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Effect of seeding date on winter canola (*Brassica napus* L.) yield and oil quality in southern Ontario

Eric R. Page, Sydney Meloche, Meghan Moran, Brian Caldbeck, and Véronique Barthelet

Abstract: Winter canola or winter oilseed rape (*Brassica napus* L.) is not commonly grown in Canada. While winter oilseed rape is the dominant growth form in Europe, Canadian canola production is dominated by spring types in western Canada. Research conducted in the 1980s indicated that the environmental conditions in southern Ontario are well suited to the production of winter canola. Since then, however, interest in the crop has ebbed, and little to no research has been conducted on the agronomic issues that potentially limit its adoption in the province. The objective of this research was to identify an optimal seeding date for winter canola in southern Ontario. Three winter canola hybrids were evaluated across five seeding dates, ranging from early September to late October. The results established the first two weeks of September as the optimal seeding period for winter canola in southern Ontario. Seeding winter canola during this period, such that greater than 600 growing degree days could be accumulated before the first fall frost, not only reduced winterkill to approximately 20%, but also maximized yield potential and ensured optimal oil quality. Winter canola showed great potential for production in southern Ontario, and its addition to current crop rotations would diversify and enhance crop production practices in this portion of the province.

Key words: canola (winter), oil quality, winterkill, oilseed rape (winter), seeding date.

Résumé : On ne cultive pas beaucoup le canola ou colza d'hiver (*Brassica napus* L.) au Canada. Alors que le colza d'hiver domine en Europe, dans l'Ouest canadien, ce sont plutôt les variétés de printemps. Des travaux réalisés dans les années 1980 avaient indiqué que les conditions environnementales observées dans le sud de l'Ontario conviennent bien à la culture du canola d'hiver. Depuis cependant, l'intérêt pour cette culture s'est effrité et peu de recherches, voire aucune, se sont attardées aux difficultés agronomiques qui pourraient en entraver l'adoption dans la province. Les auteurs voulaient établir la densité de semis optimale pour le canola d'hiver dans le sud ontarien. Pour cela, ils ont évalué trois hybrides semés à cinq dates différentes, du début de septembre à la fin d'octobre. Leurs résultats indiquent que les deux premières semaines de septembre constituent le moment idéal pour semer le canola d'hiver dans le sud de l'Ontario. Procéder aux semis à ce moment permettra à la plante d'accumuler plus de 600 degrés-jours de croissance avant la première gelée d'automne, ce qui non seulement réduira la destruction par l'hiver à environ 20 %, mais optimisera aussi le rendement potentiel et garantira la meilleure qualité d'huile possible. Le canola d'hiver présente un grand potentiel agricole dans le sud de l'Ontario et l'ajouter aux assolements actuels contribuerait à diversifier et à rehausser les pratiques culturales dans cette partie de la province. [Traduit par la Rédaction]

Mots-clés : canola (d'hiver), qualité de l'huile, destruction par l'hiver, colza (d'hiver), date des semis.

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Introduction

Winter canola or winter oilseed rape (*Brassica napus* L.) is commonly grown across many parts of Europe (Berry and Spink 2006; Tuck et al. 2006; Pullens et al. 2019). It is adapted to crop production in Europe and is grown in many countries stretching from Sweden to Spain (Eurostat 2019). In 2019, for example, rape or turnip rape-seed was seeded on 5.5 million ha across the European Union (EU), and yields ranged from 1.73 to 4.42 t·ha⁻¹, with a mean of 3 t·ha⁻¹ (Eurostat 2019). In Canada, in contrast, spring canola is by far the dominant growth form. It is a staple crop in western Canada; the bulk of the 8.5–9 million ha of canola seeded in Canada annually can be attributed to the three prairie provinces of Alberta, Saskatchewan, and Manitoba (Statistics Canada 2019a). Outside of these provinces, spring canola acreage in Canada is limited, but some production occurs in parts of British Columbia, Ontario, and Quebec.

Currently, the primary crops grown in Ontario are maize (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and winter wheat (*Triticum aestivum* L.) (Statistics Canada 2019b). In 2019, the area of arable land in the province seeded to these three crops was approximately 2.4 million ha. In contrast, the area seeded to canola in the same year was 18 900 ha (OMAFRA 2019), most of which was located in central and northern Ontario and is almost exclusively spring canola (M. Moran, personal communication). The production of spring canola in Ontario has recently faced challenges from clubroot (*Plasmodiophora brassicae* Woronin) (Gossen et al. 2015) and swede midge (*Contarinia nasturtii* Kieffer), both of which have been documented in the province (Chen et al. 2011; Williams and Hallett 2018). Clubroot is an important soil-borne disease of Brassicaceae that was first observed in western Canadian canola in 2003 (Strelkov and Hwang 2014). Infection results in the formation of club-shaped swellings on canola roots, which reduces water and nutrient uptake and causes stunting, wilting, and significant yield losses when severe. Swede midge is a gall forming insect pest of Brassicaceae that was first identified in Ontario in 2000 (Chen et al. 2011). Larval feeding prior to and during canola bolting can cause misshapen plants with twisted stems, swollen growing tips, and a loss of apical dominance, which can result in reductions in seed quality and yield.

For both swede midge and clubroot, winter canola offers a potential solution to maintain or expand canola acreage in Ontario. For instance, clubroot resistance genes have been identified in European winter canola cultivars (Rahman et al. 2011; Rahman et al. 2014; Aigu et al. 2020), and while this disease was first reported on Ontario spring canola in 2016 (Al-Daoud et al. 2018), it has yet to be observed on winter canola (M. Moran, personal communication). Similarly, it has been hypothesized that the earlier transition to reproductive growth in winter canola relative to its spring counterpart may

allow it to avoid the peak period of swede midge activity and thus, the damage to meristematic tissue that accompanies larval feeding (Chen et al. 2011). To date, swede midge damage has yet to be observed on winter canola in Ontario (M. Moran, personal communication). Thus, the incorporation of winter canola into southern Ontario crop rotations would help expand canola acreage in the province in spite of the insect pest and disease pressures that currently limit spring canola production.

The adaptation of winter canola to environmental conditions in Ontario was first evaluated in the 1980s (Beaulieu and Hume 1987). Beaulieu and Hume (1987) seeded four winter canola varieties at 32 sites across southern, central, and northern Ontario stretching from Woodslee (42.214°N, 82.748°W) to Kaspuskasing (49.603°N, 82.455°W). They observed low winter survival at locations in northern Ontario, while the most promising sites in southern Ontario were characterized as well drained with good snow cover and an absence of excess flooding and cold temperatures in spring. At sites that did not have complete winterkill, plant survival averaged 70%, and the mean yield was 2.38 t·ha⁻¹. For comparison, the mean yield of Ontario spring canola from 2012 to 2019 was 2.4 t·ha⁻¹ (OMAFRA 2019). Over the years, there has been intermittent interest in winter canola in the province and a multi-site performance trial was conducted annually up to 2010 before it was discontinued (OSACC 2010).

Since the work of Beaulieu and Hume (1987), little to no research has been conducted on the agronomic issues that potentially limited the adoption of winter canola in Ontario. Important issues to successful canola production, such as the impact of environment on oil quantity and quality and the optimal seeding date for winter survival and yield, have been addressed for other canola growing regions (Mendham et al. 1981; Holman et al. 2011; Assefa et al. 2014; Young et al. 2014), but remain unknown for Ontario. The objective of the current research was to identify an optimal seeding date for winter canola production in southern Ontario. Three winter canola hybrids were seeded at five dates, stretching from early September to late October in 2016, 2017, and 2018. The impact of winter canola hybrids and seeding date on winter survival, rate of crop development, canola yield, and oil quality and quantity were determined.

Materials and Methods

Cultural practices

Field trials were initiated in the autumn of 2016, 2017, and 2018 at the Harrow Research and Development Centre, Harrow, ON (42.035°N, 82.902°W). The soil type was a Harrow sandy loam (65% sand, 26% silt, and 9% clay) with a pH of 5.8 and 2% organic matter. A randomized split-plot design with four replicates was used to evaluate the impact of seeding date on winter survival,

yield, and seed quality of three winter canola hybrids over three calendar years. Seeding date served as the whole plot factor while winter canola hybrid was the subplot factor. There were five seeding dates in each year, ranging from 1 Sept. to 17 Oct. in 2016, from 1 Sept. to 21 Oct. in 2017, and from 1 Sept. to 19 Oct. in 2018. The same three winter canola varieties were used in all years of the experiment: Inspiration, Mercedes, and CC170-70 (Rubisco Seeds, Philpot, KY). All three hybrids are conventional winter canola hybrids (i.e., they are not herbicide tolerant). Inspiration and Mercedes are true winter hybrids from Europe that are currently grown in the United States, while CC170-70 is an early winter hybrid that matures 5–7 d ahead of true winter hybrids (B. Caldbeck, personal communication).

Whole plots consisted of nine 6-m-long rows of winter canola spaced 0.38 m apart. Subplots within these whole plots consisted of three rows of each winter canola hybrid. Prior to seeding, fertilizer (6–24–24, N–P–K at 175 kg·ha⁻¹ and 34–0–0 at 75 kg·ha⁻¹) was spread on the experimental area at the same time as a pre-plant incorporated application of trifluralin (Treflan Liquid EC, 480 g·L⁻¹, Gowan Canada Inc., Winnipeg, MB) at a dose of 0.6 kg a.i.·ha⁻¹. Winter canola was seeded with a precision vacuum seeder (Monosem Inc., Edwardsville, KS) to obtain a target plant population density of 761 905 plants·ha⁻¹ (or ~76 plants·m⁻²). Currently, the recommended seeding rate for winter canola in Ontario is 75–130 plants·m⁻² (OMAFRA 2017). Seeding rates were not adjusted for difference in the germination of seed lots, however, germination uniformly exceeded 90% in all years of study. To control volunteer winter cereals that emerged in autumn of 2017, quizalofop-*p*-ethyl (Assure II, 96 g·L⁻¹, E.I. DuPont Canada, Mississauga, ON) was applied at a dose of 0.05 kg a.i.·ha⁻¹ along with the recommended surfactant (i.e., Sure-Mix at 0.5% v/v). In the spring of all years, 41–0–0–1 (S)–0.744 (B) and 21–0–0 were broadcast over the experimental area at 490 and 63 kg·ha⁻¹, respectively. Plots were hand-weeded as needed, and there was no fungicide applied. In 2018, plots were treated with lambda-cyhalothrin (Matador, 120 g·L⁻¹, Syngenta Crop Canada Inc., Guelph, ON) at a dose of 0.083 L·ha⁻¹ when the crop was at the early flowering stage (i.e., <30% flowering) for the control of cabbage seed pod weevil (*Ceutorhynchus obstrictus* Marsham).

Measured traits and harvest procedures

Following winter canola emergence, 1 m of the middle row of each subplot was flagged, and the number of seedlings was counted. The number of seedlings killed over winter was assessed by re-counting these same flagged rows the following spring. Winter canola phenology during the growing seasons was assessed using the Biologische Bundesanstalt, Bundessortenamt and Chemical industry (BBCH) scale for mono- and dicotyledonous Plants (Meier 1997) and the number of

days from seeding to BBCH 65 (i.e., full flowering; 50% flowers open on main raceme open), BBCH 80 (i.e., pod ripening: all pods have reached final size, seed green, filling pod cavity), and BBCH 87 (70% of pods ripe, seeds black, and hard) were recorded. Weather data collected at the Harrow Research and Development Centre were used to calculate growing degree days (GDD) as follows:

$$\tau_n = \sum_{i=1}^n \left(\frac{T_{xi} + T_{ni}}{2} - T_b \right) \Delta t$$

where τ_n is GDD, T_x is the daily maximum temperature, T_n is the daily minimum temperature, and T_b is the base temperature below which growth no longer proceeds (Campbell and Norman 2012). For the purpose of this experiment, the T_b for GDD accumulation was set to 0 °C (Gabrielle et al. 1998; Robertson et al. 2002).

The interaction of seeding dates and hybrid relative maturity resulted in a range of dates where plots reached physiological maturity. As a result, subplots were desiccated and harvested individually, such that replicate subplots of a given seeding date × hybrid treatment were desiccated or harvested at the same time. Winter canola was desiccated prior to harvest using diquat (Reglone 240 g·L⁻¹, Syngenta Canada Inc., Guelph, ON) at a dose of 0.4 kg a.i.·ha⁻¹ and the appropriate adjuvant (i.e., Agral 90) according to the manufacturer's recommendation. Canola was harvested with a plot combine, and seed was placed in a forced air drier at 35 °C for 3 d prior to recording yield. The percent green and heated seed were determined for each subplot following the guidelines and protocols described in the Official Grain Grading Guide (Canadian Grain Commission 2020b). In brief, five lots of 100 seeds were randomly taken from each subplot, crushed, and evaluated for percent green and heated seed counts.

Near-infrared reflectance (NIR) spectroscopy and oil quality analyses

In the 2017–2018 and 2018–2019 field seasons, subsamples of seed from each harvested plot were sent to the Canadian Grain Commission for seed quality analysis. Subplots sent for analysis included the first three seeding dates in 2017–2018 and the first two seeding dates in 2018–2019; seeding dates with low yields were not sent for analysis. Reflectance spectra for each canola sample (log 1/R) was recorded at 2 nm intervals from 400 to 2500 nm with a NIRSystems 6500 scanning monochromator (FOSS NIRSystems Inc., Silver Spring, MD) using WINISI. The NIR Systems 6500 whole seed analyzer was calibrated with the following reference methods:

- a. oil content (%; 8.5% moisture) by ISO 659:2009 modified by the Randall method and nuclear

Table 1. Analysis of variance for the effects of seeding date on the autumn emergence, winterkill, and yield of three winter canola hybrids over three years at the Harrow Research and Development Centre.

Covariance parameter		Autumn emergence	Winterkill	Yield
		P values		
Year		0.1753	0.1760	0.1795
Replicate (rep)		—	—	—
Rep × seeding date (year)		<0.0001	<0.0001	<0.0001
Residual		<0.0001	<0.0001	<0.0001
Fixed effects	NDF/DDF			
Seeding date	4/50	0.0695	<0.0001	<0.0001
Hybrid	2/109	<0.0001	0.0005	0.0008
Seeding date × hybrid	8/109	0.2050	0.0408	<0.0001

Note: NDF, numerator degrees of freedom; DDF, denominator degrees of freedom.

- a. magnetic resonance (NMR) spectrometry according to AOCS recommended practice ak 4-95,
- b. protein content (% , 8.5% moisture) according to the Dumas method, AOCS Official Method Ba 4e-93,
- c. chlorophyll content ($\text{mg}\cdot\text{kg}^{-1}$) by AOCS Official Method Ak 2-92 (11),
- d. total glucosinolates content ($\mu\text{mol}\cdot\text{g}^{-1}$, 8.5% moisture) by glucose release according to ISO9167-3.

The free fatty acid content of the oil was determined after a cold extraction of 10 g of seed with petroleum ether (60 mL) according to [Ke and Woyewoda \(1978\)](#). Results are expressed as a percentage by weight of oleic acid in the oil.

Statistical analyses

Winter canola autumn emergence, winterkill, and yield at physiological maturity were analyzed as a split-plot design with seeding date as the whole plot fixed effect, hybrid as the split-plot fixed effect, and year, replicate, and replicate × seeding date within year as random effects ([Table 1](#)). Yields were standardized to 8.5% moisture content prior to analysis. Analyses with the same design were used for seed and oil quality parameters including percent green seed, percent heated, oil and protein content, chlorophyll content, glucosinolate content, free fatty acids, and erucic acid. The results for erucic acid are not presented, as there were no significant effects ($\alpha = 0.05$). All analyses were carried out in the PROC MIXED function of SAS (SAS Institute, Cary, NC), and means were separated using Tukey's honestly significant difference.

The relationship between autumn GDD accumulation and winterkill was evaluated through non-linear regression. For each year of the study, replicate plots were averaged within a seeding date and regressed against cumulative GDDs (base 0 °C) from seeding to the first hard frost, which was defined as when the daily mean

air temperature reached -2 °C. Data were fit to the following four parameter logistic equation in Sigmaplot (Systat Software, Inc., San Jose, CA):

$$f(x) = a + \frac{b - a}{1 + \left(\frac{x}{X_0}\right)^c}$$

where b is the upper asymptote, a is the lower response limit, X_0 is the point of inflection, and c is the slope of the curve around X_0 . Finally, the GDD to flowering, pod set, and physiological maturity (i.e., BBCH 65, BBCH 80, and BBCH 87, respectively) were analyzed as a split-plot repeated measure where seeding date, hybrids, and thermal time were considered fixed effects and replicate, years, replicate × seeding date, and replicated × hybrid within seeding date were considered random effects ([Table 2](#)).

Results

Autumn emergence of winter canola was not influenced by seeding date but did differ among the hybrids evaluated ([Table 1](#)). Across hybrids and seeding dates, the mean plant population density of canola was approximately 540 000 seedlings·ha⁻¹ or 54 plants·m⁻², which represent 71% of our target seeding density (data not shown). The emergence of Inspiration was highest with an autumn stand of 569 991 seedlings·ha⁻¹, followed by Mercedes and CC170-70 at 545 932 and 504 812 seedlings·ha⁻¹, respectively. Seed lots of each hybrid were routinely checked for germinability prior to seeding each year of the study, and the lower autumn stand of CC170-70 can at least in part be attributed to its lower percent germination relative to Inspiration and Mercedes (i.e., 93% vs. 98% and 96% germination, respectively). Although seeding date did not influence autumn emergence ([Table 1](#)), the plant population density ranged from 580 344 seedling·ha⁻¹ for plots seeded the first week of September to 465 150 seedlings·ha⁻¹ for plots

Table 2. Repeated measures split-plot analysis of variance of the effects of seeding date on the growing degrees days to BBCH 65, BBCH 80, and BBCH 87 in three winter canola hybrids over three years at the Harrow Research and Development Centre.

Covariance parameter	Z-score	
Year	0.1603	
Replicate (rep)	—	
Rep × seeding date	—	
Rep × hybrid (seeding date)	—	
Compound symmetry	0.0012	
Residual	<0.0001	
Fixed effects	NDF/DDF	P value
Seeding date	4/12	<0.0001
Hybrid	2/30	0.0045
Seeding date × hybrid	8/30	0.9968
Growth stage	2/294	<0.0001
Seeding date × growth stage	8/294	0.4930
Hybrid × growth stage	4/294	0.5781
Seeding date × hybrid × growth stage	16/294	0.9991

Note: NDF, numerator degrees of freedom; DDF, denominator degrees of freedom.

seeded the third week of September. The reduced autumn emergence of this later seeding date was heavily influenced by very low emergence of all hybrids in 2018. Seeding on 24 Sept. 2018 was preceded and followed by significant rainfall events and resulted in mean plant population densities of 183 727, 164 042, and 144 357 seedlings·ha⁻¹ for Mercedes, Inspiration, and CC170-70, respectively. These results indicate that, barring exceptional circumstances, the autumn emergence of winter canola is not influenced by the seeding dates evaluated in this study.

The percent of seedlings killed over winter was influenced by crop seeding date, hybrid, and the interaction of these factors (Table 1). In general, the extent of winterkill was <40% for all September seeding dates but increased to 60%–80% as seeding was delayed into October (Fig. 1). We attributed the significant seeding date × hybrid interaction to differential responses of the early (i.e., CC170-70) vs. true winter hybrids (i.e., Inspiration and Mercedes) when seeding happened the first week of September. Although not statistically significant, there was numerically greater winterkill for CC170-70 seeded the first week of September when compared with Mercedes and Inspiration. This result was in agreement with the observation of numerous CC170-70 individuals bolting (i.e., transitioning into a reproductive stage of development) in autumn, which resulted in their death over winter (S. Meloche, personal observation). In contrast, all individuals of Inspiration or Mercedes remained vegetative. When the relationship between winterkill and autumn GDD accumulation was examined, it was apparent that there was a minimum

Fig. 1. Effect of seeding date on the winterkill of three winter canola hybrids grown at the Harrow Research and Development Centre (42.035°N, 82.902°W) during 2016–2018.

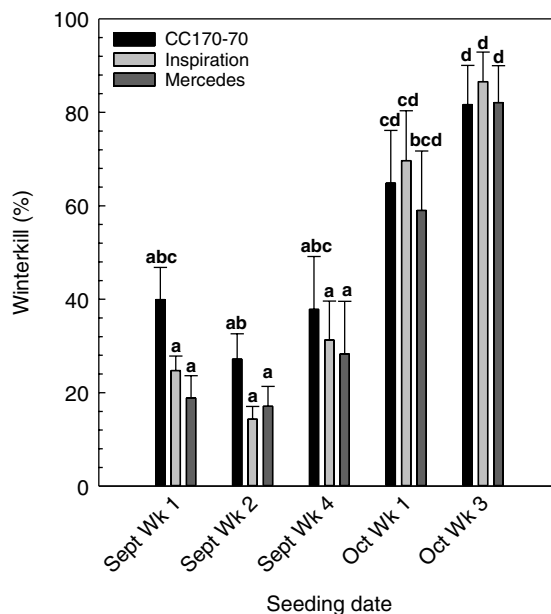
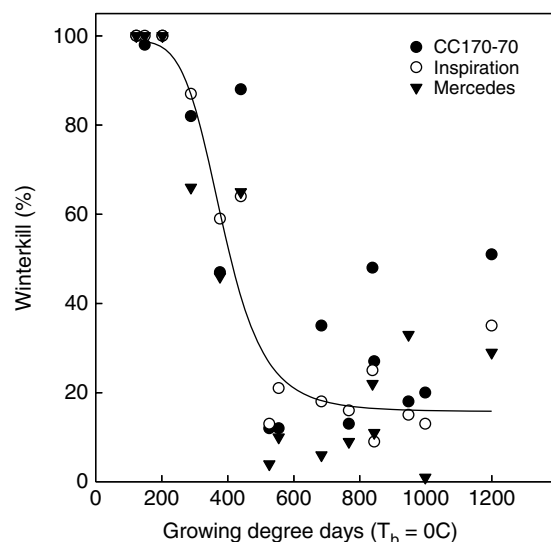
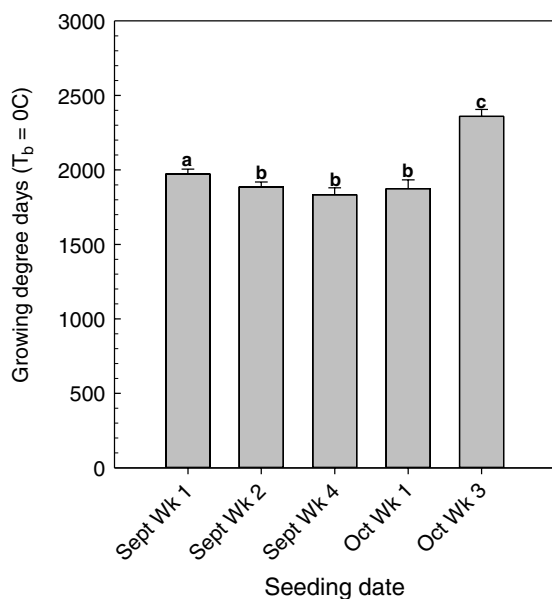


Fig. 2. Cumulative growing degree days (GDD) from seeding to the first hard frost of autumn (defined as a mean daily air temperature of -2°C) and its relationship with winterkill of three winter canola hybrids seeded over five dates during 2016–2018. The four-parameter logistic model, $f(x) = a + [b - a / 1 + (X/X_0)^c]$, was fit, where $a = 16$, $b = 99$, $c = -6$, and $X_0 = 385$.



GDD before a hard frost ($<-2^{\circ}\text{C}$) that reduced winterkill (Fig. 2). Across the three hybrids examined, winter canola seeding dates that facilitated the accumulation of >600 GDD before the first hard frost of autumn tended to have less than 20% stand reduction from

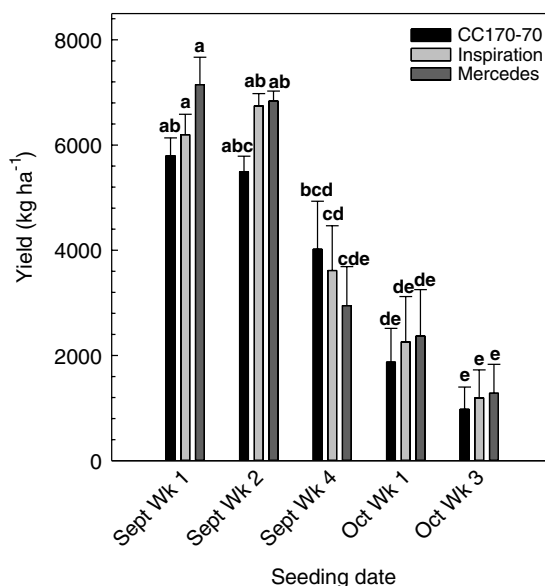
Fig. 3. Effect of seeding date on the phenological development of winter canola. The main effect of seeding date was significant, but the interaction of seeding date and stage of development was not. As such, bars represent the mean growing degree days across the three developmental stages evaluated (i.e., BBCH 65, BBCH 80, and BBCH 87).



winterkill. When at least 600 GDD were accumulated, winterkill levels remained close to 20% for Mercedes and Inspiration; however, there was notably greater variation in winterkill for CC170-70, and this can be attributed to its tendency for premature autumn bolting, as noted above. If less than 600 GDD were accumulated before the first hard frost, the average winterkill was 66%.

The number of GDD to reach BBCH 65, BBCH 75, and BBCH 87 was influenced by seeding date and hybrid (Table 2). Unsurprisingly, CC170-70 required fewer GDD to reach any of these developmental milestones than did Mercedes or Inspiration, respectively (data not shown). For example, CC170-70 required 100 and 92 GDD fewer than Mercedes or Inspiration, respectively, to reach BBCH 87. In practical terms, this difference translated into approximately 5 days during late June/early July in southwestern Ontario. Winter canola seeding date influenced phenological development in a parabolic fashion (Fig. 3). The average number of GDD required to reach BBCH 65, BBCH 80, and BBCH 87 was highest when seeding took place the third week of October (2360 GDD) and the first week of September (1973 GDD) but declined for the three intervening seeding dates (average of 1865 GDD). When seeded the third week of October, the observed delay in development the following spring was associated with very small rosettes surviving over winter (i.e., 5 cm in diameter, 3–4 leaves). Conversely, when seeded the first week of September, rosettes often grew to larger than 15 cm in diameter (i.e., 8–10 leaves) in autumn, but much of this

Fig. 4. Effect of seeding date on the yield of three winter canola hybrids grown at the Harrow Research and Development Centre (42.035°N, 82.902°W) during 2016–2018.



vegetative tissue senesced over winter and the plant grew back from the apical meristem in the spring.

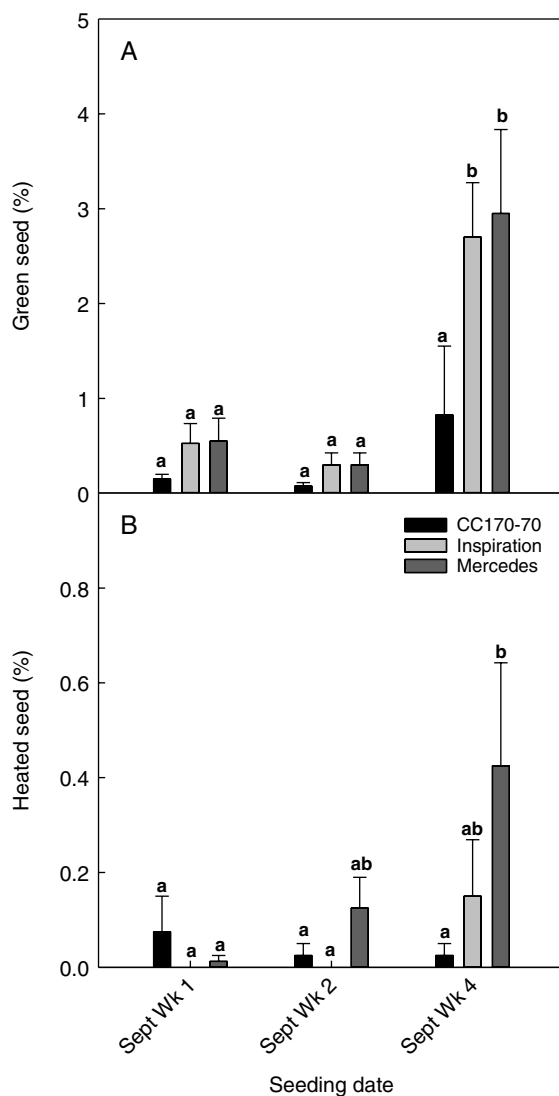
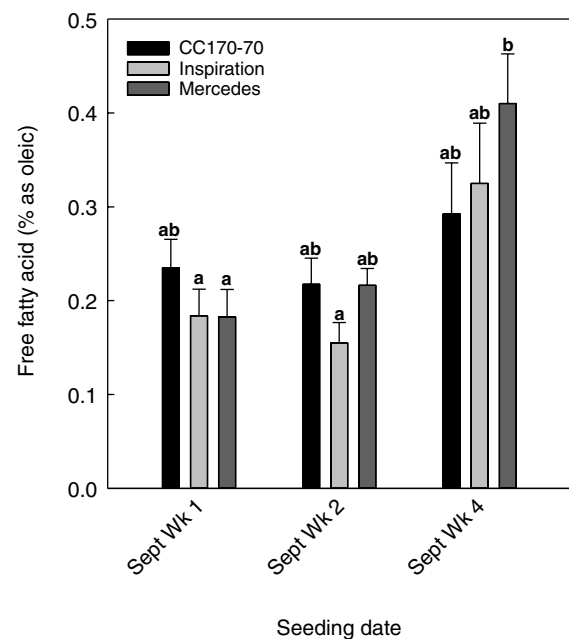
Winter canola yield was influenced by hybrid, seeding date, and the interaction of these factors (Table 1). Across the hybrids evaluated in this study, winter canola yield was the greatest when seeded during the first two weeks of September (6380 and 6358 kg·ha⁻¹, respectively) (Fig. 4). Thereafter, yields declined to 3544 and 2166 kg·ha⁻¹ when seeding was delayed to the fourth week of September and the third week of October, respectively. When averaged across seeding dates, the yield of true winter hybrids, Mercedes and Inspiration, were 12% and 9% greater than that of CC170-70, respectively. When seeded at the optimal time (i.e., the second week of September), Mercedes, Inspiration, and CC170-70 yielded 6839, 6744, and 5490 kg·ha⁻¹, respectively. While these small plot yields are higher than what has been observed for farm-scale production in Ontario, they are similar to the results reported for these hybrids in the United States National Winter Canola Variety Trials (KSU 2018, 2019).

The percent of canola seed characterized as green or heated at harvest was influenced by the interaction of seeding date and hybrid (Table 3). As seeding date was delayed from early (weeks 1 and 2) to late September (week 4), the percent green or heated seed increased, and this effect was more pronounced for true winter hybrids (i.e., Inspiration and Mercedes) than for earlier maturing germplasm (i.e., CC170-70) (Fig. 5). When Mercedes and Inspiration were seeded during the fourth week of September, the harvested crop would have been downgraded to No. 2 Canada canola based on elevated

Table 3. Analysis of variance for the effects of seeding date and hybrid on seed protein, oil quantity, and oil quality parameters in three winter canola hybrids in 2018 and 2019.

Covariance parameter	NDF/DDF	Green seed	Heated seed	Protein	Oil	Chlorophyll	Glucosinolates	Free fatty acids
		Pr > Z						
Year		0.3191	0.4023	0.4118	0.3010	0.3285	0.2604	0.2463
Rep (year)		—	0.2023	0.0635	0.2459	—	0.1647	—
Rep × seeding date (year)		0.0414	0.4632	—	0.2772	0.0451	0.3525	0.3709
Residual		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Fixed effects	NDF/DDF	Pr > F						
Seeding date	2/10	0.0012	0.0541	0.0065	0.2063	0.0023	0.5808	0.0107
Hybrid	2/10	<0.0001	0.0100	<0.0001	<0.0001	<0.0001	<0.001	0.0790
Seeding date × hybrid	4/34	0.0031	0.0260	0.1841	0.0818	0.0889	0.1122	0.0449

Note: NDF, numerator degrees of freedom; DDF, denominator degrees of freedom.

Fig. 5. Effect of seeding date on the incidence of (A) green and (B) heated seed in three winter canola hybrids.**Fig. 6.** Effect of seeding date on free fatty acid content of canola oil from three winter canola hybrids.

percent green seed (for both hybrids) and heated seed (for Mercedes only) (Canadian Grain Commission 2020b). We attributed the increased levels of green and heated seeds in later seeding dates of Mercedes and Inspiration to greater variation in crop maturity that accompanies suboptimal seeding dates and a delayed harvest during the heat and humidity of midsummer. It is interesting to note that the free fatty acid and chlorophyll content of the seed followed similar patterns as percent heated or green seed (Table 3). Free fatty acid content increased as seeding date was delayed, and this effect was more pronounced for Mercedes than the other two cultivars (Fig. 6). Chlorophyll content also increased

from 15.6 to 18.6 and 26.9 mg·kg⁻¹ as seeding date was delayed from the first week of September to the second and fourth week of September, respectively (data not shown).

Canola hybrid was the primary factor influencing oil and protein content, as well as the level of glucosinolates in the seed (Table 3). Oil content ranged from 43.9% for Mercedes to 41.6% for Inspiration while protein ranged from 18.8% to 20.8% for Mercedes and CC170-70, respectively (data not shown). As reference, western Canadian spring canola oil content averaged 44.1% and 44.6% in 2018 and 2019, respectively (Canadian Grain Commission 2020a). Total glucosinolates content followed a similar pattern as oil content and ranged from 8.7 for Mercedes to 10.7 μmol·g⁻¹ of seed for Inspiration. Of these response variables, seed protein content was the only one influenced by seeding date. Protein content increased from 19.7% to 20.5% as seeding was delayed (data not shown). As expected, seed oil content showed a reciprocal decline as protein increased; however, the decrease from 43.0% to 42.4% as seeding date was delayed was not statistically significant (Table 3).

Discussion

The results of this research have demonstrated that the optimal seeding date for winter canola production in southern Ontario was during the first two weeks of September, such that a minimum of 600 GDD could be achieved from seeding to the first killing frost (<-2 °C). This recommendation was based on reduced winterkill, maximized yield, and the assurance that seed quality parameters normally assessed at commercial elevators were within the prescribed limits. Previous research conducted in other regions has also identified optimal dates for seeding winter canola, and they varied based on climatic conditions specific to the growing region (Mendham et al. 1981; Jenkins and Leitch 1986; Moon-Tae 1995; Holman et al. 2011; Darby et al. 2012; Assefa et al. 2014; Begna and Angadi 2016). For example, in the Great Plains and mid-western United States, Assefa et al. (2014) reported that the optimal period for seeding winter canola occurred between mid-August and early September. Similarly, Begna and Angadi (2016) reported that yields of winter canola in New Mexico were greater when seeding occurred from late September to early October. While many studies have examined the impact of seeding date on winter canola oil and protein quantity, the results of the present study were the first to assess the impact of seeding date on the quality of the canola oil.

Previous studies of spring canola have also demonstrated that agronomic practices such as seeding date, row width, and fertilizer inputs can influence canola oil quality (May et al. 1994; Harker et al. 2013). For example, May et al. (1994) reported that the free fatty acid content of canola oil increased when seeding was delayed.

May et al. (1994) also observed that free fatty acid content was higher in seeds from branches than in seeds from the main stem, which led them to conclude that agronomic practices that could reduce branching could contribute to the maintenance of oil quality. Although we did not directly measure branching in the present study, our results and observations supported the hypothesis that delayed seeding reduces canola oil quality through its impact on winterkill and the resulting increase in plant-to-plant variability within the crop stand. In our study, winterkill increased when winter canola was seeded after the first two weeks of September (Fig. 1). Later seeding dates often showed increased within plot variations when assessed for stage of development (S. Meloche, personal observation). Moreover, at physiological maturity, this reduction in uniformity complicated the timing of crop desiccation and harvest. The increase in percent heated and green seed (Fig. 5) at later seeded dates was evidence of increased variability in plant architecture and phenology at the time of desiccation. Unsurprisingly, seeding dates where higher levels of green and heated seed were observed also produced oil with elevated chlorophyll and free fatty acid contents (Fig. 6). These results suggest that seeding winter canola during the optimal period helped to ensure that important oil quality parameters were maintained within desired levels for further uses down the value chain.

The yield potential for winter canola production in southern Ontario was on par with, or greater than, many locations included in the USA National Winter Canola Variety Trial (KSU 2018, 2019). Although variable by year, the locations included in the USA National Winter Canola Variety Trial commonly range from 34°N to 48°N latitude. In 2018 and 2019, the mean yields of all hybrid entries included in these performance trials were 2066 and 2694 kg·ha⁻¹, respectively. The highest yielding locations in 2018 and 2019 were Athens, GA, and Garden City, KS, where the mean hybrid yields were 4906 and 4575 kg·ha⁻¹, respectively. Mercedes was the only entry that was common to both our study and the 2018 national performance trials. The mean yield of Mercedes across the 15 tested locations in 2018 was 1927 kg·ha⁻¹, with the highest recorded yield for this hybrid, 4300 kg·ha⁻¹, observed at Athens. For comparison, the mean yield of Mercedes in the present study was 4117 kg·ha⁻¹, with the highest recorded yield of 7148 kg·ha⁻¹ (Fig. 2). Yields of CC170-70 and Inspiration showed similar ranges. These results highlight the exceptional potential for winter canola production in southern Ontario.

While the research conducted on winter canola in Ontario in the early 1980s showed promise (Beaulieu and Hume 1987), there was no subsequent work to address limitations to its adoption in the province. Results presented by Beaulieu and Hume (1987) suggested that winterkill may have been an issue for the

open pollinated varieties that were tested at that time. Anecdotal reports of slug damage and canola roots plugging tile drains may also have contributed to the declining interest of the crop in Ontario (M. Moran, personal communication). The results of the present study showed that winter canola could be successfully produced in Ontario. Its addition to the current crop rotation of maize, soybean, and winter wheat could have significant benefits for Ontario farmers. The diversification of cropping systems through the incorporation of new crops with varying periodicity, growth habits, and agronomic practices will help increase the resilience of a system in face of challenges such as insect pests, disease, or environmental variability (Liebman and Schulte-Moore 2015). In Ontario, the management of herbicide-resistant weeds is presently one of the foremost challenges facing producers (Vink et al. 2012; Page et al. 2018; Kreiner et al. 2019). The addition of a broad-leaved winter crop to the current crop rotation would enhance the options for herbicide resistance management particularly of the problematic winter annual species, *Conyza canadensis* L. As a broad-leaved alternative to winter wheat, winter canola could facilitate the management of winter annual grasses, and it has been demonstrated that the yield of winter wheat increased when it followed canola in crop rotations (Bushong et al. 2012). The incorporation of winter canola into rotation also raised the possibility of double cropping with soybean, as the harvest of winter canola is advanced relative to that of winter wheat (Page et al. 2019).

The results of this research established the first two weeks of September as the optimal seeding period for winter canola in southern Ontario when the crop received at least 600 GDD before the first killing frost. It should be noted that Ontario is a large and diverse province and that this recommendation is specific to the most southern counties of the province. We predict that seeding date should be appropriately advanced when producing winter canola in more northerly regions of the province. Nevertheless, seeding winter canola during this optimal period not only reduced the incidence of winterkill while maximizing yield potential, but it also helped to ensure that the resulting oil was of optimal quality. Winter canola showed great potential for production in southern Ontario and its addition to current crop rotations would diversify and enhance crop production practice in the province.

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