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Minimizing competition between glyphosate-resistant volunteer canola (*Brassica napus*) and glyphosate-resistant soybean: impact of soybean planting date and rate

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Abstract

In recent years, soybean acreage has increased significantly in western Canada. One of the challenges associated with growing soybean in western Canada is the control of volunteer glyphosate-resistant (GR) canola, because most soybean cultivars are also glyphosate resistant. The objective of this research was to determine the impact of soybean seeding rate and planting date on competition with volunteer canola. We also attempted to determine how high seeding rate could be raised while still being economically feasible for producers. Soybean was seeded at five different seeding rates (targeted 10, 20, 40, 80, and 160 plants m^{-2}) and three planting dates (targeted mid-May, late May, and early June) at four sites across western Canada in 2014 and 2015. Soybean yield consistently increased with higher seeding rates, whereas volunteer canola biomass decreased. Planting date generally produced variable results across site-years. An economic analysis determined that the optimal rate was 40 to 60 plants m^{-2}, depending on market price, and the optimal planting date range was from May 20 to June 1.

Introduction

Cultural weed-management techniques can have a substantial impact on crop competitiveness and crop productivity. One important method of cultural weed management is optimal seeding rate. Soybean is generally a poor competitor with weeds but seeding rate can improve crop competitiveness due to both increased plant stand and more rapid canopy development (Blackshaw et al. 2002; Guillermo et al. 2009).

The recommended seeding rate for soybean in Saskatchewan is approximately 493,000 to 630,000 seeds ha^{-1} (44 to 57 plants m^{-2}) (Saskatchewan Pulse Growers 2017). Increasing soybean seeding rate has a significant effect on reducing weed populations by improving crop competitiveness (Guillermo et al. 2009; McWhorter and Barrentine 1975; Nice et al. 2001; Norsworthy and Oliver 2001). Several studies have also reported a yield increase in soybean with higher seeding rates, largely due to improved weed control, light interception, and rapid canopy development (Cox and Cherney 2011; Elmore 1998; Place et al. 2009). However, high seeding rates also can pose agronomic challenges, because increased plant density increases intraspecific competition for resources, and increases potential for disease (Krupinsky et al. 2002; Pennypacker and Risius 1999)

Planting date can also have an impact on crop yield and competitiveness with weeds, although studies results have been inconsistent with regard to competitiveness. Soybean has a higher competitive ability with weeds when planted early (Klingman and Oliver 1994), but others have reported soybean to be more competitive with weeds with delayed planting (Coulter and Nafziger 2007; Liebman et al. 2001; Rushing and Oliver 1998). The effects of planting date on soybean yield are also inconsistent. Delaying planting significantly reduces soybean yield (De Bruin and Pedersen 2008; Hardman and Gunsolus 1994; Robinson et al. 2009), and other studies have reported yield increases with late soybean planting (Buhler and Gunsolus 1996; Rushing and Oliver 1998). These differences in crop competitiveness and soybean yield response to planting date are due to many factors, such as the species and emergence timing of weeds, time of weed removal, and environmental conditions. Nevertheless, integrating various

Table 1. Soil classification and descriptions for each site-year.

Site-year[a]	Soil type	Soil descriptions				
		pH	Organic matter	Sand	Silt	Clay
			%			
Saskatoon[a] 2014	Dark brown chernozem	7.9	2.4	19	36	45
Scott[a] 2014	Dark brown chernozem	5.8	3.1	29	53	18
Indian Head[a] 2014	Black chernozem	7.4	3.4	13	21	66
Carman[b] 2014	Black chernozem	5.5	6.0	54	15	31
Saskatoon 2015	Dark brown chernozem	7.9	2.4	19	36	45
Scott 2015	Dark brown chernozem	5.6	5.3	31	59	11
Indian Head 2015	Black chernozem	7.4	3.4	13	21	66
Carman 2015	Black chernozem	5.5	6.0	54	15	31

[a]Saskatchewan, Canada.
[b]Manitoba, Canada.

Table 2. Planting dates and growing degree days for planting date treatments at Saskatoon, Scott, and Indian Head, Saskatchewan, Canada; and Carman, Manitoba, Canada, in 2014 and 2015.

Site-year	Planting date treatment	Planting date	GDD[a]
Saskatoon 2014	Early	May 22	15.7
	Intermediate	June 1	72.7
	Late	June 9	85.5
Carman 2014	Early	May 23	5.6
	Intermediate	May 29	59.6
	Late	June 11	160.2
Saskatoon 2015	Early	May 13	21.2
	Intermediate	May 26	75.6
	Late	June 5	88.9
Scott 2015	Early	May 15	10.7
	Intermediate	May 26	37.1
	Late	June 5	71.7
Indian Head 2015	Early	May 19	23.7
	Intermediate	May 28	74.8
	Late	June 10	134.4
Carman 2015	Early	May 26	65.6
	Intermediate	June 11	156.5
	Late	June 23	235.6

[a]GDD, growing degree day (base temperature:10 C).

seeding rates and planting dates can maximize productivity and significantly improve soybean competitiveness (De Bruin and Pedersen 2008; Lee et al. 2008).

A major weed of soybean in western Canada is volunteer canola, which is an early emerging species (Lawson et al. 2006). Dicot weeds such as volunteer canola tend to cause greater yield loss in soybean compared with yield loss associated with monocot weed competition (Nave and Wax 1971). Volunteer glyphosate-resistant (GR) canola poses a challenge to producers growing GR soybean, because of limited herbicide options for control; thus, integrated methods are needed. However, integrating methods may not always be successful. For example, mechanical weed control combined with banded herbicide application provided no difference in weed density or soybean crop yield compared with conventional herbicide control (Swanton et al. 2002).

There is potential for integrated weed management in soybean crops to better manage volunteer GR canola, for which herbicide options are limited (Geddes and Gulden 2018). Geddes and Gulden (2018) found a positive response of soybean to integrated weed management practices, although they did not look at the impact of planting rate and date combined. It is not known whether these two cultural control methods can affect competition between volunteer GR canola and GR soybean. The present study was conducted to evaluate the impact of GR soybean planting date and rate on GR volunteer canola.

Materials and Methods

Site Description

Field experiments were conducted in 2014 and 2015 at the Kernen Crop Research Farm (52.25°N, 106.88°W) in Saskatoon, Saskatchewan, Canada; at the Western Applied Research Corporation Research Field (52.35°N, 108.82°W) in Scott, Saskatchewan; at the Indian Head Agricultural Research Foundation Research Farm (50.52°N, 103.65°W) at Indian Head, Saskatchewan; and at the University of Manitoba Research Farm (49.50°N, 98.00°W) in Carman, Manitoba, Canada. Saskatoon and Scott are located on a dark brown soil; Indian Head and Carman are located on black soils. Soil descriptions are presented in Table 1.

Experimental Procedure

The experimental design was a split plot with 15 treatments and four replications. Main plots were planting date (early, intermediate, and late) and subplots were seeding rates (targeted 10, 20, 40, 80, and 160 plants m^{-2} corresponding to 101,880; 203,775; 407,550; 815,100; and 1,630,200 seeds ha^{-1}). Plots were seeded in late May, early June, and mid-June in 2014 and in mid-May, late-May, and early June in 2015. Planting dates in 2014 were later than targeted, because of environmental conditions, which delayed seeding. Actual planting dates are listed in Table 2. Main plots at Saskatoon and Scott measured 10 m wide by 6 m long, main plots at Indian Head were 13.5 m wide by 10.7 m long, and plots at Carman were 12.5 m wide by 8 m long. Each subplot at Saskatoon and Scott measured 2 m wide by 6 m long, subplots at Indian Head were 2.7 m wide by 10.7 m long, and subplots at Carman were 2.5 m wide by 8 m long. Border plots were seeded at all sites to minimize border effects. All plots received a 450 g ae ha^{-1} application of glyphosate immediately after seeding to control emerged weeds.

The soybean cultivar used was P001T34R (DuPont Pioneer, Mississauga, Ontario, Canada). It was pretreated with a copack of thiamethoxam plus fludioxonil plus metalaxyl (Cruiser Maxx® Beans; Syngenta Canada, Guelph, Ontario, Canada) and sedaxane (Vibrance® 500 FS) applied at rates of 195 mL plus 10 mL 100 kg^{-1} of seed, respectively (i.e., Cruiser Maxx Vibrance Beans; Syngenta Canada, Guelph, Ontario, Canada). Soybean seed was preinoculated with *Bradyrhizobium japonicum* (Optimize®; Syngenta Canada, Guelph, Ontario, Canada) inoculant, and granular *Penicillium bilaii* (TagTeam®; Syngenta Canada, Guelph, Ontario, Canada) was applied at a rate of 3 kg ha^{-1} at the time of seeding. Soybean was seeded 3-cm deep with a cone seeder equipped with disc openers spaced at 40 cm at the Saskatoon location; hoe openers were used at the other locations. A soybean survival rate of 75% (OMA 2009) was used to determine seeding rates; therefore, actual seeding rates were 16, 27, 53, 106, and 215 seeds m^{-2}. Actual planting dates and cumulative growing degree-dates (base temperature 10 C) (Zhang et al. 2001) for each planting date are presented in Table 2.

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Table 3. Predicted soybean yields at various seeding rates from 10 to 160 plants m^{-2}.

Seeding rate	Soybean yield
plants m^{-2}	kg ha^{-1}
10	341
20	473
40	713
50	822
60	924
70	1,019
80	1,106
90	1,186
100	1,259
160	1,542

Volunteer canola was seeded at a rate of 80 seeds m^{-2} using a 50% survival rate (Canola Council of Canada 2015) to establish a target plant density of 40 plants m^{-2}. Canola ('Dekalb 72-65 RR'; Bayer Crop Science Canada, Calgary, Canada) was cross-seeded with a plot drill across the entire trial immediately following each soybean planting date.

Volunteer canola biomass sampling was conducted at the canola podding stage. Aboveground shoot-biomass samples were collected in two 0.5-m^2 quadrates per plot from the front and back of each plot. Samples were cut just above the ground surface, with the canola separated and placed in brown paper bags. All material was oven dried at 80 C for 72 h and weighed. Soybean crop height was measured just prior to biomass sampling by measuring the distance from the ground to the top of the plant on five to 10 plants per plot. Plots were harvested with a small plot combine and samples were dried, cleaned, and weighed to determine final seed yield. Soybean is considered dry at 14% moisture content; therefore, yields were adjusted to 14% moisture content. Volunteer canola seeds that were cleaned out of soybean samples were also weighed to determine volunteer canola seed contamination.

Statistical Analysis

Residuals were initially tested to ensure that the assumptions of ANOVA were met. The Shapiro-Wilk test in PROC UNIVARIATE (SAS Institute, Cary, NC) was used to assess normality and the Levene test was used to assess homogeneity of variance. Where there was heterogeneity between sites, the REPEATED statement was used to account for this heterogeneity. If model fit was improved by modeling heterogeneity, then this model was used. Where model fit was not improved, the original PROC MIXED model was used.

Data were analyzed with the PROC MIXED procedure in SAS, version 9.3. Rate, date, and rate*date treatments were considered fixed effects in the model, whereas random effects consisted of site-year, block, and site-year interactions with fixed effects. To assess the significance of random effects and their interactions with fixed effects, covariance parameters were examined using the COVTEST option of PROC MIXED in SAS, version 9.3, to determine if the site-years could be combined and if conclusions could be drawn from a broader (population-based) inference space (SAS Institute 2014).

Orthogonal polynomial contrasts were calculated to determine whether variables had a linear or quadratic response to seeding rate. Analysis of covariance was used to calculate linear or quadratic regression coefficients for seeding-rate responses (Yang and Juskiw 2011). Nonlinear curves were fit using SigmaPlot 12® (Systat Software, Inc., San Jose, CA) Contrasts were used to determine if regression coefficients were significantly different between sites. Sites with similar regression coefficients were combined for analysis.

Economic Analysis

An economic analysis was conducted wherein the soybean market price was CAD\$0.44 kg^{-1} (CAD\$11.85 bushel^{-1}), which is an average price based on the market price projection for 2016 of CAD \$0.39 kg^{-1} (Saskatchewan Crop Insurance Corporation 2016), current market price of CAD \$0.42 (Rayglen Commodities 2016) and average market price of CAD \$0.49 from 2013, 2014, and 2015 (Agriculture and Agri-Food Canada 2015). Based on the recommended seeding rate of 40 plants m^{-2}, the average soybean seed cost is CAD \$233.17 ha^{-1} for seed and seed treatment (Government of Manitoba 2016). Gross income was calculated by multiplying soybean seed yield by market price. A contribution margin was calculated by subtracting the seed cost from the gross income.

Differences in soybean yield and volunteer canola-shoot biomass were determined by comparing each seeding rate with the standard rate of 40 plants m^{-2}.

Soybean seed yield and dockage predictions were computed for all seeding rates using the quadratic equation, $y = ax^2 + bx + c$, where a is the quadratic coefficient, b is the linear coefficient, c is the y intercept, and x is the seeding rate. Prediction values used are from combined analysis of each variable. Coefficient values for parameters a, b, and c to predict seed yield were as follows: $a = -0.034$; $b = 13.277$; and $c = 189.81$. Coefficient values for parameters a, b, and c to predict dockage were as follows: $a = 0.00213$; $b = -0.6335$; and $c = 73.67$.

Volunteer canola-shoot biomass predictions for all seeding rates were calculated using the linear response formula $y = ax^2 + b$, where a is the linear coefficient and b is the y intercept. Coefficient values for parameters a and b to predict canola shoot biomass are as follows: $a = -15.95$ and $b = 3{,}134.18$. Predicted yields for seeding rates used in the experiment, as well as seeding rates that were not used in the experiment, are shown in Table 3.

Results and Discussion

Soybean

The main effects of planting date and site were not significant when site-years were combined, but there was a site-year*date interaction for soybean plant height (Tables 4 and 5). Overall, soybean plant height exhibited a positive linear relationship with increasing seeding rate ($P < 0.0001$) (Table 4; Figure 1). For example, soybean plant height increased by 9.25% as seeding rate was increased from 10 plants m^{-2} to 160 plants m^{-2}. When plant height data were combined across site-years, plant height tended to be greater at intermediate and late planting dates (56 and 56 cm, respectively) when compared with the early planting dates (48 cm), although the difference was not significant ($P = 0.09$). The planting-date effect was statistically significant at Indian Head in 2015 and at Saskatoon in 2014 and 2015, but not for the remaining four site-years, which likely accounted for the overall site-year*date interaction. At the three sites where planting date was significant, the early planting date was shorter than the intermediate and late planting date (Table 4), which is consistent with the overall trend from the combined analysis.

Table 4. ANOVA results for the fixed effects (rate, date, and rate by date interaction) and random effects (site-year and site-year by treatment interactions) on soybean and canola variables.

	P value[a]					
	Soybean				Canola	
Source	Height	Biomass	Yield	TSW[b]	Biomass	SC[b]
Rate	<.0001	<.0001	<.0001	0.09	<.0001	0.0012
Date	0.0909	0.6321	0.9519	0.1757	0.5445	0.3341
Date*rate	0.1328	0.6499	0.9835	0.9185	0.852	0.7346
Site-year[c]	0.0795	0.1141	0.4114	0.0581	0.0733	0.1849
Site-year*rate	0.1723	0.0105	0.009	0.0895	0.023	0.0138
Site-year*date	0.014	0.016	0.0156	0.0411	0.0251	0.0694
Site-year*date*rate	0.2948	0.0071	0.0023	0.0271	0.2186	0.6752
Rate, linear	<.0001	<.0001	<.0001	0.0067	<.0001	<.0001
Rate, quadratic	0.2418	0.0211	0.0324	0.6365	0.2625	0.3201

[a]P values for random effects (site-year and site-year by treatment interactions) were assessed using the Wald Z test (COVTEST in SAS).
[b]Abbreviations: SC, seed contamination; TSW, thousand seed weight.

Table 5. Mean soybean plant height at three planting dates at two sites in Saskatchewan, Canada, where height had a site-year*date interaction.

Planting date[a]	Indian Head, 2015[b]	Saskatoon, 2014[b]	Saskatoon, 2015[b]
		cm	
Early	38.9 C	68.4 B	33.8 C
Intermediate	52.9 B	79.5 A	47.8 B
Late	61.9 A	64.1 B	57.6 A
$LSD_{0.05}$	5.6	5.5	4.8

[a]Abbreviation: $LSD_{0.05}$, least significant difference at the α level of 0.05.
[b]Means followed by different letters are significantly different within site-years at given LSD values.

Soybean seed yield increased consistently across site-years with regard to seeding-rate effects ($P < 0.0001$), but due to significant differences between regression coefficients and site-year*date*rate interactions, data were not combined across all site-years (Table 4). When site-years were analyzed separately, five of the seven site-years had a date*rate interaction, and the remaining two (Carman and Scott in 2015) had a seeding-rate effect only. Of the five site-years that had a date*rate interaction, the early planting date had the highest soybean yield at Indian Head in 2014 and Saskatoon in 2014 (Figure 2), whereas the late planting date yield was highest at Carman in 2014, Indian Head in 2015, and Saskatoon in 2015 (Figure 2). The date*rate interaction at these five site-years may have been due to a difference in the magnitude of the response to seeding rate at different planting dates. For example, at Indian Head in 2014, a seeding rate increase from 40 plants m^{-2} to 80 plants m^{-2} produced a soybean seed yield increase of 43% at the intermediate planting date and 82% at the early planting date (Figure 2). Similarly, soybean seed yield at Carman in 2014 increased by 52%, 69%, and 39% at the early, intermediate, and late planting dates, respectively, when the seeding rate was increased from 40 plants m^{-2} to 80 plants m^{-2}. Conversely, at Carman in 2014, seed yield increased by 55%, 25%, and 21% at the early, intermediate, and late planting dates when seeding rate was increased from 80 plants m^{-2} to 160 plants m^{-2} (Figure 2).

The late and intermediate planting dates had highest soybean yields at Indian Head in 2015, with the early planting date yielding significantly less (Figure 2). The magnitude of the seed-yield increase at higher seeding rates also varied with planting date. For example, increasing seeding rate from 20 plants m^{-2} to 40 plants m^{-2} increased soybean seed yield by 30%, 60%, and 57% at the early, intermediate, and late planting dates, respectively. However, when seeding rates were increased from 40 plants m^{-2} to 80 plants m^{-2} and 80 plants m^{-2} to 160 plants m^{-2}, the magnitude of seed-yield increase was highest at the early date in both cases (Figure 2). Results at Saskatoon in 2015 were similar, with the late planting date having the highest soybean yield and the early planting date having the lowest yield. The magnitude of the yield increase again varied with planting date at these sites.

Although planting-date treatments tended to show inconsistent effects that depended on conditions at each site-year, soybean seed yields tended to be greatest when planting occurred after May 20 and before June 11, indicating an optimal planting date range for soybean in western Canada. However, planting around June 11 is likely to be too late for the short growing season of western Canada, and soybean planted this late is unlikely to mature before the first fall frost. The long-term average date for the first frost in Saskatchewan is between September 9 and 15, and the first frost generally occurs from September 11 to 16 at Carman (Saskatchewan Crop Insurance Corporation 2017; Manitoba Agriculture, 2017). Volunteer canola would also be well established by June 11, which may present a large disadvantage to soybean if the volunteer canola is not well managed before planting. Therefore, we recommend an optimal planting date range from May 20 to June 1 in western Canada.

Soybean seed yield at the Carman and Scott locations in 2015 was combined across planting dates because date had no effect at these site-years and there was no rate*date interaction (Table 4). At both site-years, soybean seed yield increased consistently with increasing seeding rates (Figure 2). At Carman in 2015, seed yield had a linear relationship with seeding rate, and the overall range of yield was much lower compared with the Scott site. Yield ranged from 670 to 1,040 kg ha^{-1} as density increased from 10 plants m^{-2} to 160 plants m^{-2}, whereas seed yield ranged from 190 to 1,420 kg ha^{-1} at Scott (Figure 2).

Soybean seed yield consistently increased with increasing seeding rates in this study, but the incremental response tended to decrease with increasing seeding rates. This is likely due to the law of constant final yield, where total standing plant biomass initially increases in proportion to density, levels off, and then remains constant as density increases more (Weiner and Freckleton 2010). However, in most cases, maximum yield was not achieved at the densities tested in this experiment, and we did not achieve constant final yield. Plant densities required to

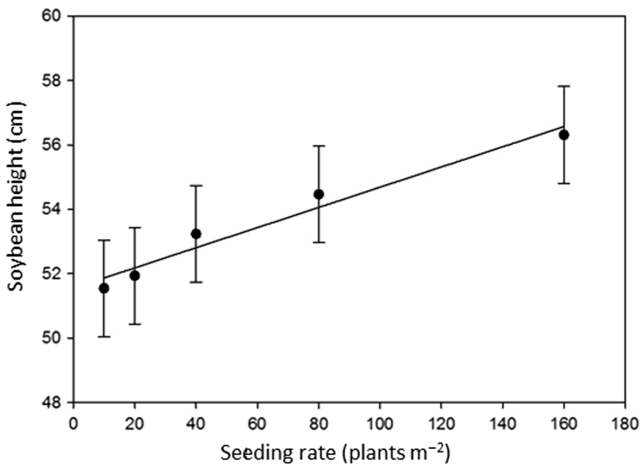

Figure 1. Soybean plant height response to seeding rates of 10, 20, 40, 80 and 160 plants m^{-2}. Data points represent the means of all site-years at each seeding rate. Bars indicate ±1 standard error of the mean. The linear equation is $y = 0.0313x + 51.55$. $R^2 = 0.9622$.

achieve maximum yield, calculated by differentiating the quadratic formula, ranged from 142 to 250 plants m^{-2}. Several studies have also reported that increasing soybean seeding rate increased yield (Cox and Cherney 2011; Elmore 1998; Place et al. 2009). Studies have also found that increasing seeding rate in other pulse crops, such as field pea (*Pisum sativum* L.) and lentil (*Lens culinaris* Medik.), results in higher yield and lower weed biomass in organic production systems (Baird et al. 2009a, 2009b).

Volunteer Canola

Seeding rate had a significant effect on volunteer canola-shoot biomass ($P < 0.0001$) and there was also a significant site-year*date interaction for canola biomass (Table 4). However, there was no planting-date effect when site-years were combined. It is likely that there was a site-year*date interaction because two of the seven site-years (Indian Head in 2014 and Saskatoon in 2014) exhibited a planting-date effect, whereas the remaining five had no statistically significant date effect (Table 4). However, trends were consistent across all site-years and so site-years and planting dates were combined.

A significant site-year*rate interaction also existed for volunteer canola-shoot biomass and seed contamination (Table 4). At site-years when canola biomass was less than 1,500 kg ha^{-1} (Carman and Indian Head in 2014, and Carman in 2015), increasing seeding rate had a smaller effect on canola-shoot biomass (Figure 3). This led to a site-year*rate interaction, because the response to seeding rate differed within site-years as a function of the amount of volunteer canola present at each site. In contrast, the remaining four site-years with volunteer canola biomass greater than 1,500 kg ha^{-1} had much steeper declines in volunteer canola-shoot biomass as seeding rates increased (Figure 3).

A consistent trend was observed in all site-years wherein volunteer canola-shoot biomass ($P < 0.0001$) and seed contamination ($P = 0.0012$) tended to decrease linearly with increasing seeding rate (Table 4; Figures 3 and 4). Volunteer canola biomass and seed contamination were highest at lower seeding rates due to poor crop competition. For example, when seeding rate was increased from 40 plants m^{-2} to 80 plants m^{-2}, the decrease in volunteer canola biomass ranged from 17% to 45% across site-years, with the exception of the Scott location in 2015, which increased only 6% (Figure 2). Similarly, volunteer canola seed contamination declined between 9% and 34% across all site-years when seeding rate was increased from 40 plants m^{-2} to 80 plants m^{-2} (Figure 4). When seeding rate was increased from 80 plants m^{-2} to 160 plants m^{-2}, the decrease in volunteer canola biomass ranged from 6% to 62% (Figure 3), whereas the decrease in canola seed contamination ranged from 21% to 56% across all site-years (Figure 4).

Seeding rate effects observed in this study generally were consistent across both the soybean crop and volunteer canola. Increasing the seeding rate resulted in greater soybean height and seed yield, and also positively influenced soybean's competitive ability against volunteer canola. Lower weed densities and biomass have been reported in several studies when soybean was seeded at high densities (Guillermo et al. 2009; McWhorter and Barrentine 1975; Nice et al. 2001; Norsworthy and Oliver 2001). Crops seeded at a higher population density tend to have a competitive advantage over weeds, due to rapid canopy development and, therefore, improved competitiveness, as well as increased plant stand (Guillermo et al. 2009; Place et al. 2009).

Economic Analysis

Maximum soybean yield was not reached at any seeding rate in most site-years; therefore, an economic analysis was conducted to determine the optimal seeding rate for growers and the economic benefit of different seeding rates. The highest contribution margin (i.e., net income) was observed at a seeding rate of 10 plants m^{-2} at \$90.37 ha^{-1}, but it became negative at seeding rates greater than 80 plants m^{-2}, because of high seed costs (Table 6). Net income consistently decreased with increasing seeding rates, because yield increases were not great enough to offset the increased seed cost. As seeding rate increased, the decline in contribution margin became larger. For example, the difference in contribution margin between 10 and 20 plants m^{-2} was only −\$1.22, whereas the difference between 40 and 50 plants m^{-2} was −\$10.75.

Although maximum soybean yield was not reached at most of the site-years in this study, it is very likely that seeding rates higher than those included in this study will not be economically feasible for growers. Based on the economic analysis, the grower's contribution margin will be negative when seeding rates exceed 80 plants m^{-2}, due to high seed costs (Table 6). Surprisingly, the highest net income was reached at 10 plants m^{-2}, which is one-fourth of the current recommended seeding rate. However, this seeding rate produced very high volunteer canola-shoot biomass and contamination. If volunteer canola is not well controlled at such a low seeding density, it will set seed and replenish the seed bank for the following years—volunteer canola can produce up to 3,600 seeds m^{-2} (Gulden et al. 2003) and can persist in soil for several years. This adds an additional cost, because the volunteer canola will require control in the following years and continue to compete with sequential crops for several years.

Given the aforementioned information, it appears that during years with low or average market prices for soybean, 40 plants m^{-2} is likely the best option for growers, because seeding rates below 40 plants m^{-2} have very high levels of volunteer canola contamination, but the contribution margin continues to decrease at seeding rates higher than 40 plants m^{-2}. However, when market prices are high, growers will see a benefit to increasing the seeding rate to 50 to 60 plants m^{-2}, because this will potentially increase soybean yield by 15% to 30% and offset seed costs while minimizing volunteer canola competition. Seeding rates higher than 70 plants m^{-2}

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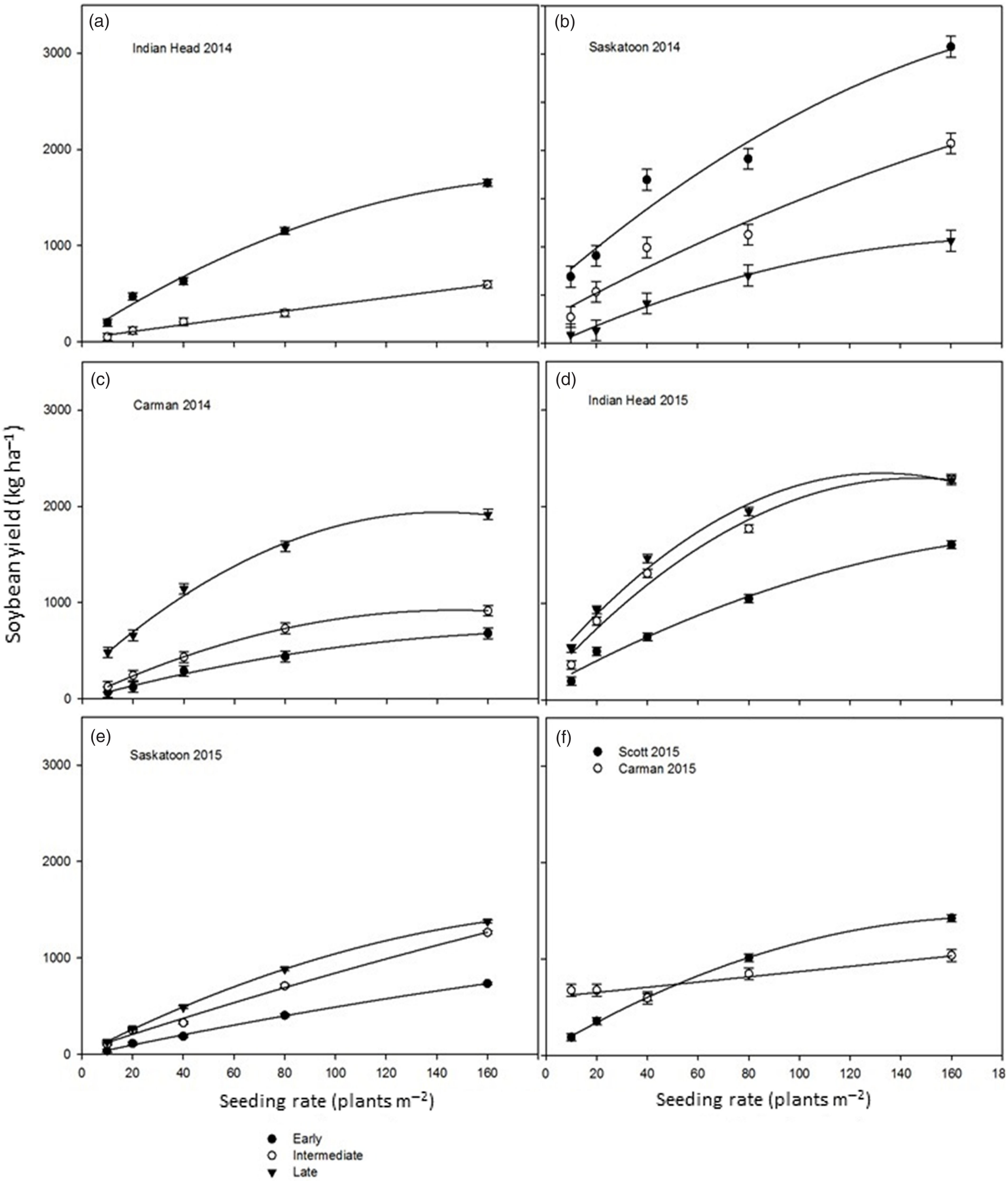

Figure 2. Effect of seeding rate and planting date on soybean yield at (a–e) site-years where there were site-year*date*rate interactions; and (f) Carman in 2015 and Scott in 2015, where there were no site*date*rate interactions. Bars indicate ±1 standard error of the mean. Line equations for planting dates: (a) Early: $y = -0.0434x^2 + 16.794x + 76.618$. $R^2 = 0.9928$. Intermediate: $y = -0.001x^2 + 3.6416x + 35.209$. $R^2 = 0.9901$. (b) Early: $y = -0.0461x^2 + 23.054x + 541.87$. $R^2 = 0.9616$. Intermediate: $y = -0.0188x^2 + 14.358x + 237.1$. $R^2 = 0.9605$. Late: $y = -0.0322x^2 + 12.107x - 52.423$. $R^2 = 0.9944$. (c) Early: $y = -0.0182x^2 + 7.1369x + 0.8078$. $R^2 = 0.994$. Intermediate: $y = -0.0422x^2 + 12.421x + 6.5059$. $R^2 = 0.9999$. Late: $y = -0.0839x^2 + 23.785x + 253.42$. $R^2 = 0.9947$. (d) Early: $y = -0.032x^2 + 14.315x + 131.45$. $R^2 = 0.9864$. Intermediate: $y = -0.098x^2 + 28.647x + 203.9$. $R^2 = 0.9816$. Late: $y = -0.1155x^2 + 30.608x + 320.99$. $R^2 = 0.9872$. (e) Early: $y = -0.006x^2 + 5.6412x - 14.268$. $R^2 = 0.9984$. Intermediate: $y = -0.0064x^2 + 8.7189x + 34.508$. $R^2 = 0.9945$. Late: $y = -0.0303x^2 + 13.441x + 1.7394$. $R^2 = 0.9998$. (f) Scott 2015: $y = -0.0438x^2 + 15.612x + 45.428$. $R^2 = 0.9997$. Carman 2015: $y = 2.7054x + 596.86$. $R^2 = 0.8698$.

are generally not economic for growers because the yield benefits are not great enough to offset the high seed costs.

Taken together, our results demonstrate that cultural weed control methods, such as altering soybean seeding rate and planting date, can substantially affect soybean yield and reduce competition from volunteer canola. However, the effects of planting date on soybean development were inconsistent and differed among site-years. The early planting date had the greatest soybean

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Table 6. Soybean and volunteer canola production and economic factors for all seeding rates.

Seeding rate	Seed cost	Market price	Soybean yield[a]	Canola biomass[b]	Soybean yield difference[c]	Canola biomass difference[c]	Dockage[a]	Gross income[d]	Contribution margin[e]
plants m^{-2}	\$ ha^{-1}	\$ kg^{-1}	kg ha^{-1}		%			\$ ha^{-1}	
10	58.29	0.44	341	3,182	−52.2	19.18	72.36	148.66	90.37
20	116.58	0.44	473	3,012	−33.66	12.81	66.26	205.74	89.15
40	233.17	0.44	713	2,670	0	0	55.44	310.36	77.19
50	291.46	0.44	822	2,337	15.29	−14.25	47.40	357.90	66.44
60	349.75	0.44	924	2,177	29.59	−22.65	43.40	402.31	52.56
70	408.04	0.44	1,019	2,018	42.91	−32.31	39.83	443.67	35.63
80	466.34	0.44	1,106	1,988	55.12	−34.3	39.24	481.50	15.17
90	524.63	0.44	1,186	1,699	66.34	−57.15	33.96	516.38	−8.24
100	582.92	0.44	1,259	1,539	76.58	−73.49	31.67	548.17	−34.75
160	932.67	0.44	1,542	623	116.27	−328.57	28.70	671.35	−261.32

[a]Soybean seed yield and dockage predictions were calculated using the quadratic equation: $y = ax^2 + bx + c$.
[b]Canola-shoot biomass predictions were calculated using the linear response formula: $y = ax^2 + b$
[c]Difference in soybean yield and canola-shoot biomass was determined by comparing each seeding rate with the standard rate of 40 plants m^{-2}.
[d]Gross income was calculated by multiplying soybean seed yield by market price.
[e]Contribution margin was calculated by subtracting the seed cost from the gross income.

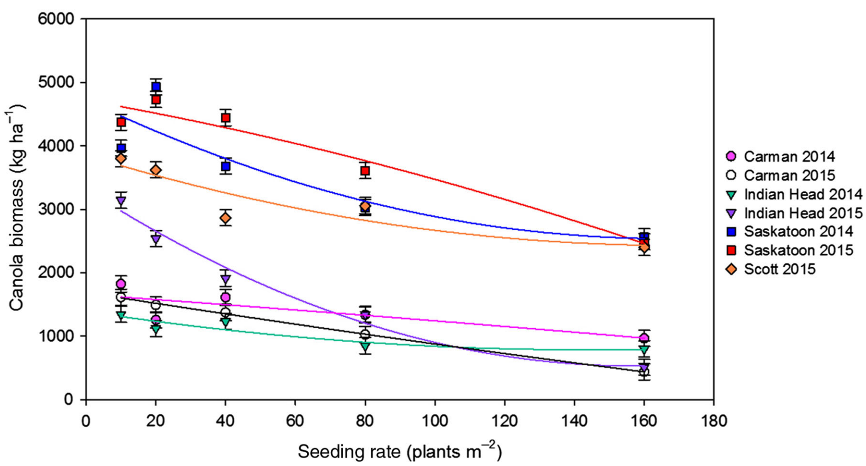

Figure 3. Volunteer canola-shoot biomass response to seeding rate across all seven site-years. Bars indicate ±1 standard error of the mean. Line equations: Carman 2014: $y = -0.0024x^2 - 3.8977x + 1656.8$. $R^2 = 0.6356$. Carman 2015: $y = 0.005x^2 - 8.6171x + 1689.3$. $R^2 = 0.9985$. Indian Head 2014: $y = 0.0293x^2 - 8.4452x + 1392.7$. $R^2 = 0.8503$. Indian Head 2015: $y = 0.1125x^2 - 35.422x + 3319.2$. $R^2 = 0.9783$. Saskatoon 2014: $y = 0.0789x^2 - 26.284x + 4727.2$. $R^2 = 0.7678$. Saskatoon 2015: $y = -0.0276x^2 - 9.698x + 4720.6$. $R^2 = 0.952$. Scott 2015: $y = 0.0495x^2 - 16.785x + 3852.8$. $R^2 = 0.8231$.

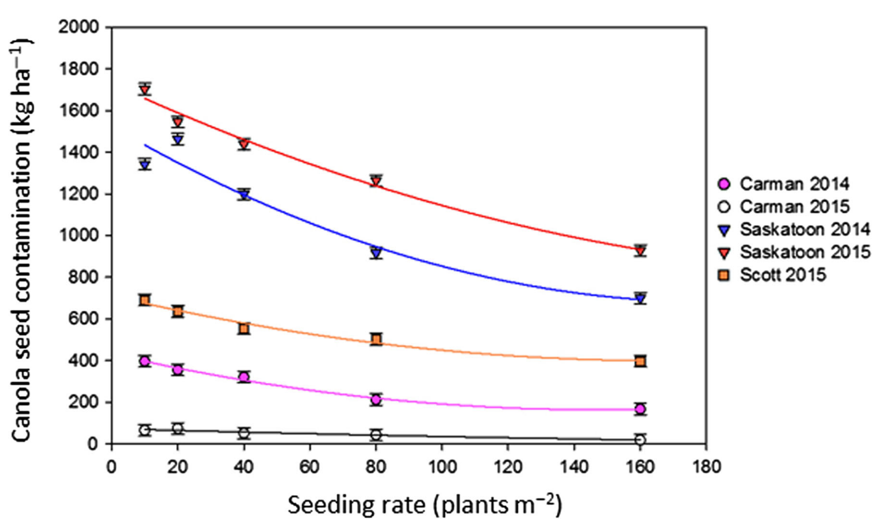

Figure 4. Volunteer canola contamination response to seeding rate at five all site-years. Bars indicate ±1 standard error of the mean. Line equations: Carman 2014: $y = 0.0124x^2 - 3.6442x + 431.67$. $R^2 = 0.9903$. Carman 2015: $y = 0.0007x^2 - 0.4482x + 73.264$. $R^2 = 0.9253$. Saskatoon 2014: $y = 0.0253x^2 - 9.2581x + 1525.3$. $R^2 = 0.9429$. Saskatoon 2015: $y = 0.0145x^2 - 7.3056x + 1730.3$. $R^2 = 0.9857$. Scott 2015: $y = 0.0111x^2 - 3.7214x + 710.71$. $R^2 = 0.9756$.

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emergence and seed yield at Indian Head and Saskatoon in 2014. These two site-years were also the only two in which planting date affected volunteer canola biomass, with the early planting date having the lowest canola-shoot biomass. This indicates that early planted seeds were able to effectively compete with volunteer canola and the finding is similar to that of Klingman and Oliver (1994), who reported that soybean yield loss due to weed interference increased as planting date was delayed from early May to early June. In our experiment, plants from the early planting date matured earlier and may have reduced yield losses due to frost damage. Several studies have reported higher soybean yields with early planting (De Bruin and Pedersen 2008; Hardman and Gunsolus 1994; Kane et al. 1997; Parvez et al. 1989; Robinson et al. 2009). However, some of these studies used planting dates that are either too early or too late for western Canada. The latest planting date produced the greatest yield at Carman in 2014, Indian Head in 2015, and Saskatoon in 2015, and soybean emergence was greatest at many of these sites as well. This contrasts with results at the two Saskatchewan sites in 2014, but other studies have also reported that yields of later-seeded soybean can be higher than early-seeded soybean (Buhler and Gunsolus 1996; Rushing and Oliver 1998). The authors suggested this was often due to inadequate rainfall early in the season and decreased weed competition with later planting.

In summary, planting-date effects were variable across site-years, whereas seeding rate effects were fairly consistent. Earlier seeding tended to improve the crop's competitiveness with volunteer canola, whereas late seeding may reduce the ability of the soybean crop to compete with early emerging volunteer canola. Based on planting date results, the optimal planting date range for soybean in western Canada is May 20 to June 1. Higher seeding rates resulted in greater soybean yield and lower volunteer canola biomass and seed contamination. Based on the economic analysis, the optimal seeding rate is 40 plants m^{-2} in years with low or average market prices. When market prices are high, increasing the seeding rate to 50 to 60 plants m^{-2} will increase soybean yield significantly, decrease volunteer canola competition and dockage, and increase net income for the grower. Improving crop competition with higher seeding rates will also decrease the contribution of canola seed to the seedbank and, therefore, decrease volunteer canola populations in sequential crops.

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