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Source: Canadian Journal of Plant Science, 102(3) : 698-709

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/CJPS-2020-0186

Canadian Science Publishing

ARTICLE

Effect of precision planting and seeding rates on canola plant density and seed yield in southern Alberta

Gurbir Singh Dhillon, Lewis Baarda, Mike Gretzinger, and Ken Coles

Abstract: Precision planters are recently being adopted for seeding canola to improve crop establishment and seed yield. This study determined the effect of seeding canola using precision planters (30.5 and 50.8 cm seeding row width) and conventional air drill seeders at different rates (20, 40, 60, 80, and 160 seeds m^{-2}) on plant density and seed yield. The study was conducted for 4 yr (2016 to 2019) at three locations in southern Alberta. Plant density increased with higher seeding rates following the negative exponential function distribution. The yield-density relationship was non-linear asymptotic in nature and weak-to-moderate in strength at most site-years. The parameters of yield-density relationship did not show statistically significant differences among the air drill and precision planters. When averaged among seeding rates, canola yield was higher for the narrow row precision planter at 5 site-years and for the air drill at 2 site-years out of a total of 12 site-years. Under irrigated and high-precipitation conditions, seed yield in narrow-row precision planted canola was higher than air drill seeded canola. There was an average increase of 463 kg ha^{-1} (10%) in the seed yield in narrow-row precision planted canola compared with the air drill seeded canola among irrigated systems; however, under water-limited conditions, seed yield in air drill seeded canola was comparable or higher than the precision planted canola. Wide-row planter led to poor crop establishment and seed yield under both irrigated and dryland conditions, attributed to higher in-row plant density due to wider row spacing.

Key words: precision planter, canola, emergence, plant density, seeding rate.

Résumé : Depuis peu, on recourt à des semoirs de précision pour planter le canola et en améliorer le développement ainsi que le rendement grainier. Les auteurs voulaient déterminer les effets de cet appareil (écartement des lignes de 30,5 ou de 50,8 cm) et des semoirs pneumatiques usuels, réglés de diverses manières (20, 40, 60, 80 ou 160 graines par m^2), sur la densité du peuplement et le rendement grainier. L'étude a duré quatre ans (de 2016 à 2019) et s'est déroulée à trois endroits, dans le sud de l'Alberta. La densité des plants augmente avec le taux de semis selon une fonction de distribution exponentielle négative. Les liens entre le rendement et la densité du peuplement sont de nature asymptotique non linéaire, et leur robustesse varie de faible à modérée pour la plupart des sites-années. Les paramètres de la relation entre le rendement et la densité du peuplement ne varient pas de manière statistiquement significative entre le semoir pneumatique et le semoir de précision. Quand on calcule la moyenne d'après le taux de semis, on constate que le rendement est plus élevé à cinq années-sites pour le semoir de précision à faible écartement et à deux années-sites pour le semoir pneumatique, sur un total de douze années-sites. Lorsqu'il y irrigation ou que les précipitations abondent, le canola semé avec un semoir de précision à faible écartement enregistre un rendement supérieur à celui planté avec un semoir pneumatique. Le rendement grainier du canola cultivé sous irrigation augmente en moyenne de 463 kg par hectare (10 %) quand il est semé avec un semoir de précision à faible écartement plutôt qu'avec un semoir pneumatique. Toutefois, quand l'eau manque, le rendement grainier obtenu avec le semoir pneumatique est comparable ou supérieur à celui relevé avec le semoir de précision. Le semoir de précision à grand écartement donne de piètres résultats au niveau de l'établissement de la culture et du rendement grainier, tant sous régime irrigué qu'avec l'aridoculture. On l'attribue au nombre supérieur de plants par rang qui résulte du plus grand écartement. [Traduit par la Rédaction]

Mots-clés : semoir de précision, canola, levée, densité des plants, taux de semis.

Received 3 July 2020. Accepted 1 February 2022.

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Introduction

Canola (*Brassica napus* L.) is a major oilseed crop on the Canadian prairies. Due to its growing consumption and demand, canola production in the Canadian prairies has increased from 1.8 million tonnes (Mt) in 1981 to 18.6 Mt in 2019. The Canola Council of Canada projects that canola production must be increased up to 25 Mt by 2025 to meet the increasing market demand in Canada (Morrison et al. 2016). To meet this projection at current canola acreage (~ 8.3 Mha), an average canola yield of approximately 3 Mg ha^{-1} is required, thus requiring an approximately 35% increase in the current average canola yield (~2.2 Mg ha^{-1}) in Canada.

Despite the availability of high-quality (>90% germination) seeds, canola stand establishment has often been observed to be variable and low. Average seedling emergence rates of approximately 40% to 60% have been reported in western Canada (Harker et al. 2003, 2012). Poor stand establishment decreases crop competitiveness to weeds and increases dependence on herbicide applications (Harker et al. 2003). Compensatory crop growth to correct for suboptimal stand density may lead to delayed flowering and maturity stages, higher growing-season temperatures, higher risk of fall frost, and increased green seed abundance (Angadi et al. 2000; Kutcher et al. 2010; Harker et al. 2012). In contrast, high-density canola stands may increase intraspecific competition for resources (Lithourgidis et al. 2011), increase susceptibility to lodging and disease infestation (Jurke and Fernando 2008), and reduce crop harvestability (Thomas 2003). Gan et al. (2016) observed that the optimum stand density required to obtain maximum canola seed yield varies with different environments. Thus, regional assessments of seeding rates required to optimize canola stand establishment for maximum seed yield are warranted. Furthermore, canola seed cost has increased substantially with the advent of hybrid varieties in the last few decades (Shirtliffe 2009; Hartman and Jeffrey 2021). The determination of seeding rates required to maximize seed yield can reduce production costs and result in significant savings for the producers.

Multiple studies conducted in the western Canadian region have demonstrated the importance of stand uniformity and early season vigor in improving canola yields (Elliot et al. 2008; Yang et al. 2014; Harker et al. 2015). The agronomic performance of canola is a function of available resources (Gan et al. 2012). Uniform stand distribution increases the availability of resources such as light, water, and nutrients and decreases intrarow plant competition (Pronk et al. 2007; Lithourgidis et al. 2011). Yang et al. (2014) observed that fertile pod formation and seed set may be enhanced for canola grown across different environmental conditions by improving the uniformity of plant spatial distribution. They reported an increase of 20%–32% in seed yield for spatially uniform canola stands compared with non-uniform stands. Angadi et al. (2003) noticed that the reduction of plant population from 80 to 40 plants m^{-2} did not reduce yield in uniformly distributed stands, but the yield was significantly reduced in non-uniform stands.

The uniformity of spatial distribution of crops can be improved through precision planting technology which is designed to place seeds at equal distances along the crop rows. Precision planters can help in the establishment of spatially uniform crop stands and reduce intrarow plant competition compared with conventional seeders. A study conducted in western Australia found that precision seeding of canola may enable sowing at lower rates without an associated reduction in yield (Harries and Seymour 2016). Another study carried out in southern Australia found a significant improvement in lentil and canola yield through precision planting (McDonald et al. 2019). Precision planters also ensure uniform seeding depth, which leads to more even emergence and more uniform crop development. Thus, precision planters can potentially improve the proportion, uniformity, and rapidity of canola emergence. Harker et al. (2012) observed a strong influence of seeding depth on canola emergence, with the emergence improving from 37% to 62% as seeding depth decreased from 4 to 1 cm. Thomas (2003) reported higher canola yield in western Canada when seeded at a depth of 12 to 25 mm compared with deeper seeding depths.

Precision planters are increasingly being used to seed canola in western Canada, particularly in the regions where they have already been used for seeding other crops such as corn, soybeans, dry beans, and sugarbeets. Despite their potential advantages, there is a lack of studies that have determined the efficacy of incorporating precision planters in the agricultural production of small-seeded crops such as canola in this region. This study compared the performance of precision planter and conventional air drill for the seeding of canola. Field experiments were conducted at three locations in southern Alberta from 2016 to 2019 to determine the influence of precision planters (30.5 and 50.8 cm rows) and conventional air drill on plant density and seed yield in canola at five different seeding rates (20, 40, 60, 80, and 160 seed m^{-2}). Our objectives were to determine (*i*) the variation in canola plant density at different seeding rates, (*ii*) the relationship between plant density and seed yield, and (*iii*) the effect of precision planter and air drill on plant density and seed yield in canola.

Methodology

Study sites and experimental design

This study was conducted at three locations in southern Alberta, including under dryland conditions at Lethbridge (LB) and Medicine Hat (MH), and under irrigated conditions at Lethbridge (IR). Lethbridge is located in the Dark Brown soil zone, while Medicine Hat is located in the Brown soil zone. The choice of these

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locations enabled the inclusion of a wide range of the soil moisture conditions experienced on the Canadian prairies. The study was conducted at these locations for 4 yr from 2016 to 2019 for a total of 12 site-years of data collection. At each location, precision planters with 30.5 and 50.8 cm row spacing and a conventional air drill with 30.5 cm row spacing were used to seed canola at five different seeding rates (20, 40, 60, 80, and 160 seed m^{-2}). These seeding rates correspond to the targeted plant population of 50–80 plants m^{-2} recommended by the Canola Council of Canada (2020) for maximum seed yield with an expected seedling emergence of 40%–60% under field conditions (Harker et al. 2003, 2012). The experiment was designed as 3 × 5 factorial design with a total of 15 treatments, each replicated four times in a randomized complete block design at each study location.

Agronomic management of crops

The trial plots were 6 m in length and consisted of four rows. Row spacing varied (30.5 and 50.8 cm) with the type of treatment. Canola hybrid Pioneer 45M35 was sown at 1.3 cm depth during the first 2 wk of May at five different seed rates (20, 40, 60, 80, and 160 seed m^{-2}). For the planting of canola, a precision vacuum planter (Model: NG Plus 4; Manufacturer: Monosem Inc., Edwardsville, KS) at 30.5 and 50.8 cm row spacing and a custom-built, zero-till air drill (Manufacturer: AgTech Centre, Lethbridge, AB) at 30.5 cm row spacing were used. The air drill is a pull-type plot drill fitted with double shoot, disc/hoe openers and an on-row packer wheel with double-shoulder offset to close the furrow (Model: MK III, Manufacturer: Pillar Lasers Inc., Warman, SK). For seed metering, it uses a seed cup assembly which employs individual row metering with a notched grain metering wheel (Model: MH-310; Manufacturer: Morris Rod Weeder Co. Ltd., Yorkton, SK). Precision vacuum planter is a 4-row unit fitted with 38.1 cm (15") Tru-Vee disk openers. The packing system includes an aluminum seed firmer wheel and rubber V closing wheel with parallel linkage. For seed metering, it includes vacuum meter housing and a seed disc placing individual seeds at equal distances. Row spacings on this planter were altered to 30.5 and 50.8 cm. The same seeding and planting equipment was used in all experiments. Before seeding, soil samples at each test site were analyzed for selected nutrient contents to determine fertilizer requirements. Nitrogen fertilizer (46-0-0) was applied through side-banding, and phosphorus was applied in the seed row (10-34-0) at recommended rates based on soil testing for the target levels of 112 kg ha^{-1} of nitrogen and 196 kg ha^{-1} of phosphorus. Herbicide application was performed using glyphosate (Roundup WeatherMax, 540 g a.e. L^{-1}, solution) and carfentrazone-ethyl (Aim EC, 240 g a.i. L^{-1}, emulsifiable concentrate) at 1.35 kg a.e. ha^{-1} and 17.3 g a.i. ha^{-1}, respectively as pre-seed burndown. Glyphosate (Roundup WeatherMax, 540 g a.e. L^{-1}, solution) was used at the rate of 0.65 kg a.i. ha^{-1} for control of weeds at the 3-leaf stage (BBCH 13) and lambda-cyhalothrin (Matador 120 EC, 120 g a.e. L^{-1}, emulsifiable concentrate) was used at the rate of 10 g a.i. ha^{-1} for the control of cabbage seed pod weevil at the beginning of the flowering stage. Irrigated trials were conducted under an overhead irrigation system (center-pivot sprinkler system). The scheduling and amount of irrigation was dependent on the amount of precipitation received and the crop requirements. A total of 101.6, 342.9, 146.05, and 178 mm of irrigation water was provided during the growing seasons in years 2016, 2017, 2018, and 2019, respectively.

Data collection

Plant density was determined by counting plants in two 1-m rows at two representative places (front and back) in each plot. This measurement was conducted at the 4-leaf stage (BBCH 14). Canopy closure was estimated using normalized difference vegetation index (NDVI) and fractional green canopy cover (FGCC; Patrignani and Ochsner 2015). NDVI measurements were obtained for years 2016 and 2018, while FGCC measurements were obtained for years 2017–2019. NDVI was measured using a GreenSeeker crop sensing system (Trimble, Westminster, CO). The GreenSeeker sensor measures the NDVI by generating light at red and near-infrared wavelengths (660 and 780 nm, respectively) and measuring the difference in reflectance from the target crops (Verhulst and Govaerts 2010). FGCC measurements were taken using a smartphone camera (Samsung S8 phone camera; field of view: 80) mounted to a tripod using the Canapeo Android App (Patrignani and Ochsner 2015). This app measures the FGCC based on color ratios of red to green, blue to green, and an excess green index (Patrignani and Ochsner 2015). Both measurements were taken at or near solar noon, at 1 m height above crop canopy, in a diagonal direction across the plots. These measurements were taken on June 20 or 21 in each year of the study. At maturity, the crop was harvested using a plot combine (2013 Wintersteiger Classic; Wintersteiger Inc. Saskatoon, SK) that collected and weighed canola seed samples using calibrated on-board balance, and moisture sensors. Seed yield of individual plots was determined as kg ha^{-1} and adjusted to a standard moisture level (10%).

Statistical data analysis

Preliminary ANOVA across the 12 site-years showed a significant treatment by site-year interaction for the variables included in this study. Thus, separate statistical analyses were conducted for each site-year.

Effect of seeder type

The effect of type of seeding equipment on multiple response variables including plant density, seed yield, and canopy closure was determined. For plant density and seed yield, linear mixed models were constructed using the lmer function in the R statistical software

(R Core Team 2020). Seeder type was included as the fixed factor in the linear mixed models to determine their effect on response variables. The treatment effects of seeding rate on different response variables were not discerned through the linear mixed model analysis, but through the non-linear regression analysis (described in the next section). The seeding rate was considered a class variable and added as a random factor in the model. A random slope and random intercept structure were included for this factor to account for the variance associated with different seeding rates and their interaction with the seeder type, respectively. Replicate block was also included as a random intercept factor in the model. LSMEANS were compared using Tukey's Highly Significant Difference when the seeder treatment showed a statistically significant main effect ($\alpha = 0.05$). Residuals were tested for normality by examining the q-q plots of residuals, and for homogeneity of variance by inspecting the distribution of residuals against fitted values. For proportional response variables, including NDVI and FGCC, generalized linear mixed models with beta distribution were constructed with the seeder type as the fixed factor and seeding rate and replicate block as random factors.

Effect of seeding rate

The relationship between seeding rate and plant density was determined by using non-linear regression analysis using the NLIN procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC). The asymptotic regression model (also known as monomolecular growth, or Mitscherlich law) was used with the constraint that response variable (i.e., plant density; y) equals zero at the intercept. The following equation was used:

$$(1) \qquad y = a[1 - \exp(-bx)]$$

where y is plant density, x is the seeding rate, a is the fitted parameter representing maximum attainable plant density, and b is another fitted parameter proportional to the relative rate of increase in plant density when seeding rate increases.

Similarly, the non-linear regression analysis was conducted to describe the relationship between plant density and yield using the equation provided by Silvertown and Lovett Doust (1993):

$$(2) \qquad y = w_m x/(1 + cx)$$

where y is the seed yield, x is plant density, w_m is a fitted parameter representing maximum potential yield per plant, and c is the fitted parameter representing the area necessary to achieve w_m.

Both non-linear regression analyses were performed separately for each site-year. All the data points within a site-year (instead of mean values) were included within the regression analyses. The regression functions were chosen based on the criteria of providing best fit to the data, and biologically meaningful parameters. Separate parameters were estimated for each planter type and compared with determine statistically significant differences between the planters at $\alpha = 0.05$. An approximate measure of coefficient of determination (pseudo-R^2) was estimated by using the residual sum of squares of each regression using the following formula (Shirtliffe and Johnston 2002):

$$(3) \qquad \text{Pseudo} - R^2 = 1 - \frac{\text{SS(residual)}}{\text{SS(total corrected)}}$$

where SS (residual) represents the residual sum of squares and SS (total corrected) represents the corrected total sum of squares for the non-linear regression.

Results and Discussion

Preliminary statistical analysis revealed a significant treatment by site-year interaction of seeding rate and planter type for their effect on plant density and yield (data not shown). These results indicated that the environmental conditions (represented by site-years) had a major impact on canola performance as influenced by seeding rate and seeding technology. These trends may have been prompted by high variation in the growing season precipitation among site-years (Table 1). Other studies in the western Canadian region have similarly found a strong effect of environmental conditions on crop response to various agronomic treatments, such as the effect of planting density on canola (Gan et al. 2016) and seeding date and cultivar effect on soybean (MacMillan and Gulden 2020).

Plant density

Plant density showed a non-linear relationship with seeding rates following a negative exponential increase with higher seeding rates. While the density-seeding rate relationship fit an asymptotic regression function, the plant densities did not reach an asymptote within the observed range of seeding rates for most site-years (Fig. 1). This trend was especially true for the narrow-row precision planter where asymptotic plant densities were not achieved at any site-year. Conversely, the wide-row precision planter showed a decrease in maximum plant density at highest seeding rates at some site-years (i.e., LB-2019, IR-2018, IR-2019) thus indicating a parabolic relationship. However, the negative exponential function showed a better fit to the data compared with parabolic function at these site-years similar to other site-years. A moderate to strong relationship between the seeding rate and plant density was observed with the pseudo-R^2 values ranging from 0.46 to 0.93 for different site-years (Table 2).

When averaged among seeding rates, plant density in the narrow-row precision planted canola exceeded that for the air drill seeded canola at 3 site-years, while the differences between them were not statistically

Table 1. Total monthly precipitation (mm) received during the crop growing season (May to August) at the study locations in years 2016, 2017, 2018, and 2019, and long-term averages (1961–2018)

Location	Year	May	June	July	August	Total (May-Aug.)
Lethbridge	2016	68.4	23	105.5	46.1	243
	2017	45.1	68.3	4.7	7.9	126
	2018	22.2	47.1	25.4	20.6	115.3
	2019	51.4	19.4	44.7	27	142.5
	Long-term	52.1	78.7	42	39.3	212.1
Medicine Hat	2016	90	51.1	92.6	72.4	306.1
	2017	32.4	64.1	15.5	15.9	127.9
	2018	19.7	27.4	22.9	10.3	80.3
	2019	18.5	60.1	4.9	27.5	111
	Long-term	41.9	66.6	39.5	33.7	181.7

Note: Source: Government of Alberta (https://acis.alberta.ca/weather-data-viewer.jsp).

Fig. 1. The relationship between plant density and seeding rate for different planters (AD, air drill; PP nr, precision planter 30.5 cm row spacing; PP wr, precision planter 50.8 cm row spacing) at 12 site-years (IR, Lethbridge irrigated; LB, Lethbridge dryland; MH, Medicine Hat dryland). Symbols indicate average plant densities and lines represented fitted regression. Bars represent ±1 standard error of the mean. [Colour online.]

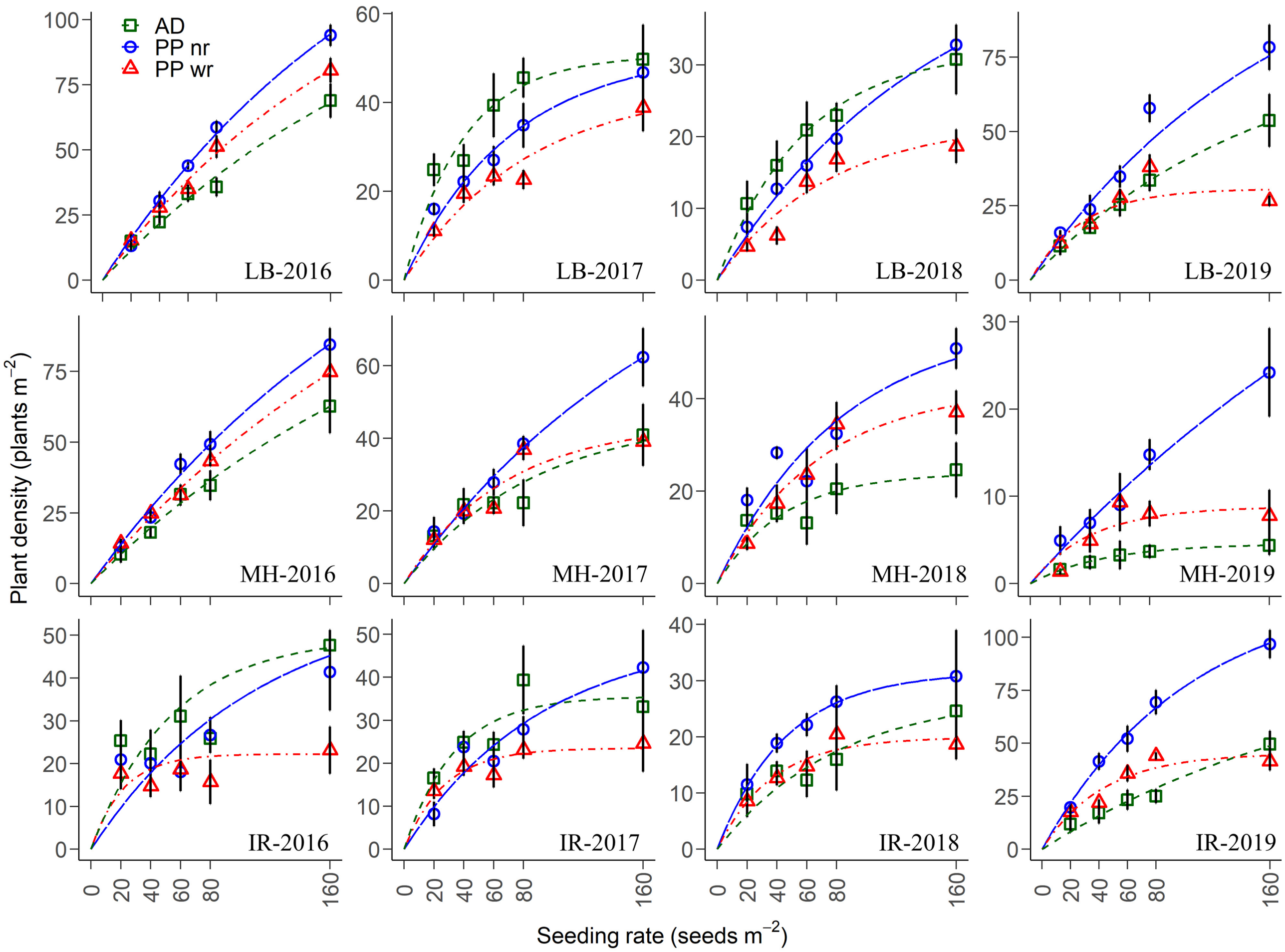

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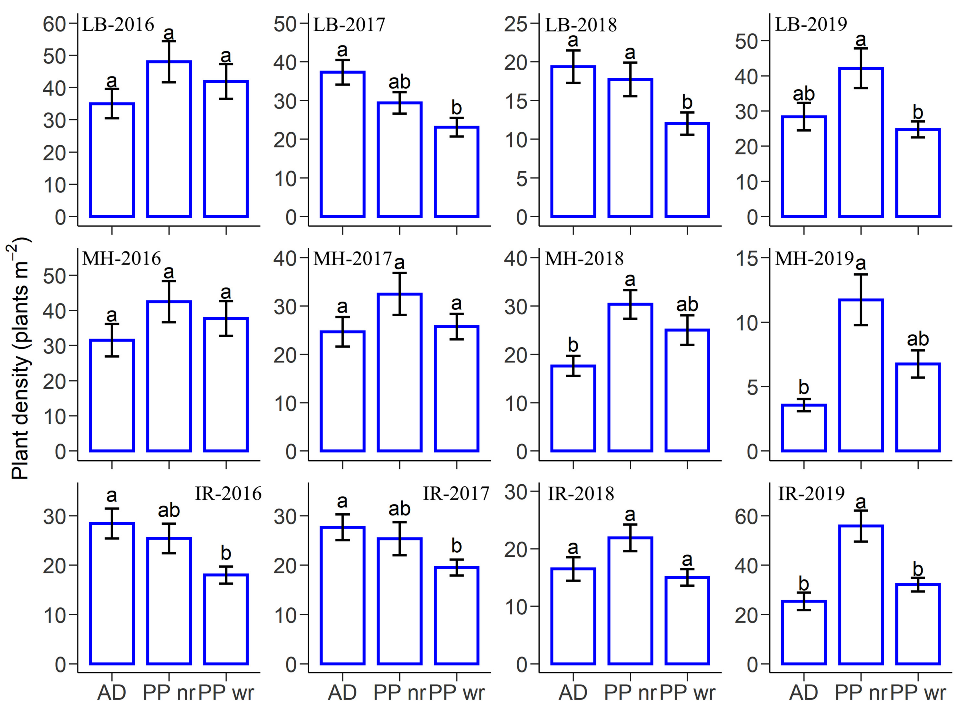
Table 2. The parameters *a*, *b*, and pseudo-R^2 estimate for the non-linear [$y = a(1\text{-}\exp(\text{-}bx))$] relationship between plant density (*y*) and seeding rate (*x*) for different planters for 12 site-years.

SY	Parameter *a* PP nr	Parameter *a* PP wr	Parameter *a* AD	Parameter *b* PP nr	Parameter *b* PP wr	Parameter *b* AD	Pseudo-R^2
LB-2016	175.3a (38.2)	140a (31.7)	134.3a (45.3)	0.005A (0.001)	0.005A (0.002)	0.004A (0.002)	0.93
LB-2117	51.7a (7.9)	43.7a (9.5)	50.7a (4.4)	0.014A (0.004)	0.012A (0.005)	0.025A (0.006)	0.68
LB-2018	48.4a (14.4)	22.1a (5.1)	32.3a (3.8)	0.007A (0.003)	0.014A (0.006)	0.017A (0.004)	0.73
LB-2019	122.3a (38.2)	30.7b (5)	80.7ab (31.3)	0.006A (0.003)	0.029A (0.014)	0.007A (0.004)	0.81
MH-2016	172.5a (55.6)	156.9a (60.8)	128.1a (56.5)	0.004A (0.002)	0.004A (0.002)	0.004A (0.002)	0.90
MH-2017	110.5a (42.1)	44.3a (7.8)	46.3a (11.1)	0.005A (0.003)	0.015A (0.005)	0.012A (0.005)	0.71
MH-2018	56.9a (10.3)	42.6ab (8.0)	23.9b (5.1)	0.012A (0.004)	0.015A (0.006)	0.023A (0.012)	0.59
MH-2019	63.8a (56.4)	8.8a (2.3)	4.5a (3.1)	0.003A (0.003)	0.025A (0.017)	0.021A (0.037)	0.70
IR-2016	59.5ab (20.8)	22.2b (4)	49.7a (7.9)	0.009A (0.005)	0.047A (0.033)	0.019A (0.007)	0.65
IR-2017	50.3a (12.7)	23.5b (3.7)	35.6a (4.3)	0.011A (0.005)	0.037A (0.020)	0.030A (0.011)	0.47
IR-2018	31.6a (4.1)	19.9a (3.4)	27.5a (7.9)	0.022A (0.007)	0.028A (0.013)	0.013A (0.007)	0.46
1 R-2019	123a (14.2)	45.3b (4.9)	92.5ab (51.1)	0.01B (0.002)	0.024A (0.007)	0.005A (0.003)	0.88

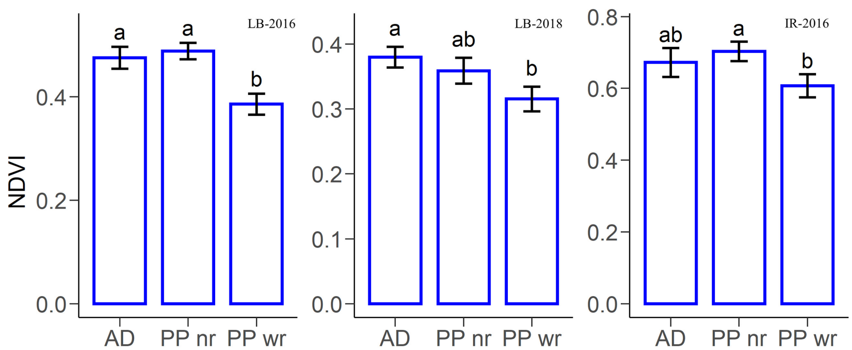
Note: SY, site-year; AD, air drill; PP nr, precision planter 30.5 cm spacing; PP wr, precision planter 50.8 cm spacing; IR, Lethbridge irrigated; LB, Lethbridge dryland; MH, Medicine Hat dryland. The standard errors of mean are given in parentheses. Different letters within each site-year indicate a statistically significant difference among planters at $p < 0.05$ for each parameter. The lowercase letters provide mean comparison for parameter *a*, and the uppercase letters provide mean comparison for parameter *b*.

Fig. 2. Plant density averaged among seeding rates (20, 40, 60, 80, and 160 seed m^{-2}) for different planters (AD, air drill; PP nr, precision planter 30.5 cm row spacing; PP wr, precision planter 50.8 cm row spacing) at 12 site-years (IR, Lethbridge irrigated; LB, Lethbridge dryland; MH, Medicine Hat dryland). Bars represent ±1 standard error of the mean. Different letters within each site-year indicate a statistically significant difference among planters at $p < 0.05$. [Colour online.]



significant at the remaining 9 site-years (Fig. 2). Similarly, the wide-row precision planted canola had lower plant density than the narrow-row precision planted canola at 3 site-years, while the differences between them were not statistically significant at the remaining 9 site-years (Fig. 2). These data indicate that the narrow-row precision planter may lead to better stand establishment in canola compared with the air drill and wide-row precision planter. Precision planters can place seeds at precise distances along a row and uniform seeding depths, thus reducing intra-row plant competition, ensuring proper seed to soil contact, and

Fig. 3. Normalized difference vegetation index (NDVI) averaged among seeding rates (20, 40, 60, 80, and 160 seed m^{-2}) for different planters (AD, air drill; PP nr, precision planter 30.5 cm row spacing; PP wr, precision planter 50.8 cm row spacing) at 3 site-years (IR, Lethbridge irrigated; LB, Lethbridge dryland; MH, Medicine Hat dryland). Only the site-years with statistically significant differences in NDVI for different planters are shown here. Different letters within each site-year indicate a statistically significant difference among planters at $p < 0.05$. Bars represent ±1 standard error of the mean. [Colour online.]



contributing to increased crop establishment (McDonald et al. 2019). Higher emergence and stand density in canola are recommended since they contribute to increased seed yield (Angadi et al. 2003) and facilitate competitive crop canopies to check weeds in early growth stages, thus, requiring fewer herbicide applications (Morrison et al. 1990).

In addition, the comparison of parameter *a* (from the regression function in eq. 1; representing maximum attainable, or asymptotic, plant density) among the seeders indicated a trend of numerically higher asymptotic plant density for the narrow-row precision planter compared with wide-row precision planter and air drill (Table 2). While parameter *a* was numerically higher for the narrow-row precision planter compared with other seeders at all site-years, the differences were statistically significant at only 5 site-years (4 site-years compared with wide-row planter and 1 site year compared with air drill). The inter-plant competition is expected to be less at low seeding rates but increase with higher seeding rates. Thus, at higher seeding rates, uniform seed placement and superior depth control provided by the narrow-row planter facilitates better stand establishment. The wide-row precision planter led to lower plant density than the narrow-row precision planter because of the larger inter-row width for wide-row planter; more seeds have to be placed in each row to obtain the same seed density as the narrow-row planter. Thus, a higher number of seeds are placed in each row, which increases the competition between plants and is detrimental to early-season canola performance.

Canopy closure

Canopy closure was estimated using the NDVI and FGCC measurements. NDVI was measured for a total of 6 site-years. Air drill and narrow-row precision planter did not show a statistically significant difference in the NDVI at any site-year (data not shown). However, the wide-row precision planter was observed to have lower NDVI than the narrow-row precision planter and the air drill at 2 and 3 site-years, respectively (Fig. 3). FGCC measurement was obtained for 7 site-years during the study period. Air drill and narrow-row precision planter did not show a statistically significant difference in FGCC at 5 out of 7 site-years. For the remaining 2 site-years, FGCC was significantly higher for the air drill for LB-2018 and narrow-row precision planter for IR-2019 (Fig. 4). Wide-row precision planter had lower FGCC than the narrow-row precision planter and the air drill at 1 and 3 site-years, respectively. These data indicate that canopy closure for the air drill and narrow-row precision planter were relatively similar, but the wider row spacings for wide-row precision planter may have impacted the canopy closure obtained by the crops.

Seed yield

Yield-density relationship

Seed yield of canola showed a statistically significant relationship with planting density at 7 out of 12 site-years (Fig. 5). Among these site-years, the relationship between seed yield and plant density was asymptotic for all types of seeders, thus indicating that the greatest yields were obtained at highest plant densities. The density-yield functions indicated a weak to moderate relationship with the pseudo-R^2 values ranging from 0.37 to 0.67 at these site-years (Table 3). The weak to moderate strength of density-yield relationships can be attributed to the plasticity of canola yield components across a range of plant densities (Angadi et al. 2003). Previous studies such as Clarke and Simpson (1978) and Sierts et al. (1987) found that canola can compensate for reduced plant densities by increasing other yield components such as number of pods per plant, and number of seeds per pod. Similarly, Kutcher et al. (2013) observed that plant densities were not reliable indicators of yield in canola.

Fig. 4. Fractional green canopy cover (FGCC) averaged among seeding rates (20, 40, 60, 80, and 160 seed m^{-2}) for different planters (AD, air drill; PP nr, precision planter 30.5 cm row spacing; PP wr, precision planter 50.8 cm row spacing) at 4 site-years (IR, Lethbridge irrigated; LB, Lethbridge dryland; MH, Medicine Hat dryland). Only the site-years with statistically significant differences in FGCC for different planters are shown here. Different letters within each site-year indicate a statistically significant difference among planters at $p < 0.05$. Bars represent ±1 standard error of the mean. [Colour online.]

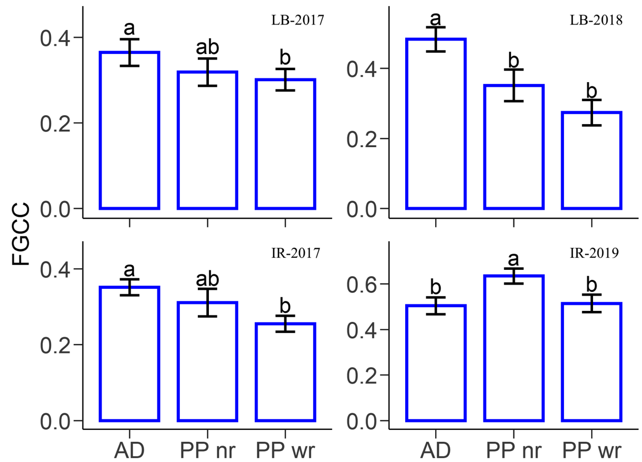


Fig. 5. Yield-density relationship for different planters (AD, air drill; PP nr, precision planter 30.5 cm row spacing; PP wr, precision planter 50.8 cm row spacing) at 12 site-years (IR, Lethbridge irrigated; LB, Lethbridge dryland; MH, Medicine Hat dryland). Symbols indicate average plant densities and lines represented fitted regression. Bars represent ±1 standard error of the mean. [Colour online.]

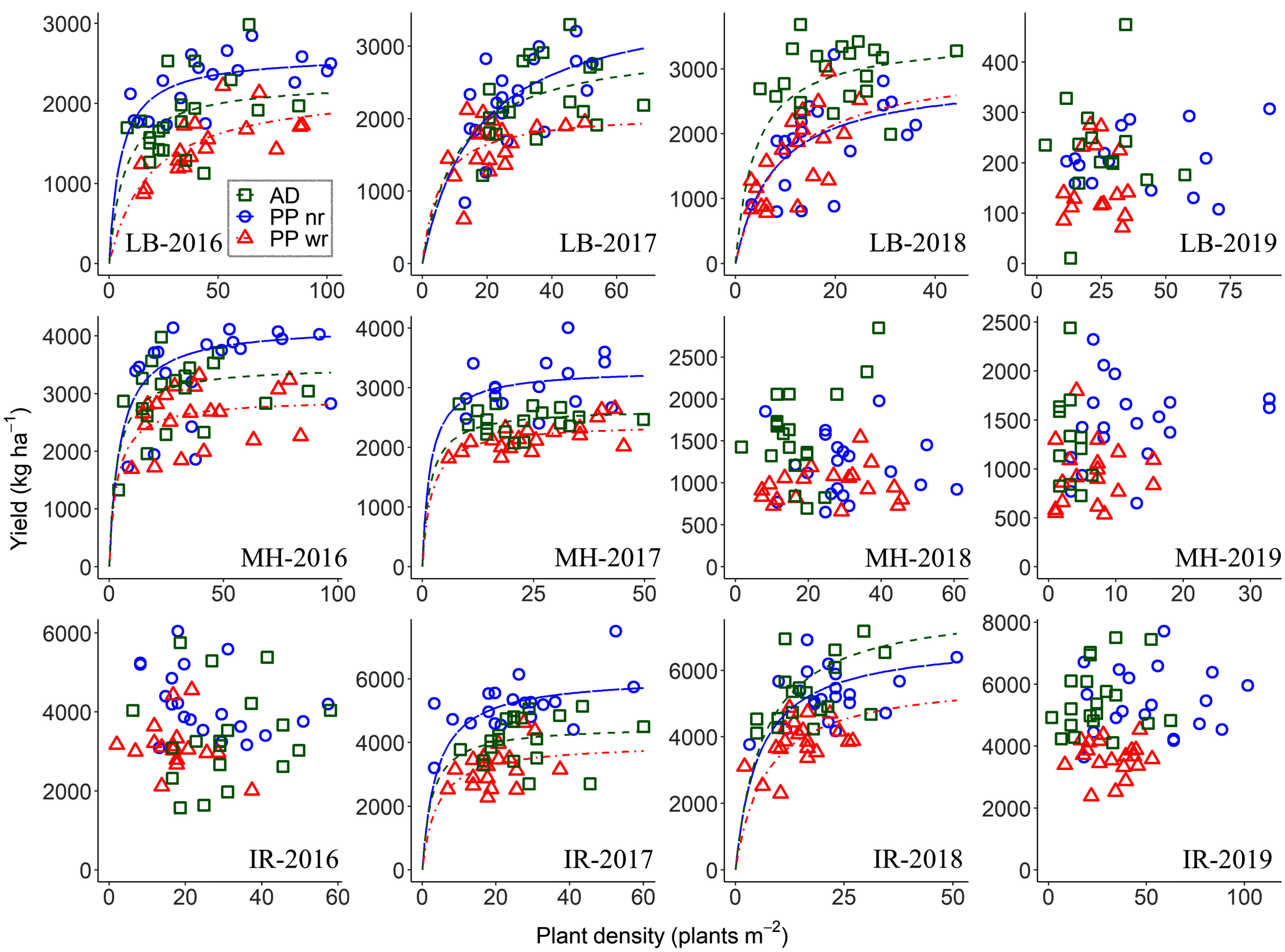


Table 3. The parameters *c*, w_m, and pseudo-R^2 estimate for the non-linear [$y = w_m x/(1+cx)$] relationship between seed yield (*y*) and plant density (*x*) for different planters for 7 site-years.

SY	Parameter *c*			Parameter w_m			Pseudo-R^2
	PP nr	PP wr	AD	PP nr	PP wr	AD	
LB-2016	0.19a (0.09)	0.05a (0.03)	0.14a (0.08)	504.7A (204.2)	120.2A (46.9)	321.8A (141.2)	0.57
LB-2117	0.06a (0.03)	0.19a (0.16)	0.09a (0.06)	219.4A (65.3)	387.9A (269.4)	277.3A (133)	0.49
LB-2018	0.13a (0.07)	0.11a (0.07)	0.25a (0.14)	375.5A (147.6)	342.5A (124.3)	873.3A (125)	0.64
MH-2016	0.21a (0.11)	0.29a (0.29)	0.30a (0.17)	891.5A (389.0)	855.4A (751.5)	1048.8A (536.2)	0.37
MH-2017	0.56a (0.45)	0.49a (0.41)	0.59a (0.25)	1854.6A (1382.1)	1170.6A (900.7)	1558.5A (603.7)	0.67
IR-2017	0.26a (0.20)	0.25a (0.22)	0.39a (0.44)	1569.9A (1606.6)	1000.8A (711.5)	1753.8A (1820.8)	0.61
IR-2018	0.18a (0.06)	0.14a (0.07)	0.15a (0.05)	1275.6A (330.6)	820.9A (261.4)	1236.4A (259.4)	0.55

Note: SY, site-year; AD, air drill; PP nr, precision planter 30.5 cm spacing; PP wr, precision planter 50.8 cm spacing; IR, Lethbridge irrigated; LB, Lethbridge dryland; MH, Medicine Hat dryland. The standard errors of mean are given in parentheses. Different letters within each site-year indicate a statistically significant difference among planters at $p < 0.05$ for each parameter. The lowercase letters provide mean comparison for parameter *c*, and the uppercase letters provide mean comparison for parameter w_m.

Table 4. Probability (*p*) values for the effect of seeder type on plant density, seed yield, fractional green canopy cover (FGCC), normalized difference vegetation index (NDVI) of canola for all site years.

	LB				MH				IR			
	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Plant density	0.11	0.005	0.01	0.03	0.08	0.34	0.02	0.04	0.02	0.04	0.11	0.03
Yield	<0.001	0.003	<0.001	0.012	<0.001	<0.001	0.015	0.004	0.002	<0.001	0.003	<0.001
FGCC	NA	0.05	<0.001	0.28	NA	0.66	NA	NA	NA	0.008	0.45	<0.001
NDVI	<0.001	NA	<0.001	NA	0.18	NA	0.86	NA	<0.001	NA	0.29	NA

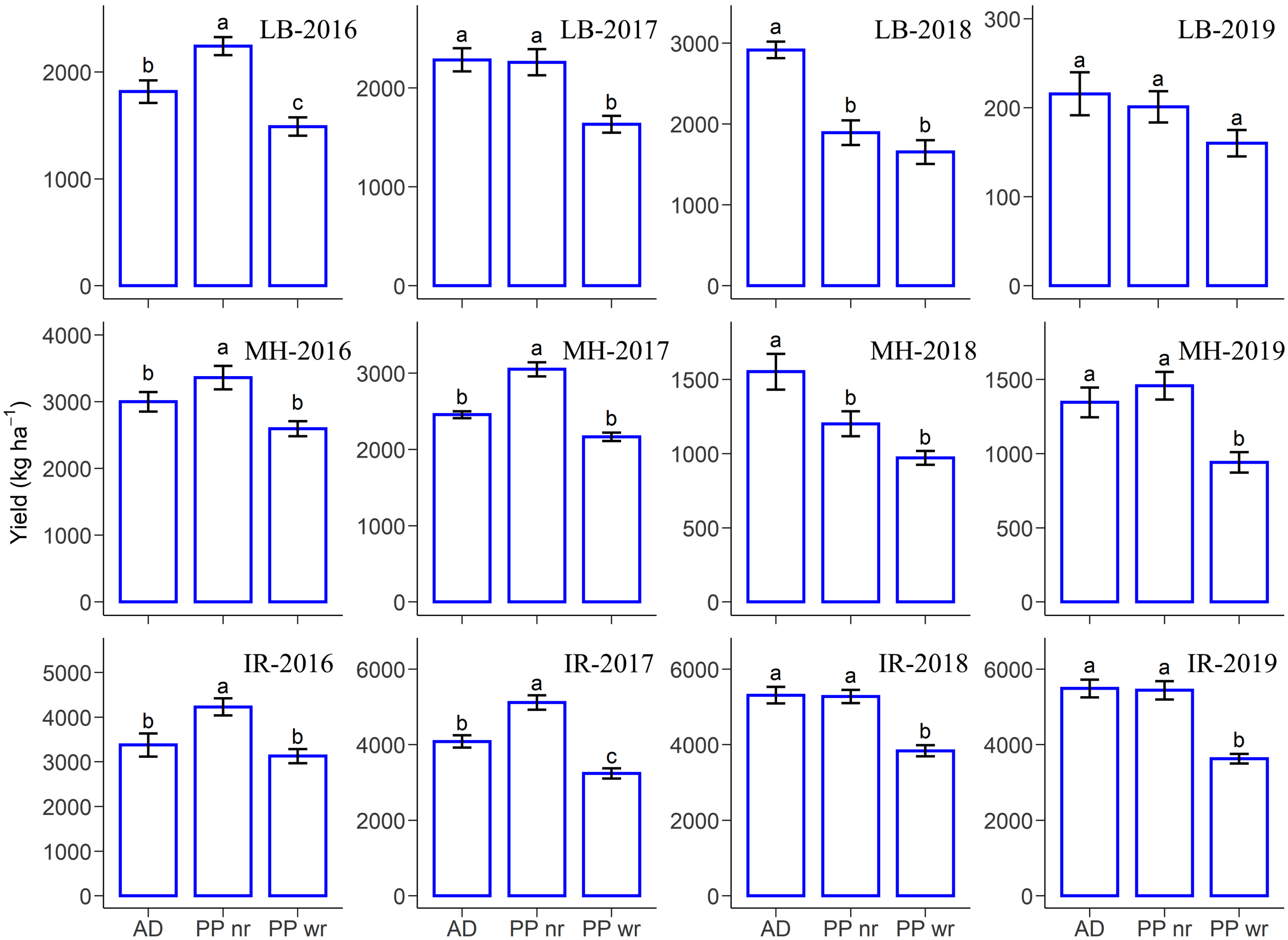
Note: IR, Lethbridge irrigated; LB, Lethbridge dryland; MH, Medicine Hat dryland. For plant density and seed yield, the *p* values were obtained using linear mixed model analysis. For NDVI and FGCC, the *p* values were obtained using generalized linear mixed model analysis with beta distribution.

Five out of 12 site-years did not show any relationship between yield and density (Fig. 5). Of these 5 site-years, 3 site-years (i.e., LB-2019, MH-2018, and MH-2019) had the lowest average seed yields (less than 1300 kg ha^{-1}) and 1 site-year (i.e., IR-2019) recorded highest average seed yield (4841 kg ha^{-1}) compared with other site-years. Thus, low-yield and high-yield environments, in general showed a lack of relationship between yield and density. At low-yield environments, other factors such as moisture or nutrient availability may be limiting canola yield thus masking the effect of plant density. Similarly, factors such as adequate irrigation and high fertility may have overcome the limitation of low plant density at high-yielding environments such as IR-2016 and IR-2019. Gan et al. (2016) also found the seed yield not to be correlated with plant density at the high-yield sites and attributed it to high nutrient availability and adequate precipitation at those sites. The comparison of parameters included in yield-density function (eq. 2) revealed a lack of statistically significant differences between the planters for any parameter at any site-year (Table 3). This observation indicates that the relationship between plant density and yield was not affected significantly by the type of seeder.

Effect of planters

Canola seed yield showed statistically significant differences between the narrow-row precision planter and air drill at 7 out of 12 site-years (Table 4; Fig. 6). Out of these 7 site-years, seed yield was higher for the narrow-row precision planter at 5 site-years and for the air-drill at 2 site-years. Upon closer examination, the trends in seed yield for air drill and narrow-row precision planter were observed to be related to environmental conditions, including precipitation and irrigation. At the irrigated site-years, seed yield for the narrow row precision planter was higher at 2 out of 4 site-years, with no statistically significant differences in yield between the narrow-row precision planter and air drill at the remaining 2 site-years (Fig. 6). Thus, the air drill did not lead to higher seed yield compared with narrow-row precision planter at any site-year under irrigated conditions. Averaged among irrigated site-years, the seed yield of narrow-row precision planted canola was 463 kg ha^{-1} (10%) higher than the air drill seeded canola. In comparison, the average seed yields for narrow-row precision planted canola (1960 kg ha^{-1}) and air drill seeded canola (1958 kg ha^{-1}) were similar among the dryland environments. Seed yield for narrow-row

Fig. 6. Seed yield averaged among seeding rates (20, 40, 60, 80, and 160 seed m^{-2}) for different planters (AD; air drill; PP nr, precision planter 30.5 cm row spacing; PP wr, precision planter 50.8 cm row spacing) at 12 site-years (IR, Lethbridge irrigated; LB, Lethbridge dryland; MH, Medicine Hat dryland). Bars represent ±1 standard error of the mean. Different letters within each site-year indicate a statistically significant difference among planters at $p < 0.05$. [Colour online]



precision planter was higher than air drill at 3 out of 8 dryland site-years, including LB-2016, MH-2016, and MH-2017 (Fig. 6). Of these site-years, LB-2016 and MH-2016 had received higher than average growing season precipitation, which was 15% and 69% higher than the long-term average precipitation at these sites, respectively (Table 1). Thus, narrow-row precision planters led to higher seed yield compared with the air drill under irrigated or high-precipitation environments. These conditions are generally favorable for crop growth, where uniform stand establishment enabled via precise seed placement by the narrow-row precision planters may be providing a competitive advantage by reducing inter-plant competition. Regular planting arrangement has been shown to reduce intra-row plant competition (Kemp et al. 1983), which can lead to increased seed yield in canola. Yang et al. (2014) found that canola yield can be increased by up to 32% with spatially uniform stands compared with non-uniform stands in a study carried out in western Canada.

In contrast, seed yield for air drill was higher compared with narrow-row precision planter at LB-2018 and MH-2018 site-years under dryland conditions (Fig. 6). These site-years had received considerably less growing season precipitation, which was 46% and 56% lower than the long-term average precipitation received at these sites, respectively (Table 1). While the reasons for this observation are not clear from this study, certain hypotheses can be drawn for further future investigations. Less precise spatial placement of seeds sown by air drill may be enabling higher coverage of the ground by air-drill seeded plants, thus allowing them to access inter-row soil moisture. Previous studies have suggested that certain crop configurations with non-regular plant spacing may enable soil moisture access to elongated roots during the crop's reproductive and grain-filling stages, thus increasing crop yield in water-limited environments (Longenecker et al. 1969; Loomis 1983). Alternatively, higher plant competition may reduce early-season vegetative growth and increase soil water availability during the grain filling stage, as reported for asymmetrical, double-row plant configuration (Blum and Naveh 1976) and clumped plant configuration (Bandaru et al. 2006) in sorghum. Canola seed yield trends under dryland conditions, as observed in this study, while not conclusive, warrant further investigation through future studies of the impact of spatial patterns of canola plant establishment on its water-use efficiency in water-limited environments.

Seed yield for the wide-row precision planter was less than the narrow-row planter at 9 out of 12 site-years, and the difference between them not statistically significant for the remaining 3 site-years (Table 4; Fig. 6). Lower seed yield for the wide row planter may be attributed to lower plant density and canopy covering. Poor stand establishment may affect seed yield, especially in the Canadian prairie region, as these regions have short crop growing seasons, thus providing limited time for canola to adapt and compensate for poor crop establishment (Mendham and Salisbury 1995; Angadi et al. 2003). The reduction in yield may be further exacerbated by high in-row plant density for wide-row planters, which leads to increased competition for resources among plants. Lower availability of resources is known to reduce the capacity of canola to compensate for low initial growth (Sultan 2000; Gan et al. 2012).

Conclusions

The results from this 4-yr study provide critical information regarding the adoption of precision planters in canola production. The adoption of wide (50.8 cm) row planters to seed canola may lead to a significant reduction in crop yield, and thus, the adoption of wide-row planters for canola seeding is not recommended. However, the seed yield for narrow-row precision planter was higher than the air drill at 5 site-years, particularly under irrigated or high precipitation conditions. The seed yield for air drill was higher than narrow-row precision planter at 2 site-years that received limited precipitation, while 5 site-years did not show a statistically significant difference between them. The yield-density relationship could be obtained at only 7 out of 12 site-years and showed a weak to moderate relationship. The parameters of yield-density relationship did not differ among different types of seeders.

Acknowledgements

Funding for this project provided by the Canola Agronomic Research Program (CARP) of Canola council of Canada (years 1 to 3) and Canadian Agricultural Partnership (CAP) (year 4) is gratefully acknowledged. The authors thank the associate editor and the reviewers for their valuable feedback that helped in improving the manuscript.

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