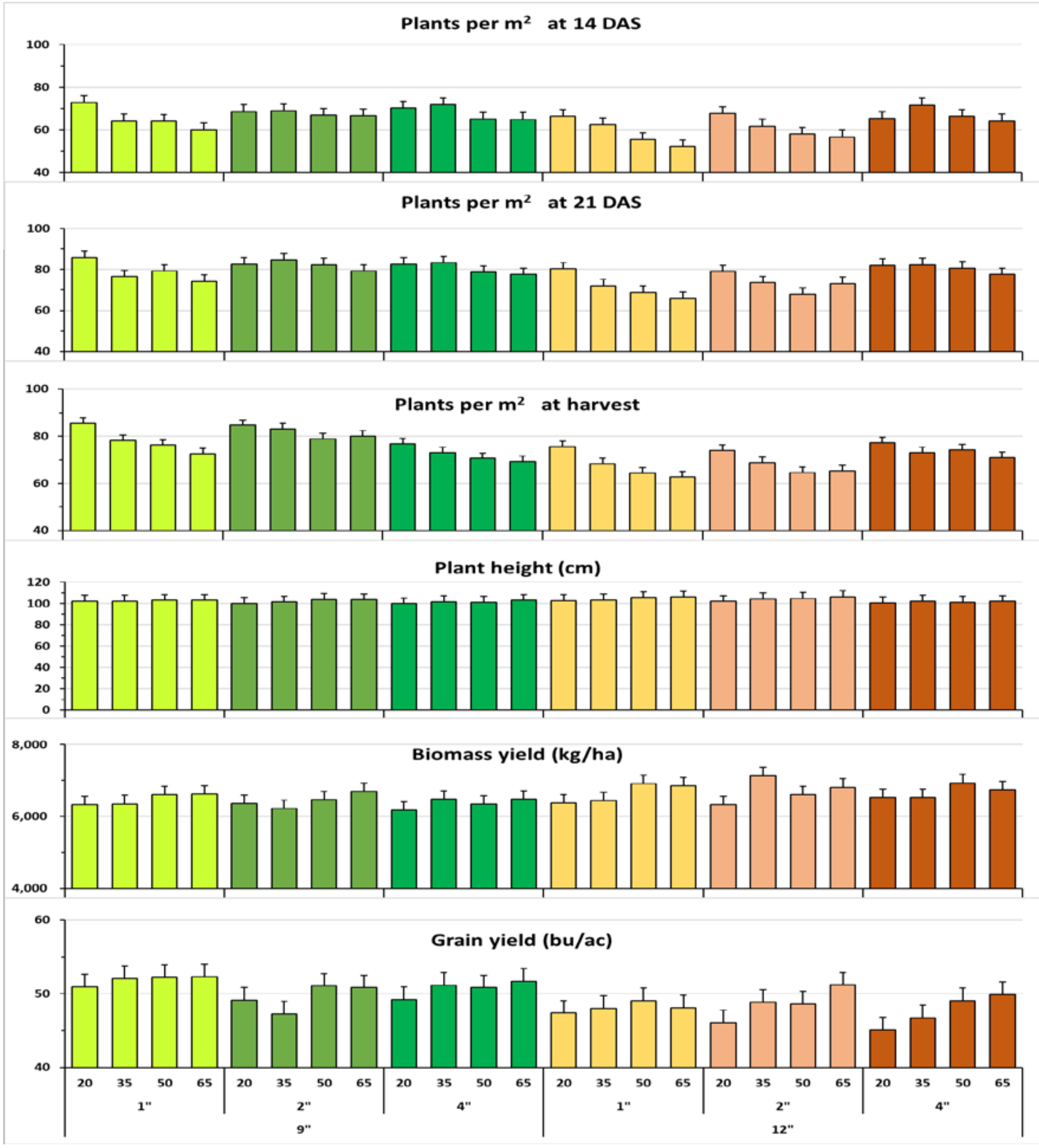

Fig. 25. Effect of increasing rate of seed-placed P fertilizer at various row spacing and opener width on plant density, plant height, biomass yield, and grain yield averaged over locations and years. Error bars denote Tukey's HSD at α = 0.05 level of significance.

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Discussion

Results of this study indicate that indeed increasing seed bed utilization (SBU) by either narrowing RS from 12" to 9" and/or increasing OW from 1" to 4" results in reduced P toxicity of seed-placed P fertilizer, leading to increased number of plants per unit area. Increasing the rate of seed-placed phosphorus increases the toxic effect on seed and seedlings, leading to reduced plant population (Fig. 25). This toxicity was reduced by increasing SBU thus, reducing the concentration of P fertilizer near the seed (Fig. 24). While in 2018, no significant adverse effects were observed by increasing the OW on plant establishment except at Saskatoon, in 2019, it was observed that using a 4" opener may lead to seeding problems. In 2019, it was observed that increasing OW caused seeding problems as the rear openers of the drill threw too much soil on rows of front openers, thus burying the seeds in those rows too deep. This was more significant at Saskatoon, Lethbridge, Brooks and Scott (Fig. 19; Appendix 1). At Lethbridge, in particular, rows 2, 4, 6 & 8 were buried so deeply at 4" OW that only four rows (1, 3, 5 & 7) had plants in them going forward. Hence, plant density 14 DAS, was significantly low at 9" RS than at 12" RS. The exception was at Lethbridge where plant density was higher at 9" RS than at 12" RS, despite the significant reduction in the number of rows from eight to four at the 9" RS.

While the reduction in plant density with increasing OW was more obvious in 2019, particularly at 14 and 21 DAS, a similar pattern was observed at later assessment stages in 2018. In particular, at harvest, it was observed that plant density at 4" OW with 9" RS was lower than that at 1" or 2" OW (Fig. 24). This means that at narrow RS such as 9", there may be sufficient soil disturbance that may prevent emergence of canola seedlings causing significant drop in plant population. The change in plant density with time, suggests that while there may be a higher number of emerging seedlings with increased OW, if these seedlings had to push through more soil, they may result in weaker plants that don't make it to harvest. Hence, when using narrow RS, seeding speed should be taken into consideration to ensure that rear openers do not throw too much soil on seed rows opened by front openers. The two locations (Saskatoon and Lethbridge) where this problem was most pronounced have clay soil texture. On the other hand, Melfort with silt clay loam to clay loam soil, and Scott and Brooks with loam soil, were less impacted. In contrast, at 12" RS, plant density increased with opener size from 1" to 4". However, the increased toxicity at 1" and 2" openers with 12" RS, resulted in significant reduction in plant density when compared to plant densities at these opener sizes with 9" RS (Fig. 24). The reduced plant density at 4" OW and 9" RS was not different from the enhanced plant density at 4" OW at 12" RS. This suggests that, producers using 12" RS can reduce toxicity of seed-placed P by increasing OW up to 4". On the other hand, producers using 9" RS may cause reduction in plant density if they exceed 2" OW in trying to reduce seed-placed P toxicity in canola.

Averaged over the two seasons (2018 and 2019) and locations, the effects of these treatment combinations on plant density did not translate into similar effects on biomass yield, grain yield and other canola crop characteristics. By and large, no significant biomass yield or grain yield were observed in 2018, except at Scott where biomass decreased at 4" OW and 9" RS (Fig. 9). Considering the current configuration of 1" OW and 9" RS in the guidelines for safe rate of seed-placed P fertilizer, in our study, no improvement in grain yield was obtained by increasing OW to 4" as a result of the establishment issues discussed above. However, grain yield was

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significantly lower with all opener sizes at 12" RS than that at 1" and 4" openers with 9" RS (Fig. 24). This shows the overall advantage of 9" RS over the 12" RS.

Despite the reduction in plant population with increasing rate of seed-placed P fertilizer, significant increase in grain yield was observed in response to PR, albeit small absolute increments. This is usually attributed to the compensatory abilities of the canola plant which takes advantage of the reduced plant population by branching out more such that the individual plants that survive produce more than they would at a higher plant population. Much as we are aware that canola can compensate for reduced plant population, we are wondering how much of that compensation was actually due to increasing P availability. We have speculated that while increasing P rate resulted in increased P toxicity, leading to death of some seed and seedlings, the increased amount of available P helped surviving plants at higher rates of P yield better than the more numerous plants at low rates of P.

Lack of precipitation at most locations also contributed to the reduced treatment effects. Under very dry conditions in both 2018 and 2019, the seeds did not have sufficient moisture to initiate the germination process. This may have been exacerbated by the presence of phosphorus fertilizer. In 2019 in particular, it was not until sufficient precipitation (or irrigation as in the case of Saskatoon) was received that germination commenced. It is speculated that this lag in time also resulted in gradual reduction in P toxicity, resulting in a lower reduction in plant density with increasing P rate. This may sound ironic because guidelines indicate that P fertilizer toxicity may be exacerbated by low soil moisture conditions. Under dry conditions of 2019 in particular, canola seed simply remained dormant and did not germinate until soil moisture became available. Therefore, soil moisture conditions which allow canola seed to germinate but not sufficient enough to overcome the salt toxicity of seed-placed P fertilizer can cause significant reduction in plant density.

In this study, we observed less toxic effects of seed-placed P fertilizer at different SBU ratios than expected, indicating that, canola can tolerate higher levels of seed-placed P when N and S are not placed with the seed. By banding the N and S fertilizer away from the seed, we removed a significant source of toxicity which, otherwise, would enhance toxicity of seed-placed P in canola. We can only speculate that the results could have been different had N and S been applied in the seed row.

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Study limitations and recommendations

The ability of this study to deliver on all proposed objectives has been limited by a few things. First and foremost, the exclusion of seed-placed N and S, resulted in higher rates of seed-placed P looking safe enough. Therefore, for producers who are placing N and S away from the seed at seeding, they could increase the rate of seed-placed P a little more without causing significant damage to canola seedlings.

The second limitation is the failure to separate the beneficial effect of increased P rate with the compensatory ability of a canola crop. Given the reduction in plant density with increasing seed-placed P rate, it was expected that yield would also be low. Much as we are aware that canola can compensate for reduced plant population, we are wondering how much of that compensation was actually due to increasing P availability. We have speculated that while increasing P rate resulted in increased P toxicity, leading to death of some seed and seedlings, the increased amount of available P helped surviving plants at higher rates of P yield better than the more numerous plants at low rates of P. This can only be determined by supplying the same amount of P to all treatments. This could be done for example by applying say amount of P as total, but increasing amounts as seed-placed P fertilizer and the balance side banded.

The third limitation was replication in time. The two years of this study were not sufficient to lead to strong conclusions of the findings. Year had a significant interaction effect with other factors. With two years only, the treatment effects are likely to cancel each other out. A third year, would have consolidated the results much better.

Hence, this study does not have sufficient information to meet Objective Number 3, i.e. generate guidelines specifying safe maximum rates of seed-placed P fertilizer for canola. To achieve this, all three limitations described here need to be addressed.

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