PROJECT DETAILS

- **Title**: Manipulating agronomic factors for optimum canola harvest timing, productivity and crop sequencing
- **Funders:** Alberta Canola, SaskCanola, Manitoba Canola Growers, Canola Council of Canada and Agriculture and Agri-Food Canada
- **Research program:** Canadian Agricultural Partnership (CAP)
- **Principal investigator:** Brian Beres
- **Collaborators/additional investigators:** Charles Geddes, Breanne Tidemann, William May, Ramona Mohr
- **Year completed:** 2023

Final report

Introduction

Canola tends to be a dominant cash crop of most small grains cropping systems in the Canadian Prairies. However, high canola commodity prices can be offset by expensive inputs such as hybrid seed and multiple pre-harvest operational steps. An optimal seeding rate can maximize canola seed yield, reduce production costs, and result in significant savings for the producers (Dhillon et al., 2022). Seeding rate recommendations for optimal stand density and yield response vary between 100-150 seeds m^{-2}, the latter required to achieve the optimum stand density of 75-80 plants m^{-2} (Harker et al. 2003; Harker and Hartman 2016). While this density improves the weed competitive ability and reduces the percentage of green seed amount, grain yield responses were not observed beyond 100 seeds m^{-2} (Harker and Hartman 2016). Thus, in response to balancing crop input costs with maximum net returns, consideration toward lowering the optimal stand threshold by 25% (or more) has been proposed and is widely practiced. For example, the Canola Council and Harker et al. (2016) report that, despite canola seed providing the greatest impact on canola production second to only nitrogen, over half of western Canadian growers plant at rates that achieve <40 plants m^{-2}. The argument is that crops such as canola and winter wheat have superior compensatory mechanisms (branching/tillering) that buffer against yield declines or weed management implications from the lower seeding rates. While pod numbers in the field may not decline significantly with lower sowing densities, the canopy architecture may be altered such that substantially more branches than main stems are produced. How this augmented feature interacts with both harvest timing and harvest method (straight-cutting vs. swathing) is not fully understood. This could result in an erroneous determination of % seed color change and subsequent harvest, which increases the risk for seed loss. Lesser than ideal plant stands are not always an artifact of a low seeding rate as biotic and abiotic factors can cause detrimental effects on plant stands. Thus, agronomic information in the context of how lowered plant stands influence crop phenology and canopy architecture will improve harvest timing and minimize seed losses.

There is a movement toward the adoption of pod shatter reduction canola hybrid cultivars and straight-cutting at harvest (Brackenreed, 2019) in order to improve operational logistics and costs by removing the swathing operation. The elimination of swathing and switching to straight-cut harvesting may not result in a yield penalty nor increase seed losses (Haile et al. 2014). However, hybrid selection can cause differential seed loss and seedbank additions, and may be more apparent in swathing treatments than straight-cutting treatments. Innovations to mitigate pod shatter such as pod sealant products have been studied and did not reduce pod-shattering (Haile et al. 2014). A separate survey study concluded hybrid selection might not contribute to harvest losses, which the authors concluded was more readily prevented with management such as earlier windrowing and harvest dates (Cavalieri et al. 2016). Of course, hybrid selection could either facilitate or prevent earlier harvests depending on the growing degree-day requirements of the selected hybrid. Other studies suggest greater losses occur from straight-cutting and scientists have used implements to ‘push canola’ instead of traditional cutting/swathing. While this method has potential the authors conclude it can delay crop maturity and reduce stubble heights (Irvine and Lafond 2010). These results would be detrimental to subsequent crops such as winter wheat that rely upon early-harvested canola with stubble heights that exceed 15 cm. Our proposal would build upon these findings by validating which phenomena repeat when swathing occurs at 60% seed color change or at 90% seed color change; and when straight-cutting occurs at 10% seed moisture vs. 5% seed moisture. Not only would cultivar selection potentially interact with the harvest method, but it is plausible that the presence of greater or fewer branches, as influenced by the seeding rate, would also influence straight-cutting efficiency. Lastly, the seeding rate by harvest method could potentially interact with crop sequencing from the canola phase to the succeeding crop, particularly if it was a wheat phase with a winter growth habit. This project will employ a sound agronomic and cross-disciplinary approach that will deliver science-based solutions to overcome canola harvest and production issues for use by the canola value chain including stakeholders, producers, and policy-makers. The project seeks to establish the risks and benefits associated with an integrated system when manipulations are made to seeding rate and cultivar selections, and the impact those decisions have on straight-cutting and swathing harvest systems. This study will test the following hypothesis:

1) Are harvest timing determinations and recommendations density-dependent?
2) Should harvest timing recommendations be modified based on the harvest management system or cultivar?

Objectives

1) Understand how manipulations made to seeding rate, pod shatter reduction hybrid, and swath/straight-cutting timing alter crop yield and quality.
2) Refinement of best grower practices in relation to the determination of optimal swathing/straight-cutting timing methodology as plant density changes and as subsequent changes to canopy architecture, whole plant moisture, seed color, and moisture changes occur.
3) Determine how the integration of seeding rate, cultivar selection, and harvest management system influence canola canopy architecture, i.e., pods/branches per plant and per unit area.
4) Provide an economic analysis for low vs. high seeding rate systems and straight-cutting vs. swathing scenarios.

Materials and methods

Site description and experimental design

Experiments were conducted at four locations, Lethbridge (49°41’N, 112°45’W) and Lacombe (52°26’N, 113°44’W), AB, Indian Head (50°32’N, 103°40.06’W), SK, and Brandon (49°51’N, 99°58’W), MB, Canada, over four growing seasons (2018, 2019, 2021, and 2022). The trial was suspended for the 2020 season as we were not allowed to access AAFC fields in a timely manner. A new area at these locations was selected each year of the study, which was a full factorial that consisted of three seeding rates, two pod shatter reduction hybrids, and four harvest methods (Table 1). The treatments were arranged in the field as a factorial randomized complete block design with four replicates. The followings are the details of the treatments included in this study.

Seeding rates: 60, 120, and 180 seeds m^{-2}, to achieve a target plant density of 40, 70, and 100 plants m^{-2}, respectively.

Pod shatter reduction hybrids: L233P (early-maturing) and L255PC (late-maturing). The 'early' and 'late' pod shatter reduction hybrid cultivars were chosen with similar expected responses for those traits not factored into the treatment design i.e. disease resistance.

Harvest methods: Swathing at 60% seed color change (SCC) and 90% SCC, Straight-cutting (SC) at 10% seed moisture, and SC at 5% seed moisture (or allow a minimum of one week between SC treatments). The 10% and 5% seed moistures are used to simulate a delayed harvest scenario. The moisture was managed with preharvest desiccant as needed to achieve uniform whole plant moisture, and to test pod shatter reduction trait responses to factors associated with delayed straight-cutting. Seed moisture content was determined using a commercially sourced portable grain moisture device. Seed color was measured using the 'Canola Swathing Guide' developed by the Canola Council of Canada (Anonymous 2015).

Plots were sown into standing stubble using a zero-tillage drill - experimental plot unit dimensions varied for each site. Each study area was treated with glyphosate (RoundUp®, Monsanto, St. Louis, MO, USA) a few days prior to seeding applied at a rate of 900 g a.i. ha^{-1} using a motorized sprayer calibrated to deliver a carrier volume of 45 L water ha^{-1} at 275 kPa pressure. In-crop herbicides Liberty (1.35L/ac), Centurion + Amigo (1.35L/ac), or Centurion (50 mL/ac) were used based on the weed spectrum present at each site-year. All plots received an appropriate amendements of phosphorus, potassium, and sulphur fertilizers depending on soil test results in the fall prior to seeding (Western Ag Labs PRS® soil test system).

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Data collection

Crop emergence counts for each plot were performed at two to four weeks after emergence by staking and counting two rows 1 m in length in each plot. The same area was used to perform fall stubble counts after harvest. Crop phenological data, such as date of bolting (BBCH 30), date of onset of flowering (BBCH 61), date of completion of flowering (BBCH 61), date of pod formation (BBCH 75), date of maturity were collected following guidelines developed by the Canola Council of Canada (Anonymous 2019). Leaf area index (LAI) and chlorophyll (Chl) levels were collected using a handheld AccuPAR LP 80 Ceptometer® and a FieldScout CM1000 Chlorophyll (Spectrum Technologies, Inc., Aurora, IL, USA), respectively, on a weekly basis starting from the 3rd leaf unfolded (BBCH 13) to pod formation (BBCH 75). Normalized difference vegetative index (NDVI) (Rouse et al. 1974) was recorded using a Green seeker optical sensor (NTech Industries Incorporation, Ukiah, CA, USA) at the same growth stages as LAI and Chl determinations. The NDVI values were calculated using the equation

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$$

where ρ_{NIR} and ρ_{RED} are spectral reflectance at near-infrared and red wavebands, respectively. The sensor was passed over the crops at a height of approximately 1 m above the canopy. All measurements were taken within 2 h of solar noon. Lodging was taken at physiological maturity using the scale of 1 to 10 where 1 = erect and 10 = completely lodged and flat on the ground (Roques and Berry 2016). All yield components such as the number of branches, number of fertile pods, pods weight, number of seeds, and seed weight per main raceme, primary branch, and secondary branch were recorded using the protocol developed by Angadi et al. (2003). Seed or pod shattering note was recorded using a categorical scale of 1 to 5, where 1= minimum to zero and 5= excessive.

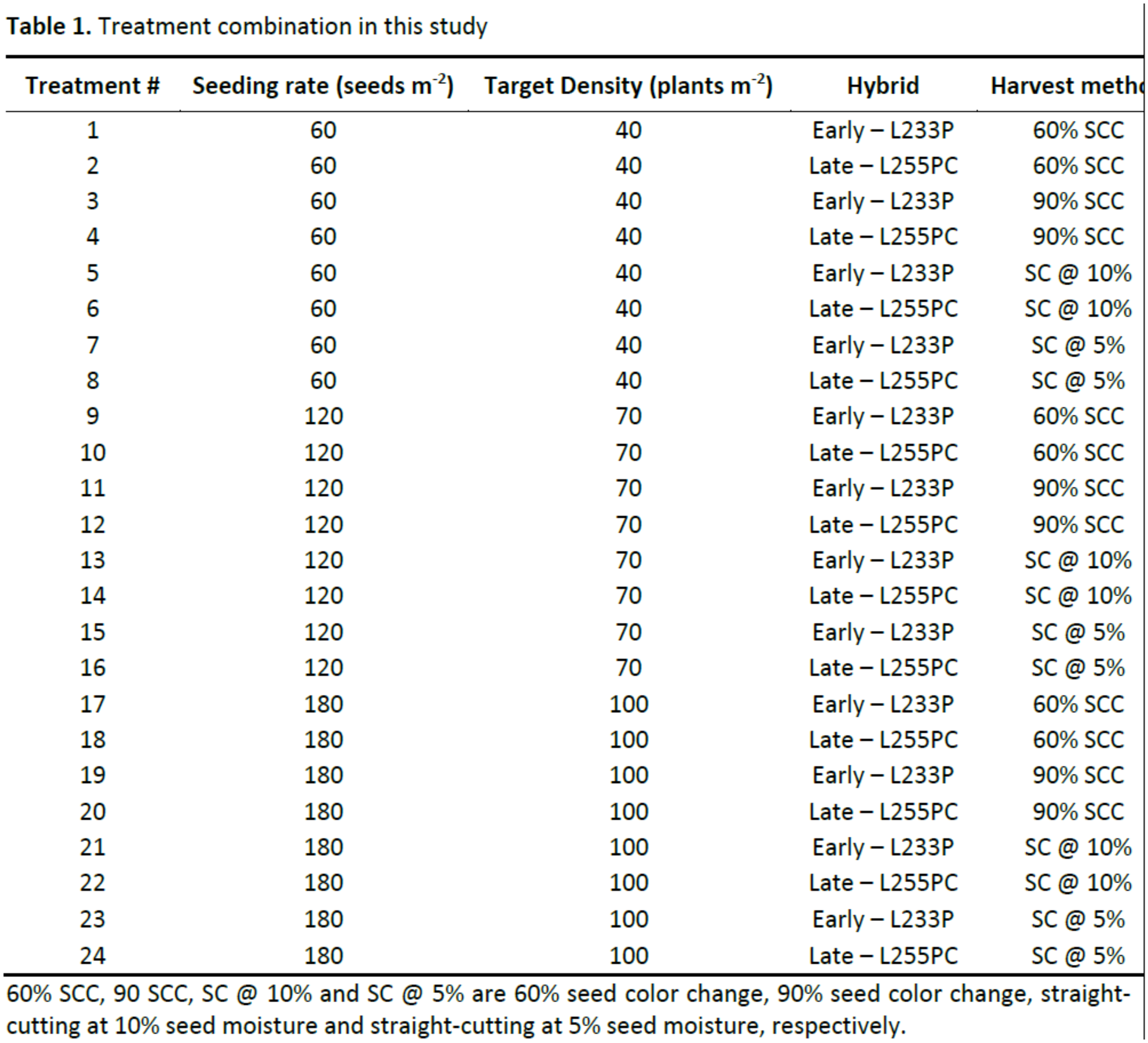

Table 1. Treatment combination in this study

Treatment #	Seeding rate (seeds m^{-2})	Target Density (plants m^{-2})	Hybrid	Harvest meth
1	60	40	Early – L233P	60% SCC
2	60	40	Late – L255PC	60% SCC
3	60	40	Early – L233P	90% SCC
4	60	40	Late – L255PC	90% SCC
5	60	40	Early – L233P	SC @ 10%
6	60	40	Late – L255PC	SC @ 10%
7	60	40	Early – L233P	SC @ 5%
8	60	40	Late – L255PC	SC @ 5%
9	120	70	Early – L233P	60% SCC
10	120	70	Late – L255PC	60% SCC
11	120	70	Early – L233P	90% SCC
12	120	70	Late – L255PC	90% SCC
13	120	70	Early – L233P	SC @ 10%
14	120	70	Late – L255PC	SC @ 10%
15	120	70	Early – L233P	SC @ 5%
16	120	70	Late – L255PC	SC @ 5%
17	180	100	Early – L233P	60% SCC
18	180	100	Late – L255PC	60% SCC
19	180	100	Early – L233P	90% SCC
20	180	100	Late – L255PC	90% SCC
21	180	100	Early – L233P	SC @ 10%
22	180	100	Late – L255PC	SC @ 10%
23	180	100	Early – L233P	SC @ 5%
24	180	100	Late – L255PC	SC @ 5%

60% SCC, 90 SCC, SC @ 10% and SC @ 5% are 60% seed color change, 90% seed color change, straight-cutting at 10% seed moisture and straight-cutting at 5% seed moisture, respectively.

The entire plot was harvested with a Wintersteiger Delta plot combine (Wintersteiger AG, Salt Lake City, UT, USA) equipped with a straight-cutting header, pickup reel, and crop lifters for straight-cutting or a modified Sund raking pickup when harvesting swathed treatments. Seed yield per plot was weighed on-board and is corrected to an 8.5 % moisture content. A 2 kg seed subsample was used to determine thousand seed weight (from 250 seeds) and test weight (kg hL$_{-1}$), oil and protein contents, and % green seeds. Seed oil content (dry matter basis) was measured using samples of 25 g of dry whole seed per sub-subplot, using an Oxford continuous-wave, low resolution nuclear magnetic resonance (NMR) instrument (Anonymous 1998). Seed protein content was measured by near-infrared reflectance spectroscopy technology (Foss Decater Grain Spec, Foss Food Technology Inc, Eden Prairie, MN). Seed/total loss (kg ha$_{-1}$)prior to harvest and at harvest were recorded after the cleaning of lost seeds or pods by a leaf blower or vacuum. Pre-swathing/pre-straight-cutting seed loss, seed loss at swathing, seed losses outside the combine track and inside the combine track during the combining operation were recorded separately. Total sed loss for the swathing treatments is the sum of seed loss at swathing, sed losses outside the combine track and inside the combine track, and that for the straight-cutting are seed loss outside the combine track plus that inside the combine track.

Statistical Analysis

Univariate mixed model analysis was conducted with the MIXED and GLIMMIX procedures of SAS (Littell et al. 2006; SAS Institute 2013). The effects of environment (site by year combinations) and replicate were considered random, and the effect of the applied treatments was considered fixed. A Gaussian error distribution was used for the PROC GLIMMIX portion of the analysis. When the data were analyzed individually by environment, the replicate was treated as a random effect.

A preliminary PROC MIXED analysis was conducted to estimate starting covariance parameter estimates. These estimates were ‘passed’ to a PROC GLIMMIX analysis using the PARMS statement along with the *noiter* option (SAS Institute 2013). Exploratory analyses revealed that residual variances were heterogeneous among environments. The AICc (corrected Akaike’s information) model fit criterion confirmed that it was beneficial to model residual variance heterogeneity among environments. Variance heterogeneity was modeled using the RANDOM statement for PROC GLIMMIX. The COVTEST statement of PROC GLIMMIX was used to conduct a likelihood ratio significant test for covariance parameter estimates were different from 0.

An extension of the previously described MIXED model (sensitivity analysis of variance) (Littell et al. 2002) was implemented to further explore a notable environment by treatment interactions for two important canola parameters, seed yield, and oil content. A covariable (environment means) by treatment (all combinations of hybrid by seeding rate by harvest method) interaction was included in the model statement to determine if treatment differences varied among environments. Separate slope regression coefficients (sensitivity coefficients) were estimated using *noint* option with the PROC GLIMMIX model statement. Regression (sensitivity) means were estimated at different levels for the environment means to examine how treatment differences varied with changing environment means.

Random forest analysis was conducted to model the effect of all canola yield components on yield. The analysis was conducted using the PROC HPFOREST procedure (SAS Institute 2015). The data set was partitioned into a training (65% of the total data set) and validation (35% of the total data set) data set. The model was tuned with max trees set to 100, vars_to_try set to 25, max depth set to 50, and leaf size set to 6, which are close to the default settings for PROC HPFOREST. The top yield component predictors were selected for subsequent analysis using the MSEOOB. Predictor selections occurred up to the point where MSEOOB leveled off near its least level.

A partial least squares (PLS) analysis was performed using the PROC PLS procedure of SAS (SAS Institute 2013) for selected predictors, yield component and in-season vigor variables (LAI, Chl, and NDVI), from random forest analysis, and with yield as the response variable. VIP and standardized regression coefficients were estimated to give a general idea of the relative importance of the yield component and in-season vigor predictors. Wold (1995) indicated that the most important predictors for a PLS analysis will have a VIP > 0.8. The second component of the PLS analysis entailed the estimation of a set of orthogonal factors that maximize predictive power, i.e., latent variable (LV) represents a composite weighting of the effect of the above-mentioned predictors towards canola yield. R-squared values from PLS analysis were used to determine the most important LVs (five in this case). Scores from each LV were used to calculate an Xloading, which is the correlation of actual predictor data with the scores from each LV. The LV scores associated with yield components or in-season vigor variables (predictor extract) were then subjected to the PROC MIXED model described previously. A combination of MIXED model results for LV scores and Xloadings was used to quantify

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the effects of treatments on yield components and in-season vigor variables, and their subject effect on yield.

A grouping methodology was used to explore treatment responses and variability for canola yield, test weight, and protein and oil content as described by Francis and Kannenberg (1978). The mean and coefficient of variation (CV) were estimated for each treatment combination across years and replications. Means were plotted against CV and used to categorize the biplot data into four quadrants/groups, which included high mean grain yield and low variability (Group I), high mean grain yield and high variability (Group II), low mean grain yield and high variability (Group III), and low mean grain yield and low variability (Group IV).

Results and discussion

Canola seed yield and quality

The main effects of seeding rate, hybrid, and harvest method on canola seed yields were significant (Table 2). Canola seeded at the rate of 180 seeds m^{-2} (~ 80 plants m^{-2}) produced the highest seed yield; however, there was no yield difference between the 120 seeds m^{-2} (~ 56 plants m^{-2}) and 180 seeds m^{-2}, which indicated that, regardless of hybrid selection, 120 and 180 seeds m^{-2} seems to be biological optimum seeding rates for canola in the Canadian Prairies. The importance of seeding rates on canola seed yields has been well documented. Whetter (2019) noted that fewer plants can reduce yield potential dramatically. In a more recent study, hybrid canola achieved 95% of its yield potential with 65 to 85 plants m^{-2}, 90% of its yield potential with 30 to 45 plants m^{-2} and 85% at 20 to 30 plants m^{-2} (Hartman and Jeffrey 2020). However, lower seeding rates increased days to maturity (Harker et al. 2003) and elevated risk of yield loss and poor weed control (McKenzie et al. 2011). Likewise, a thinner stand suffers uniformity issues and will take longer to reach maturity, which can increase the risk of frost and green seeds. No main effects of seeding rate on test weight, protein content, oil content and green seeds were detected (Table 2).

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Table 2. Mean responses of canola seed yield and quality parameters to seeding rate, canola hybrid and harvesting method in the Canadian Prairies from 2018-2022

	Yield Mg ha^{-1}	Test wt. kg hL^{-1}	Protein (%)	Oil (%)	Green seeds (%)
Seeding rate (SR)					
60 seeds m^{-2}	2.71	65.7	15.62	47.3	1.45
120 seeds m^{-2}	2.84	65.6	15.61	47.5	1.28
180 seeds m^{-2}	2.89	65.7	15.58	47.6	1.37
$LSD_{0.05}$	0.12	NS	NS	NS	NS
Hybrid (HY)					
L233P	2.76	65.2	15.94	46.5	1.26
L255PC	2.87	66.1	15.27	48.5	1.48
$LSD_{0.05}$	0.09	0.45	0.29	0.54	NS
Harvest method (HM)					
60% SCC	2.71	66.0	15.62	47.5	1.54
90% SCC	2.75	65.7	15.61	47.5	1.40
SC @ 10%	2.93	65.6	15.55	47.5	1.37
SC @ 5%	2.86	65.3	15.63	47.4	1.16
$LSD_{0.05}$	0.12	0.28	NS	NS	NS
			P-values		
Fixed effect					
SR	**0.007****	0.391	0.853	0.060	0.491
HY	**0.016***	**<.001*****	**<.001*****	**<.001*****	0.215
HM	**0.002****	**0.001*****	0.815	0.709	0.296
SR×HY	**0.045***	**0.002****	0.064	0.359	0.183
SR×HM	0.498	0.317	0.197	0.177	0.690
HY×HM	0.134	**<.001*****	0.378	**<.001*****	0.435
SR×H×HM	0.169	0.825	0.657	0.599	0.981
Random effect					
Env (site-year)	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****
Env×SR	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**0.043***
Env×HY	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**0.024***
Env×HM	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**0.004****
Env×SR×HY	**0.032***	1.000	1.000	1.000	**0.027***
Env×SR×HM	1.000	1.000	0.683	0.121	1.000
Env×HY×HM	1.000	**<.001*****	0.447	0.101	**<.001*****
Env×SR×HY×HM	1.000	1.000	1.000	1.000	0.475

*, ** and *** denote significant at $P \leq 0.05$, 0.01 and 0.001, respectively. NA=not applicable, ns=not significant. 60% SCC, 90 SCC, SC @ 10% and SC @ 5% are 60% seed color change, 90% seed color change, straight-cutting at 10% seed moisture and straight-cutting at 5% seed moisture, respectively.

The cultivars differed in seed yield, test weight, protein content and oil content. The late-maturing cultivar, L255PC, yielded substantially more than the early-maturing canola hybrid, L233P.

Our results indicate that straight-cutting when timed properly at 10% seed moisture is superior for grain yield (Table 2). However, if the timing is delayed to 5% seed moisture, the advantage of straight-cutting is negated as it produced the same yield as swathing at 90% seed color change. There does appear to be more flexibility with respect to timing of swathing as both swathing treatments produced similar yields, which was likely facilitated by the use of pod shatter reduction trait hybrids.

When the data were analyzed individually by environment, the influence of seeding rate, hybrid and harvest method on canola seed yield and oil content varied from site to site and from year to year (Table 3-6). However, the late-maturing hybrid, L255PC, consistently displayed greater seed yield and oil content than the early-maturing hybrid, L233P, in most of the growing environments. The seeding rate of 180 seeds m$_{-2}$ produced greater seed yields at “Lethbridge Dry” in 2018, Indian Head in 2021, and Brandon in all years, while 60 seeds m$_{-2}$ optimized yield at Lacombe in 2018 and 2021. These observations suggest that a higher seeding rate was needed at site-years that experienced moderate to severe abiotic stress while the lowest seeding rate maintained high yields when that stress was absent ie. Lacombe and Lethbridge Irrigated. When a difference was observed, timely straight-cutting at 10% seed moisture provided superior canola seed yield at seven site-years, whereas a delay in straight-cutting only provided a benefit at three site-years.

There was no apparent crop management effects on oil content other than hybrid selection (Table 2). The only notable deviation was at Brandon, where the combination of very high seeding rates and straight-cutting consistently improved both seed yield and oil content (Tables 3-6).

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Table 3. Mean seed yield and oil content responses to seeding rate, canola hybrid and harvest method by location in 2018

	Seed yield (Mg ha^{-1})					**Oil content (%)**				
	Leth Irr.	Leth Dry	Lac	IH	Bran	Leth Irr.	Leth Dry	Lac	IH	Bran
Seeding rate (SR)										
60 seeds m^{-2}	5.44	1.25	4.92	2.10	2.51	49.7	45.7	47.6	46.0	47.4
120 seeds m^{-2}	5.31	1.54	4.70	2.34	2.73	49.7	45.7	48.1	46.2	48.2
180 seeds m^{-2}	5.36	1.65	4.67	--	2.80	49.2	45.7	48.2	--	49.0
Hybrid (HY)										
L233P	5.06	1.39	4.65	2.15	2.59	48.8	45.0	46.7	44.9	46.4
L255PC	5.68	1.58	4.87	--	2.78	50.2	46.4	49.1	--	50.0
Harvest method (HM)										
60% SCC	5.06	1.38	4.76	--	2.51	49.9	45.8	47.5	--	47.6
90% SCC	4.99	1.48	4.82	2.18	2.50	49.7	45.5	47.9	46.2	48.1
SC @ 10%	6.00	1.51	4.80	2.20	2.77	49.2	45.6	48.3	46.1	48.4
SC @ 5%	5.44	1.55	4.67	2.31	2.95	49.3	45.9	48.0	46.1	48.8
						P-values				
SR	0.406	**<.001*****	**0.019***	0.061	**0.008****	0.183	0.995	**0.052***	0.185	**<.001*****
HY	**<.001*****	**0.019***	**0.007****	0.333	**0.0201***	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****
HM	**<.001*****	0.508	0.562	0.601	**<.001*****	0.202	0.501	0.109	0.331	**<.001*****
SRxHY	**<.001*****	**<.001*****	**0.006****	0.160	0.009**	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****
SRxHM	**<.001*****	**0.013***	0.070	0.281	**<.001*****	0.136	0.636	**0.005****	0.765	**<.001*****
HYxHM	**<.001*****	0.269	0.175	0.629	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****
SRxHYxHM	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Leth Irr., Leth Dry, Lac, IH and Bran represent "Lethbridge Irrigated", "Lethbridge Dry", Lacombe, Indian Head and Brandon, respectively. 60% SCC, 90% SCC, SC @ 10% and SC @ 5% are 60% seed color change, 90% seed color change, straight-cutting at 10% seed moisture and straight-cutting at 5% seed moisture, respectively. "--" indicates data were not available. *, ** and *** denote significant at P≤ 0.05, 0.01 and 0.001, respectively. NA=not applicable.

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Table 4. Mean seed yield and oil content responses to seeding rate, canola hybrid and harvest method by location in 2019

	Seed yield (Mg ha^{-1})					**Oil content (%)**			
	Leth Irr.	Leth Dry	Lac	IH	Bran	Leth Irr.	Lac	IH	Bran
Seeding rate (SR)									
60 seeds m^{-2}	2.77	0.13	4.22	1.79	2.00	47.8	49.9	48.8	48.7
120 seeds m^{-2}	2.93	0.16	4.31	1.86	2.31	47.7	49.6	48.4	49.2
180 seeds m^{-2}	2.86	0.11	4.30	1.91	2.39	47.5	50.2	48.0	49.4
Hybrid (HY)									
L233P	2.84	0.13	4.29	1.73	2.26	47.0	50.0	47.7	48.0
L255PC	2.87	0.14	4.27	1.97	2.21	48.3	49.8	49.2	50.2
Harvest method (HM)									
60% SCC	2.69	0.14	4.13	1.84	2.11	47.8	48.9	48.6	48.8
90% SCC	2.84	0.13	4.16	2.06	2.18	47.6	50.4	48.6	49.3
SC @ 10%	2.90	0.12	4.43	1.74	2.74	48.0	50.4	48.2	49.8
SC @ 5%	2.97	0.13	4.38	1.77	1.91	47.5	49.8	48.2	48.5
					P-values				
SR	0.314	0.945	0.631	0.507	**<.001*** **	0.477	0.105	**0.013***	**0.025***
HY	0.734	0.901	0.796	**0.003****	0.584	**<.001*****	0.340	**<.001*****	**<.001*****
HM	0.092	0.999	**0.016***	**0.027***	**<.001*****	0.315	**<.001*****	0.393	**<.001*****
SRxHY	0.767	1.000	0.517	0.060	**0.004****	**<.001*****	0.276	**<.001*****	**<.001*****
SRxHM	0.464	1.000	0.184	0.470	**<.001*****	0.874	**<.001*****	0.150	**<.001*****
HYxHM	0.330	1.000	**0.047***	**0.012***	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****
SRxHYxHM	NA	NA	NA	NA	NA	NA	NA	NA	NA

Leth Irr., Leth Dry, Lac, IH and Bran represent “Lethbridge Irrigated”, “Lethbridge Dry”, Lacombe, Indian Head and Brandon, respectively. 60% SCC, 90% SCC, SC @ 10% and SC @ 5% are 60% seed color change, 90% seed color change, straight-cutting at 10% seed moisture and straight-cutting at 5% seed moisture, respectively. *, ** and *** denote significant at P≤ 0.05, 0.01 and 0.001, respectively. NA=not applicable.

Table 5. Mean seed yield and oil content responses to seeding rate, canola hybrid and harvest method by location in 2021

	Seed yield (Mg ha^{-1})				**Oil content (%)**			
	Leth Irr.	Lac	IH	Bran	Leth Irr.	Lac	IH	Bran
Seeding rate (SR)								
60 seeds m^{-2}	3.01	3.49	2.25	4.00	47.7	47.0	47.0	46.1
120 seeds m^{-2}	3.09	3.31	2.82	4.32	47.7	47.2	47.2	46.2
180 seeds m^{-2}	3.14	3.00	3.11	4.54	47.8	47.3	47.4	46.1
Hybrid (HY)								
L233P	2.93	3.20	2.79	4.29	46.7	46.3	46.9	44.8
L255PC	3.23	3.33	2.66	4.28	48.7	48.1	47.5	47.4
Harvest method (HM)								
60% SCC	3.02	3.19	2.79	4.15	47.6	47.4	47.4	46.2
90% SCC	3.05	3.39	2.50	4.18	47.8	47.2	47.1	46.6
SC @ 10%	3.17	3.43	2.44	4.36	47.5	47.4	47.4	45.4
SC @ 5%	3.08	3.05	3.17	4.45	47.8	46.9	46.9	46.4
				P-values				
SR	0.420	**<.001*****	**<.001*****	**<.001*****	0.886	0.484	0.252	0.885
HY	**<.001*****	0.110	0.104	0.955	**<.001*****	**<.001*****	**0.015***	**<.001*****
HM	0.606	**0.002****	**<.001*****	**0.024***	0.693	0.210	0.200	**<.001*****
SRxHY	**0.006****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**0.033***	**<.001*****
SRxHM	0.639	**<.001*****	**<.001*****	**<.001*****	0.998	0.668	0.175	**0.008****
HYxHM	**0.012***	**0.004****	**<.001*****	0.134	**<.001*****	**<.001*****	0.096	**<.001*****
SRxHYxHM	NA	NA	NA	NA	NA	NA	NA	NA

Leth Irr., Leth Dry, Lac, IH and Bran represent “Lethbridge Irrigated”, “Lethbridge Dry”, Lacombe, Indian Head and Brandon, respectively. 60% SCC, 90% SCC, SC @ 10% and SC @ 5% are 60% seed color change, 90% seed color change, straight-cutting at 10% seed moisture and straight-cutting at 5% seed moisture, respectively. *, ** and *** denote significant at $P \leq 0.05$, 0.01 and 0.001, respectively. NA=not applicable.

Table 6. Mean seed yield and oil content responses to seeding rate, canola hybrid and harvest method by location in 2022

	Seed yield (Mg ha^{-1})					Oil content (%)				
	Leth Irr.	Leth Dry	Lac	IH	Bran	Leth Irr.	Leth Dry	Lac	IH	Bran
Seeding rate (SR)										
60 seeds m^{-2}	1.37	0.36	3.93	2.82	3.03	47.2	44.3	48.1	47.9	45.5
120 seeds m^{-2}	1.39	0.47	4.00	2.96	3.36	47.5	44.1	48.1	48.1	45.6
180 seeds m^{-2}	1.43	0.51	3.97	3.00	3.97	47.2	44.2	47.8	48.6	46.7
Hybrid (HY)										
L233P	1.45	0.46	3.99	2.85	3.35	46.7	43.4	45.9	47.0	44.3
L255PC	1.34	0.42	3.95	3.00	3.56	47.9	45.0	50.1	49.4	47.6
Harvest method (HM)										
60% SCC	1.16	0.37	3.95	2.84	3.26	47.5	44.5	48.4	48.4	46.0
90% SCC	1.36	0.39	4.02	2.68	3.27	47.4	43.7	48.1	48.2	45.8
SC @ 10%	1.56	0.53	3.87	3.23	3.84	47.2	44.3	48.0	48.0	46.3
SC @ 5%	1.51	0.48	4.03	2.96	3.45	47.2	44.3	47.5	48.2	45.7
P-values										
SR	0.896	0.314	0.821	0.179	**<.001*** **	0.408	0.840	0.489	**0.015***	**<.001*** **
HY	0.183	0.615	0.637	0.059	**0.012***	**<.001*** **	**<.001*** **	**<.001*** **	**<.001*** **	**<.001*** **
HM	**0.003** **	0.473	0.492	**<.001*** **	**<.001*** **	0.691	0.073	**0.030***	0.631	0.243
SRxHY	0.468	0.763	0.830	0.186	**<.001*** **	**<.001*** **	**<.001*** **	**<.001*** **	**<.001*** **	**<.001*** **
SRxHM	0.183	0.899	0.898	**0.003** **	**<.001*** **	0.887	0.493	0.394	0.434	**<.001*** **
HYxHM	**0.015***	0.906	0.857	**<.001*** **	**<.001*** **	**<.001*** **	**<.001*** **	**<.001*** **	**<.001*** **	**<.001*** **
SRxHYxHM	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Leth Irr., Leth Dry, Lac, IH and Bran represent "Lethbridge Irrigated", "Lethbridge Dry", Lacombe, Indian Head and Brandon, respectively. 60% SCC, 90% SCC, SC @ 10% and SC @ 5% are 60% seed color change, 90% seed color change, straight-cutting at 10% seed moisture and straight-cutting at 5% seed moisture, respectively. *, ** and *** denote significant at $P \leq 0.05$, 0.01 and 0.001, respectively. NA=not applicable.

Overall, eight out of 24 treatment combinations displayed consistently high and stable yields across the environments (Figure 1). Among these, the late-maturing canola hybrid (L255PC) seeded at 120 and 180 seed m^{-2} and managed with straight-cutting displayed a higher and more stable yield relative to other treatment combinations. Planting the late-maturing canola hybrid managed with a seeding rate of 180 seeds m^{-2} and a timely straight-cutting operation (L255PC-180-S/C 10%) resulted in the highest seed yield compared to all the other systems albeit with a greater degree of variability (Figure 1). The seeding rate of 180 seeds m^{-2} coupled with straight-cutting also provided higher than average seed yield and yield stability for the early-maturing hybrid, L233P. The lowest seeding rate managed with swathing treatments often led to lower yield and yield stability, irrespective of hybrid selection. In general, the late-maturing canola hybrid produced higher and more consistent test weight, but lower and more variable protein content than the early-maturing hybrid (Table 2 and Figures 2 and 3). L255PC also produced substantially higher oil content than L233P (Table 2 and Figure 4). The results also suggest that a later-maturing hybrid may be more amenable to straight-cutting as three out of four treatment combinations in Group I in Figure 1 are associated with straight-cutting for L255PC. Additionally, there appears a trend toward greater responses for the early-maturing hybrid when managing with an earlier straight-cutting method. Neither the seeding rate nor the harvest method alone affected protein and oil content, and the percentage of green seeds (Table 2). The percentage of seed color change at swathing usually has little effect on green seed levels except under abnormal situations (Anonymous 2019), which suggests our density of 60 seed m^{-2} was not low enough to alter green seed counts.

Find more information on this project and many other relevant canola studies on the Canola Research Hub.
The Canola Research Hub is funded through the substantial support of the Canadian Agricultural Partnership and the canola industry, including Alberta Canola, SaskCanola, Manitoba Canola Growers and the Canola Council of Canada.

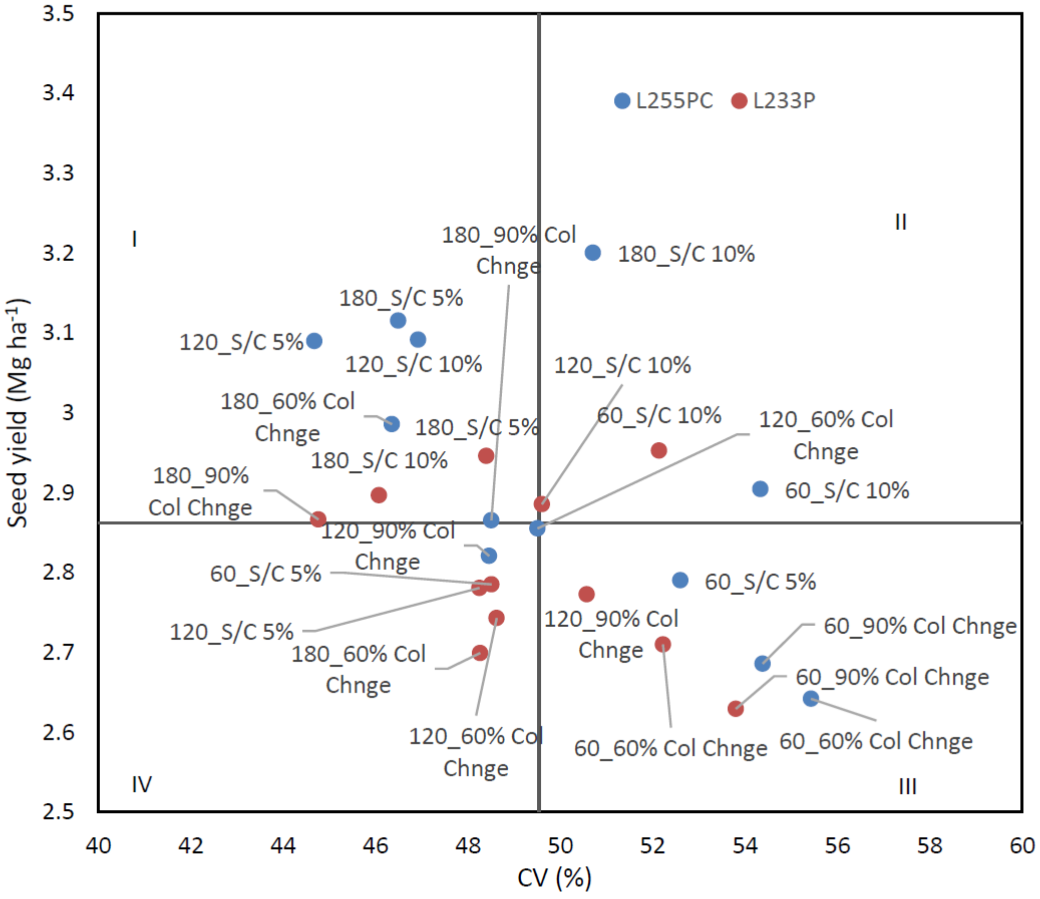

Figure 1. Biplot (mean vs. CV) for seed yield for all treatment combinations from2018-2022. The labels indicate seeding rates (60, 120 and 180 seeds m$_{-2}$) and harvest methods (60% Col Chnge=swathing at 60% color change, 90% Col Chnge=Swathing at 90% color change, S/C 10%=straight-cutting at 10% seed moisture and S/C 5%=straight-cutting at 5% seed moisture). Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: Low mean, high variability; Group IV: Low mean, low variability.

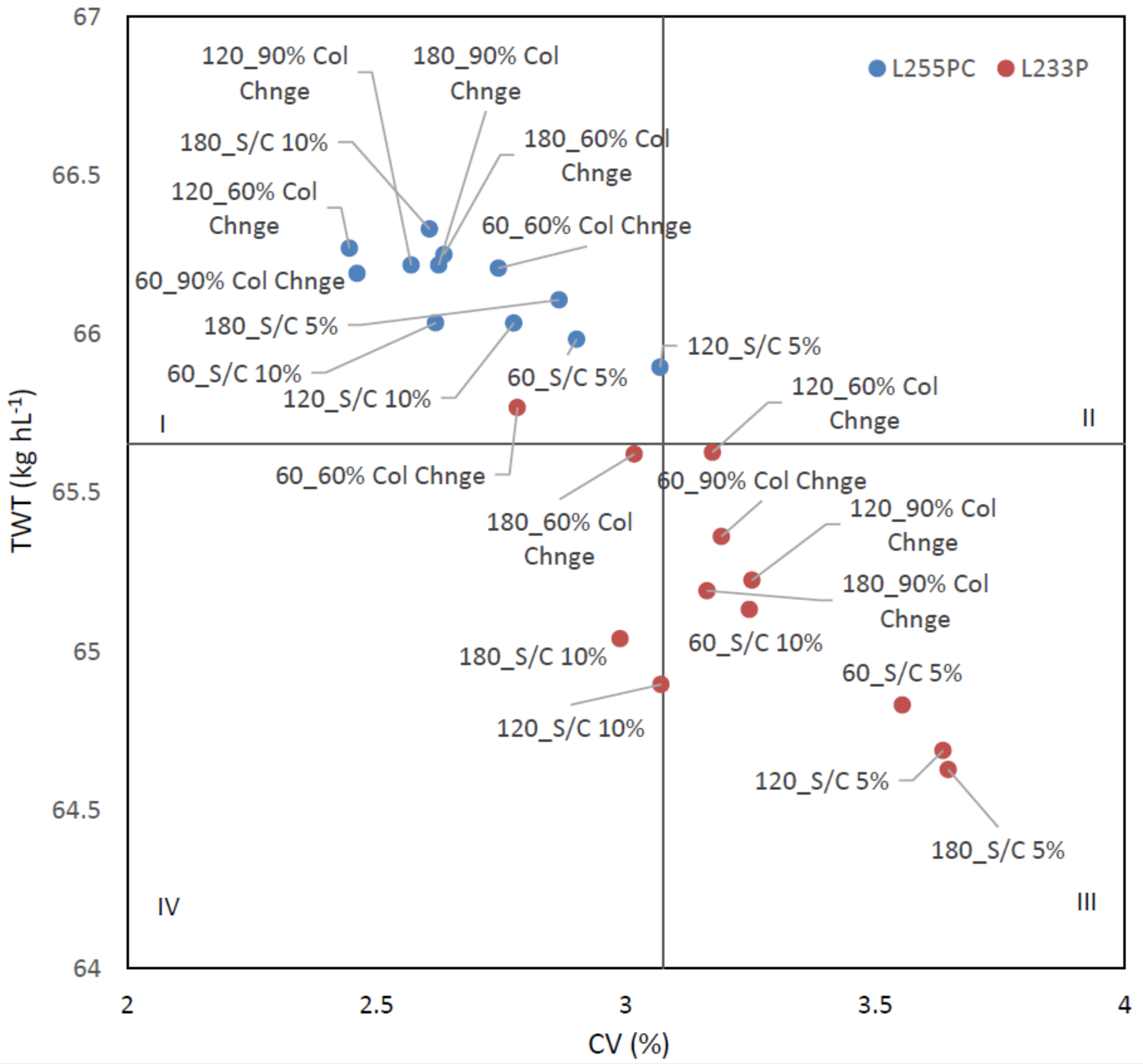

Figure 2. Biplot (mean vs. CV) for test weight for all treatment combinations from2018-2022. The labels indicate seeding rates (60, 120 and 180 seeds m^{-2}) and harvest methods (60% Col Chnge=swathing at 60% color change, 90% Col Chnge=Swathing at 90% color change, S/C 10%=straight-cutting at 10% seed moisture and S/C 5%=straight-cutting at 5% seed moisture). Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: Low mean, high variability; Group IV: Low mean, low variability.

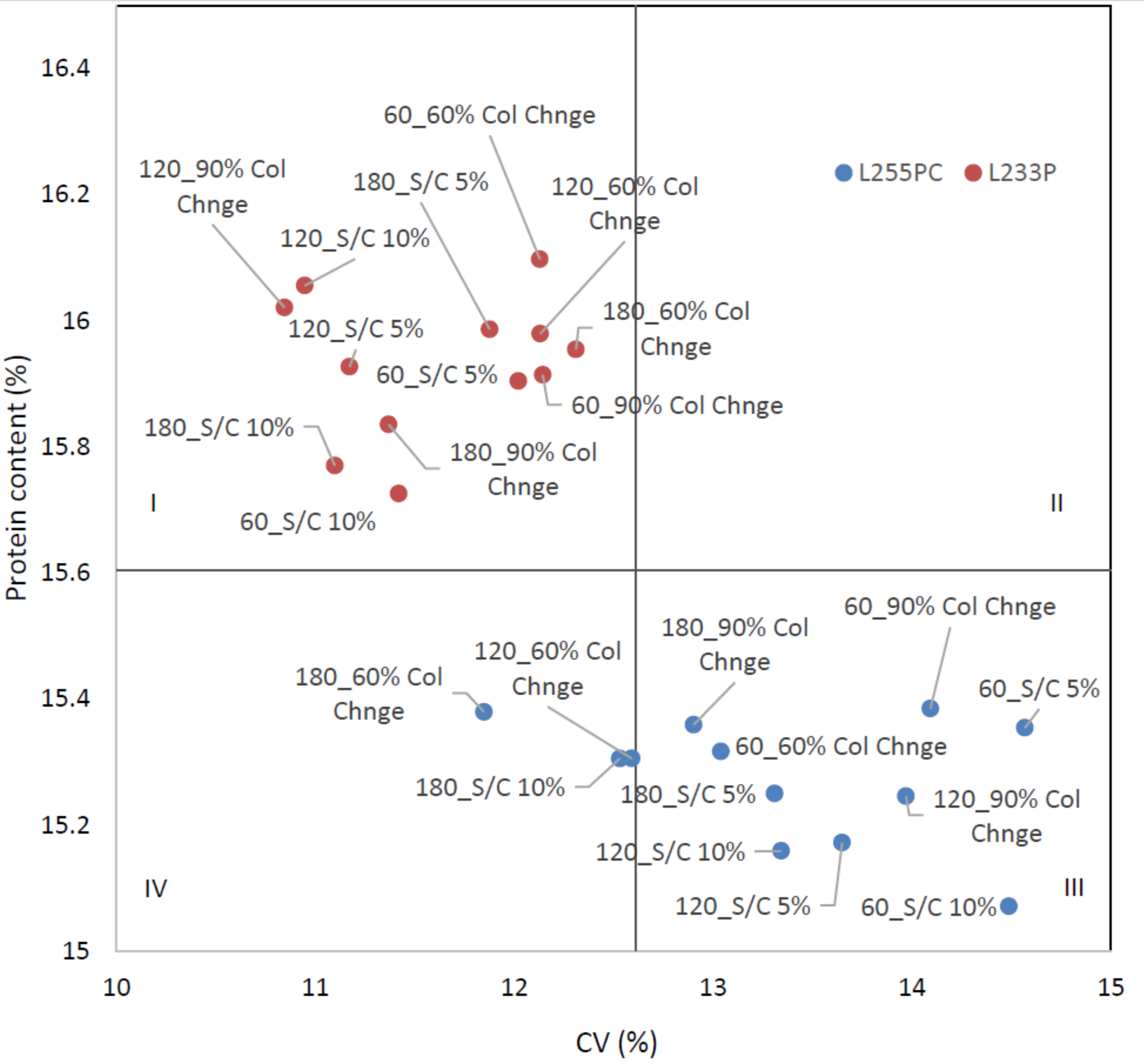

Figure 3. Biplot (mean vs. CV) for protein content for all treatment combinations from2018-2022. The labels indicate seeding rates (60, 120 and 180 seeds m^{-2}) and harvest methods (60% Col Chnge=swathing at 60% color change, 90% Col Chnge=Swathing at 90% color change, S/C 10%=straight-cutting at 10% seed moisture and S/C 5%=straight-cutting at 5% seed moisture). Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: Low mean, high variability; Group IV: Low mean, low variability.

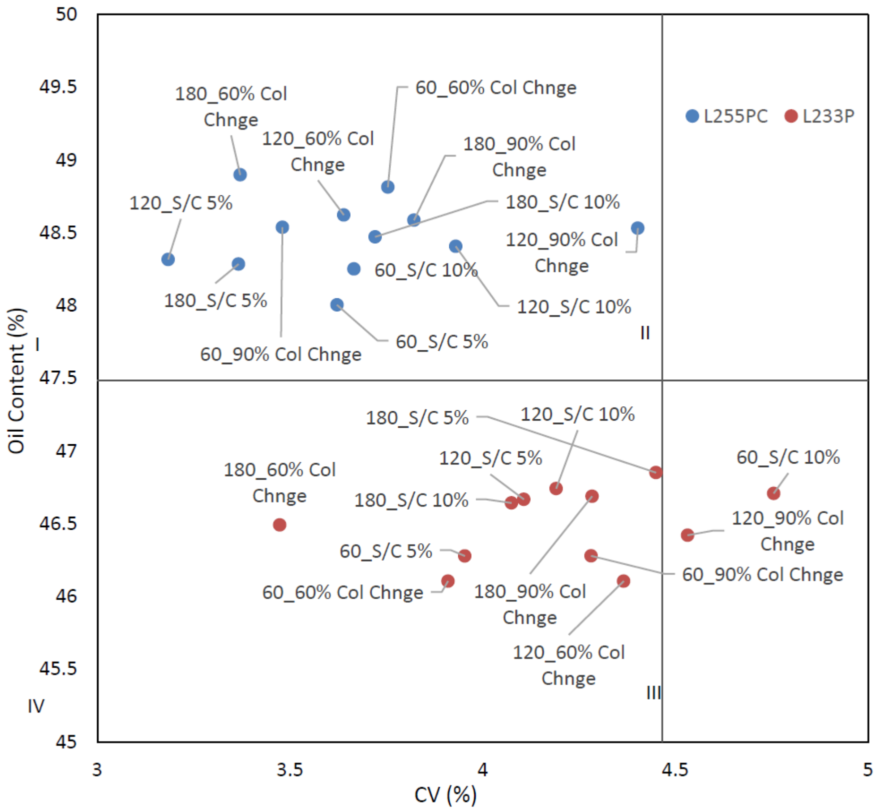

Figure 4. Biplot (mean vs. CV) for oil content for all treatment combinations from2018-2022. The labels indicate seeding rates (60, 120 and 180 seeds m^{-2}) and harvest methods (60% Col Chnge=swathing at 60% color change, 90% Col Chnge=Swathing at 90% color change, S/C 10%=straight-cutting at 10% seed moisture and S/C 5%=straight-cutting at 5% seed moisture). Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: Low mean, high variability; Group IV: Low mean, low variability.

No seed loss difference was observed among either seeding rate, hybrid or harvest method (Table 7). However, the pre-swathing/pre-straight-cutting seed losses were slightly higher with the highest seeding rate and with the late-maturing hybrid. Swathing resulted in 42% more seed loss with the late- maturing hybrid than with the early-maturing hybrid. Combining operations led to an average of 10% higher seed losses with straight-cutting than with swathing. While, total seed loss with swathing was 13% greater than straight-cutting because there are three types of seed loss involved in the swathing operation, but only two involved in straight-cutting. Our results support Haile et al. (2014) who reported that the elimination of swathing and switching to straight-cutting did not result in a seed loss increase. When the seed loss data were analyzed individually by the growing environment, total seed loss differed at Indian Head in 2019, 2021, and 2022, Lacombe in 2019 and Lethbridge in 2021 and 2022 by harvest time with swathing lost 18% more seed than straight-cutting (data now shown).

Table 7. Responses of seed loss to seeding rate, canola hybrid and harvest from 2018-2022

	PreSwLo kg ha^{-1}	SwLo kg ha^{-1}	Outside kg ha^{-1}	Inside kg ha^{-1}	Total kg ha^{-1}
Seeding rate (SR)					
60 seeds m^{-2}	24.6	12.4	23.3	27.3	55.8
120 seeds m^{-2}	27.3	13.8	23.6	28.0	59.4
180 seeds m^{-2}	31.5	11.8	23.0	24.1	53.7
LSD$_{0.05}$	NS	NS	NS	NS	NS
Hybrid (HY)					
L233P	25.0	10.7	23.2	26.4	55.1
L255PC	30.6	14.6	23.4	26.5	57.5
LSD$_{0.05}$	NS	NS	NS	NS	NS
Harvest method (HT)					
60% SCC	--	10.5	21.6	24.4	57.4
90% SCC	--	14.9	22.0	26.7	62.3
SC @ 10%	--	--	26.2	28.2	55.0
SC @ 5%	--	--	23.3	26.6	50.7
LSD$_{0.05}$	NS	NS	NS	NS	NS
			P-values		
SR	0.721	0.564	0.944	0.238	0.283
HY	0.280	0.285	0.834	0.985	0.485
HT	0.637	0.303	0.650	0.781	0.563
SR×HY	0.665	0.362	0.156	0.252	0.415
SR×HT	0.194	0.351	0.953	0.803	0.891
HY×HY	0.797	0.231	0.933	0.999	0.423
SR×HY×HT	0.076	0.569	0.917	0.960	0.506

PreSwlo, SwLo, outside, inside and total represent pre-swath/straight-cutting loss, swath loss, outside combine track loss, inside combine track loss and total harvest loss, respectively. "—" denote the means do not need to be examined.

NDVI is the most commonly used vegetation index for crop growth and grain yield estimation. Holzapfel et al. (2009) observed that NDVIs measured from the rosette stage to the flowering stage were significantly correlated with canola seed yield ($R^2=0.35$; $P < 0.001$). In this study, NDVI was responsive to the seeding rate for the 1st, 2nd, 3rd and 4th measurements, but did not respond to the seeding rate variation for the 5th and 6th measurements (Table 8). No NDVI difference was observed between the two hybrids across all six measurements. NDVI was altered by the environment, interactions of the environment by seeding rate and environment by hybrid.

Table 8. Responses of NDVI to seeding rate and canola hybrid from 2018-2022

	NDVI1	NDVI2	NDVI3	NDVI4	NDVI5	NDVI6
Seeding rate (SR)						
60 seeds m^{-2}	0.32	0.40	0.51	0.55	0.61	0.62
120 seeds m^{-2}	0.36	0.46	0.55	0.62	0.65	0.64
180 seeds m^{-2}	0.39	0.49	0.58	0.62	0.65	0.64
	0.03	0.02	0.02	0.04	NS	NS
Hybrid (HY)						
L233P	0.35	0.45	0.55	0.59	0.64	0.64
L255PC	0.36	0.46	0.55	0.60	0.64	0.62
	NS	NS	NS	NS	NS	NS
			P-values			
Fixed effect						
SR	**<.001*****	**<.001*****	**<.001*****	**0.001****	0.101	0.107
HY	0.451	0.112	0.830	0.334	0.812	0.083
SR×HY	0.405	0.792	0.697	0.352	0.679	0.567
Random effect						
Env (site-year)	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****
Env×SR	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****
Env×HY	**<.001*****	**0.020***	**<.001*****	**0.003****	0.271	**<.001*****
Env×SR×HY	1.000	0.334	0.631	0.739	0.491	0.523

The numbers 1, 2, 3, 4, 5 and 6 after NDVI represent 1st, 2nd, 3rd, 4th, 5th and 6th measurements. All the measurements occurred about one week apart, with the 1st and 6th measurements were made at growth stage BBCH 13 and BBCH 75, respectively. ** and *** denote significant effect at $P< 0.01$ and 0.001, respectively.

Sensitivity analysis was performed for two important agronomic variables, seed yield and seed oil content. The results indicated that straight-cutting and the late-maturing canola hybrid, L255PC, were more sensitive to site variations for seed yield, regardless of seeding rate (Table 9). The low seeding rate (60 seeds m^{-2}) was more sensitive to site variations for canola seed yield. Swathing at 90% seed color change was more sensitive to site variations for oil content. The early-maturing hybrid, L233P, when managed with a higher seeding rate and straight-cutting at 5% seed moisture was sensitive to site variations for oil content too.

Table 9. Sensitivity analysis for seeding rate, hybrid and harvest time effects on canola seed yield and oil content

Seeding rate (SR)	Hybrid (H)	Harvest method (HM)	Sensitive coef_Yield	Sensitive coef_Oil
60 seeds m^{-2}	L233P	60% SCC	1.00	0.93
60 seeds m^{-2}	L233P	90% SCC	1.00	1.07
60 seeds m^{-2}	L233P	SC @ 10%	1.04	1.13
60 seeds m^{-2}	L233P	SC @ 5%	0.98	0.88
60 seeds m^{-2}	L255PC	60% SCC	1.02	0.97
60 seeds m^{-2}	L255PC	90% SCC	1.00	0.96
60 seeds m^{-2}	L255PC	SC @ 10%	1.05	1.06
60 seeds m^{-2}	L255PC	SC @ 5%	1.03	0.89
120 seeds m^{-2}	L233P	60% SCC	0.96	1.06
120 seeds m^{-2}	L233P	90% SCC	0.97	1.07
120 seeds m^{-2}	L233P	SC @ 10%	1.00	1.05
120 seeds m^{-2}	L233P	SC @ 5%	0.96	1.09
120 seeds m^{-2}	L255PC	60% SCC	0.99	0.92
120 seeds m^{-2}	L255PC	90% SCC	0.97	1.21
120 seeds m^{-2}	L255PC	SC @ 10%	1.05	1.00
120 seeds m^{-2}	L255PC	SC @ 5%	1.02	0.77
180 seeds m^{-2}	L233P	60% SCC	0.92	0.90
180 seeds m^{-2}	L233P	90% SCC	0.93	1.15
180 seeds m^{-2}	L233P	SC @ 10%	0.99	1.05
180 seeds m^{-2}	L233P	SC @ 5%	0.99	1.12
180 seeds m^{-2}	L255PC	60% SCC	1.02	0.76
180 seeds m^{-2}	L255PC	90% SCC	0.97	1.09
180 seeds m^{-2}	L255PC	SC @ 10%	1.08	0.93
180 seeds m^{-2}	L255PC	SC @ 5%	1.06	0.81

60% SCC, 90 SCC, SC @ 10% and SC @ 5% are 60% seed color change, 90% seed color change, straight- cutting at 10% seed moisture and straight-cutting at 5% seed moisture, respectively. Sensitive coef_Yield and sensitive coef_oil are sensitive coefficients for yield and oil content, respectively.

The Canola Research Hub is funded through the substantial support of the Canadian Agricultural Partnership and the canola industry, including Alberta Canola, SaskCanola, Manitoba Canola Growers and the Canola Council of Canada.

Yield components

Canola seed yield is a function of plant population, number of pods per plant, number of seeds per pod, and seed weight. The ANOVA identified seeding rate effects on all yield components, with an exception of seed numbers on the secondary branches (Table 10). There was a downward trend for the number of fertile pods, pod weight, the number of seeds and seed weight as the seeding rate increased. The low seeding rate (60 seeds m^{-2}) increased the number of fertile pods, pod weight, seed numbers and seed weight on the main raceme, and primary and secondary branches, which confirmed a strong yield component compensation ability in canola. The same yield component responses to seeding rates were reported by Angadi et al. (2003) who described that the primary response of canola to lower plant population was increased pods per plant through increased branching and increased pod retention at each node. Hay and Porter (2006) observed that the growth plasticity (e.g., yield component compensation) of canola allows the crop to approach or even achieve yield potential. The small seed yield difference (5%) between 60 seeds m^{-2} and 120 seeds m^{-2} (Table 2) could be attributed to more branches and more seeds and larger seeds the lower seeding rate produced (Table 10). However, these compensatory mechanisms did not result in comparable yield as the 120 and 180 seeds m^{-2} was still superior over the lower seeding rates. Ma et al. (2016) reported that increasing the seeding rate increased seed yield due mainly to the improved plant densities because denser stands led to stronger plant-to-plant competition for resources. The late-maturing hybrid, L255PC, produced more branches per plant than the early-maturing hybrid, L233P (data not shown). Seed weight on the primary branches also differed between the two hybrids (Table 10); the early-maturing hybrid produced more large seeds on the primary branches.

Table 10. Mean yield component responses to seeding rate, canola hybrid and harvesting method of canola in the Canadian Prairies from 2018-2022

	Main raceme				Primary branches				Secondary branches			
	NFP/pl †	WFP(g) /pl	NS/pl	SW(g)/ pl	NFP/pl	WFP(g) /pl	NS/pl	SW(g)/ pl	NFP/pl	WFP(g) /pl	NS/pl	SW(g)/ pl
Seeding rate (SR)												
60 seeds m^{-2}	31.4	3.6	614	1.81	20.6	2.1	377	1.04	104	9.9	1945	4.8
120 seeds m^{-2}	29	3.3	565	1.67	18.3	1.8	331	0.93	57	5.3	1101	2.7
180 seeds m^{-2}	26.7	3.1	529	1.56	15.9	1.6	289	0.81	38	3.5	661	1.8
LSD$_{0.05}$	1.67	0.21	45	0.13	1.13	0.17	33	0.09	21	2.24	NS	1.15
Hybrid (HY)												
L233P	29.5	3.4	578	1.76	18.1	1.91	324	0.96	65	6.6	1176	3.3
L255PC	28.5	3.2	560	1.6	18.3	1.78	340	0.9	67.4	5.9	1295	2.8
LSD$_{0.05}$	NS	NS	NS	NS	NS	NS	NS	0.06	NS	NS	NS	NS
Fixed effect	*P*-values											
SR	**<.001*****	**<.001*****	**0.008****	**0.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	0.221	**<.001*****
HY	0.462	0.057	0.702	**0.018***	0.651	0.117	0.156	**0.048***	0.729	0.315	0.592	0.146
SR×HY	0.326	0.994	0.750	0.867	0.474	0.190	0.349	0.179	0.588	0.183	0.864	0.200
Random effect												
Env (site-year)	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**0.052***	**<.001*****
Env×SR	0.742	1.000	1.000	1.000	**0.036***	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**<.001*****	**0.020***	**<.001*****
Env×HY	**<.001*****	**0.028***	0.074	**0.029***	**0.019***	**0.050***	0.716	1.00	0.238	0.278	0.473	1.00
Env×SR×HY	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.935	**0.045***	0.056	1.00	0.223

†pl denote plant. NFP= number of fertile pods, WFP= weight of fertile pods, NS= number of seeds, SW= seed weight; *, ** and *** denote significant effect at P< 0.05, 0.01 and 0.001, respectively; NS=not significant.

All the investigated predictors in Table 11 were positively correlated to LV1 scores. Predictors with large loadings were more important than those with small loading values (Nguyen and Lee 2006; Geladi and Kowalski 1986; Haaland and Thomas 1988). Pod weight, seed number and seed weight on the primary branches and seed weight on the main raceme provided the top four high Xloading values, indicating that they can provide the most critical information for explaining variations in canola seed yield. Plants m^{-2} positively correlated to LV2 scores but all the other variables negatively related to LV2 scores. The pod number on the secondary branches positively correlated to LV3 scores, but the pod number of the main raceme and the primary branches did not, suggesting a possible secondary yield component compensation. Total branches on a single plant and seed number on the secondary branches were positively related to LV4 and LV5 scores, respectively, suggesting possible tertiary and quaternary yield component compensations. A significant seeding rate effect on LV2 scores indicated that the plasticity of canola differed between seeding rates. The significant seeding rate effect on LV5 scores suggests more plants might reduce the capacity of seed numbers on the secondary branches.

Table 11. Xloadings of the important seed yield predictors-yield component variables

	LV1	LV2	LV3	LV4	LV5
Plants_m2	0.068	0.686	0.098	-0.237	-0.223
Seedwt_pr	0.392	-0.041	0.118	0.201	0.200
Seedwt_mr	0.357	-0.055	-0.316	0.329	0.144
Pod#_sec	0.211	-0.375	0.435	-0.532	0.260
Pod#_pr	0.338	-0.312	-0.012	-0.092	-0.247
Seed#_pr	0.388	-0.140	0.061	0.080	-0.102
Podwt_pr	0.367	-0.085	0.128	-0.206	0.043
Pod#_mr	0.258	-0.224	-0.491	0.177	-0.123
Podwt_mr	0.346	-0.077	-0.368	0.021	0.022
Branch_total	0.152	-0.326	0.336	0.456	-0.789
Seed#_sec	0.247	-0.312	0.423	-0.463	0.334
ANOVA *P*-values					
Seeding rate (SR)	0.843	**<.001*****	0.224	0.182	**<.001*****
Hybrid (HY)	0.171	0.430	0.091	0.077	**0.007****
SR×HY	0.817	0.752	0.506	0.672	0.725
Covariance estimates *P*-values					
Site	**<.001*****	**<.001*****	**0.007****	0.236	0.859
Site×SR	**0.008****	**<.001*****	0.409	**<.001*****	**<.001*****
Site×HY	1.000	**<.001*****	0.460	1.000	0.139
Site×SR×HY	1.000	1.000	0.393	0.942	1.000

LV represents latent variable. Pod#, podwt, seed# and seedwt represent pod number, pod weight, seed number and seed weight, respectively. Mr, pr and sec are main raceme, primary branch and secondary branch, respectively. ** and *** denote significant effect at P< 0.01 and 0.001, respectively.

Covariance estimates of site and site by seeding rate were notable for LV1, LV2 and LV3, and LV1, LV2 and LV4, respectively, indicating that the yield component compensation is most susceptible to environment and environment by seeding rate changes (Table 11). The top two highest negative Xloading values for the pod number on the secondary branches in LV4 and total branches in LV5 suggest that greater pods on the secondary branches and branches on a single plant tended to have negative impacts on canola seed yields. All six LAI measurements were positively correlated to LV1 scores, suggesting that LAI variations are most related to canola yield (Table 12). The highest positive Xloading values for the 1st LAI measurement in LV2, the 4th LAI measurement in LV3, the 4th NDVI measurement in LV4 and the 6th LAI measurement in LV5, suggesting these LAI and NDVI measurements can be used as the secondary, tertiary and quaternary predictors for canola seed yield. A significant seeding rate effect on LV1 and LV3 scores indicated that LAI and Chl effects on seed yield, particularly those at the middle growth stages (the 3rd and 4th LAI and Chl measurements) were largely influenced by seeding rate.

Table 12. Xloadings of the important seed yield predictors-LAI, Chl index and NDVI

	LV1	LV2	LV3	LV4	LV5
LAI4	0.355	-0.096	0.497	-0.168	0.334
Chl4	0.383	0.007	0.117	0.359	-0.069
LAI3	0.399	-0.297	0.087	-0.321	0.181
LAI1	0.175	0.585	-0.111	-0.224	-0.090
NDVI3	0.258	0.043	0.113	0.210	-0.784
Chl3	0.323	-0.412	0.301	0.117	-0.098
LAI6	0.261	0.201	-0.402	0.143	0.330
LAI5	0.273	0.018	-0.083	-0.406	0.039
NDVI4	0.269	-0.286	-0.340	0.497	-0.274
Chl2	0.223	0.159	-0.190	0.050	0.116
LAI2	0.270	-0.202	-0.031	-0.399	0.141
Chl5	0.172	0.448	-0.543	0.197	-0.008
			ANOVA *P*-values		
SR	**<.001*****	0.750	**0.009****	0.632	0.137
HY	**0.041***	**0.028***	0.128	0.123	0.974
HT	0.643	0.774	0.729	0.916	0.825
SR×HY	0.776	0.723	0.205	0.670	0.545
SR×HT	0.977	0.681	0.334	0.999	0.264
HY×HT	0.636	0.665	0.522	0.768	0.529
SR×HY×HT	0.990	0.767	0.723	0.998	0.988

LV represents latent variable. LAI, Chl, and NDVI represent leaf area index, chlorophyll index and normalized difference vegetation index, respectively, and the numbers 1, 2, 3, 4, 5 and 6 after LAI, Chl and NDVI represent the 1st, 2nd, 3rd, 4th, 5th and 6th measurements, respectively. The 1st measurement occurred at BBCH 13 and the 6th at BBCH 75. All the measurements were taken about one week apart. ** and *** denote significant effect at $P< 0.01$ and 0.001, respectively.

Summary and conclusions

This study explored the manipulations of crop management factors, i.e. seeding rate, hybrid, and harvest method, to determine which combination of practices optimizes canola seed yield and quality. In general, seeding rates of 120 and 180 seeds m^{-2} that achieve 56 and 80 plants m^{-2}, respectively, provided higher and more stable canola yield relative to the seeding rate of 60 seeds m^{-2}. The results also indicated canola harvest management by straight-cutting at 10 % seed moisture was effective for both late- and early-maturing hybrid cultivars. Moreover, likely as a consequence of the pod-shatter reduction trait, seed loss comparisons between straight-cutting and swathing were rarely notable. The PLS analysis indicated that seed weight on the primary branches, plants m^{-2}, and pod number on the secondary branches are the most critical yield components. This would explain why the lowest seeding rate could still provide superior yields at some site-years as it caused positive compensatory responses in canopy architecture for critical yield components. However, a rate of 60 seeds m^{-2} also produced the fewest plants (35 plants m^{-2}), which would explain the highly variable nature of yield and yield stability. Conversely, the higher seeding rates provide significantly more plants but didn't influence compensatory responses to the same degree as the lower seed rate. This could mean plant stand contributes to yield stability more so than plant architecture; however, seed weight and pod number are more critical for seed yield. Therefore, a less than optimal plant stand is more susceptible to inconsistent yield, particularly in the presence of biotic and abiotic stress. Thus, a canola production system of 120 seeds m^{-2} coupled with timely straight-cutting assures high seed yield and yield stability with minimal seed loss. The temptation to reduce seeding rates below 120 seeds m^{-2} motivated by economic realities of seed input costs is understandable and can at times produce similar or at times superior yield when environmental stress is low. However, canola growers in the Canadian Prairies must be aware that those outcomes are highly variable across growing environments.

Acknowledgements

We sincerely thank the CAP funders and our R&D support teams at each field site for their commitment to this study. I am grateful and fortunate to have had our research associate, Dr. Zhijie Wang, working on this report with me.

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The Canola Research Hub is funded through the substantial support of the Canadian Agricultural Partnership and the canola industry, including Alberta Canola, SaskCanola, Manitoba Canola Growers and the Canola Council of Canada.

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Lethbridge experienced drought in 2018 and 2022, and severe drought in 2019 and 2021. The 2021 “Lethbridge Dry” data has been excluded in this report because seed yield of this site-year is extremely low. Data for treatment L255PC-180-60% SCC at Indian Head in 2018 are missing for all four replicates, therefore there are no seed yield and oil content mean estimations for 180 seed m_{-2}, L255PC and 60% seed color change for Indian Head in Table 3.

This study provides the industry, growers, and academia with enhanced knowledge of the critical yield components that determine yield potential. Planting well below the recommended rate of sowing density is commonplace and supported by both the economic realities of seed input costs and anecdotal reports of high yield achievement. The critical yield components identified offer a clearer explanation into why this risky strategy can be successful and also why it is far more variable than higher seeding rates. The study also adds clarity around the type and timing of harvest management and also validated the high efficacy of the pod shatter reduction trait.

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