PROJECT DETAILS

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- **Collaborators/additional investigators:** Murray Hartman
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Final report

Determining the economic plant density in canola

Final Report
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Abstract/Executive Summary

Seed costs for canola are high prompting many growers to seed at reduced rates. Although there have been many seeding rate studies done for canola, the optimum seeding rate and plant population for canola is not known. Metaanalysis offers a way of combining data from different experiments to conduct a combined mixed model analysis. The objective of this study is to conduct a metaanalysis of canola seeding rate and plant population trials in order to determine the optimum seeding rate and plant population. Summary data from 35 experiments were included in the dataset which comprised 176 site-years of experiments. Firstly a categorical analysis comparing yields of approximately 3 versus 5 kg ha^{-1} was conducted. It was determined that canola seeded at 5 kg ha^{-1} had on average a 4% higher yield than canola seeded at 3 kg ha^{-1}. The site years which had the greatest yield reduction were those in which the emergence of the 3 kg ha^{-1} treatment was lower than 45 plants m^{-2}. A second analysis examined the effect of canola population density on yield. In contrast to the categorical analysis it was found that the yield response of open pollinated canola differed from that of hybrid canola. In general hybrid canola reached its maximum yield at lower densities than open pollinated canola. Hybrid canola achieved 90% of its yield at 45 plants m^{-2} compared to 90 plants m^{-2} for open pollinated canola. Hybrid canola appears to maintain a large proportion of its yield at low plant densities although very few studies had low canola densities. Economically it is more profitable to seed lower seeding rates of canola when seed costs are high, and when the selling price and yield of canola is low. However reducing seeding rates have a greater risk of having lower populations which can result in large yield losses. Emergence is often low in canola making reduced seeding rates a risky decision. Canola farmers seeking to maximize returns should target populations greater than 50 plants m^{-2} (5 foot^{-2}). Plant populations lower than this will almost always have yield loss.

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Canola has been traditionally seeded at 5-6 lbs ac^{-1} (4.4 – 5.3 kg ha^{-1}) and despite many seeding rate studies, very little attempt has been made to determine what the optimum plant population or seeding rate is. Canola exhibits a large degree of plastic morphology, where the plant can compensate for low plant densities through increased branching. Because of plastic morphology canola can exhibit yield compensation over a wide range of plant populations. Seeding canola on a weight basis was an adequate practice in the past. However, several changes have occurred since canola was introduced that suggest that these recommendations should be changed. 1) The seed cost of canola is much higher than it was in the past. In 1998 open pollinated canola sold for as low as \$1.20 lb^{-1} (Canola Council of Canada, 1998). It is now common for the cost of pesticide coated hybrid canola seed to approach and in some cases exceed \$8.00 per pound, resulting in a seed cost of approximately \$40/acre. In fact with the change with the Liberty system prices of LL hybrid canola are closer to \$8.60 lb^{-1}. One could argue that when the seeding rate of canola was first determined the seed cost was incidental. This meant that producers could afford to seed at a much higher rate than was needed to maximize yield. 2) Seed size in hybrid canola is now much larger than open pollinated varieties. Although this reduces the amount of viable seeds sown per unit area, larger canola seed has greater seedling emergence and vigour (Elliot et al. 2008). 3) Herbicide tolerant technology now allows canola to be maintained weed free, often for most of the growing season. Therefore a high canola population is not needed to compete with weeds.

The combining of results from several independent research studies can allow for greater confidence in the results. A metaanalysis statistically combines the results of several studies to increase the inference of the results. Meta-analyses typically partition the error into within study and between study error (Gurevich and Hedges, 1999). In this manner, individual studies which have greater precision are weighted more heavily in the overall combined analysis. Mixed model approaches allow the error to be separated into the random effects of studies and the fixed overall effects. Metaanalysis has been very common in biomedical research; however, there have been relatively few examples of metaanalysis in agronomic research. Miguez et al. (2005) analyzed the results from 37 winter cover crop experiments that proceeded corn. They determined that legumes provided a 37% yield benefit when nitrogen was not applied. Egli and Cornelious (2008) conducted a combined analysis of 28 soybean seeding date trails to determine the optimum seeding date for soybeans in several regions.

All this suggests that canola should be seeded at a target population basis, similar to other crops with high value seed. Furthermore, the economic optimum seeding rate of canola for high value hybrid seed has not yet been determined. The objective of this research is to determine the optimum seeding rate and target plant population for canola by combining the results from past canola seeding rate experiments.

Materials and Methods

Selection of studies

A comprehensive search for seeding rate and plant population studies of *Brassica napus* conducted in the northern Great Plains of North America was undertaken. Studies that varied the seeding rate (expressed in a weight per area basis), the target plant population or the actual plant population were considered. For a study to be included it had to have recorded the seed yield of canola, the experiment had to have a replicated experimental design and the entire experiment had to have been replicated in time or space (there had to be more than one site-year).

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Electronic databases including Agricola (Ovid Technologies, New York), Web of Science (ISI, Philadelphia, PA), Google Scholar (http://scholar.google.ca/), the libraries at the University of Manitoba, University of Alberta, and the University of Saskatchewan and others were searched using combinations of the terms brassica, canola, rapeseed, seeding rate, and density. In addition individual researchers, seed companies and producer groups were contacted in order to obtain unpublished reports and in some cases raw data. When raw data was obtained the averages of the treatments were calculated for each site year.

The vast majority of the experiments did not report variance or standard errors for individual site-years. This precluded the weighting of individual site years based on the variance that is usually done with combined metaanalyses. However, as all of the reported experiments were conducted using replicated experimental designs we assumed that sampling errors were similar across experiments (Gurevich and Hedges, 1999). The number of site-years for each experiment was considered to be the replication for the categorical analysis. The standard error of the study was thus calculated based on the variation of the average response and the number of site-years the experiment was conducted at.

Most of the experiments had additional categorical variables in addition to seeding rate or population density. The categorical variables that were identified as possibly influencing the response of canola yield to seeding rate included, breeding systems (hybrid or open pollinated), the year experiment was initiated, nitrogen rate, and seeding date.

Categorical analysis

Many of the studies (9 experiments, 43 site-years) had only two different seeding rates that were compared so regression analysis was not possible. A large proportion of all studies had seeding rates of approximately 3 and 5 lbs acre^{-1} or 3 and 6 lbs acre^{-1} (2.6 and 4.4-5.3 kg ha^{-1}). Thus an initial analysis was performed assuming seeding rate was a categorical variable with a rate of either 3 or 5 lbs acre^{-1}. When other categorical variables were not considered in the statistical model, the mean yield across categorical variables was used for a given site-year. For this analysis a response ratio approach (Hedges et al. 1999) was used where the dependent variable was the relative yield of the 5 kg ha^{-1} (Yield$_5$) treatment compared to the yield at 3 kg ha^{-1} treatment (Yield$_3$). The response ratio was transformed using the natural log to maintain normality (Hedges et al (1999). This transformation results in a positive value of LogRR indicating a higher yield for the 5 kg ha^{-1} whereas a negative value indicates a higher yield in the 3 kg ha^{-1} treatment.

$$\mathrm{LogRR} = \mathrm{Ln}\left[\frac{\mathrm{Yield}_5}{\mathrm{Yield}_3}\right]$$

The variance ($\mathrm{v_i}$) of each ith study was calculated using the method of Hedges et al. (1999):

$$\mathrm{v_i} = \frac{\mathrm{SD^2}_5}{\mathrm{n}_5 * \bar{\mathrm{Y}}^2{}_5} + \frac{\mathrm{SD^2}_3}{\mathrm{n}_3 * \bar{\mathrm{Y}}^2{}_3}$$

where SD^2 is the squared standard deviation for each treatment, $\bar{\mathrm{Y}}^2$ is the squared yield for each treatment and n is the number of site years.

The overall effect of categorical seeding rate as well as the other categorical variables were explored using a mixed model analysis in SAS where studies were the random variable. The variance of each study $\mathrm{v_i}$, as calculated in equation X was used in the analysis and modeled with the repeated statement. The method and SAS code was adapted from those used by van Houwelingen et al. (2002), Miguez et al. (2005) and Hoeksema & Forde (2008).

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The analysis was conducted in a hierarchical fashion where the first analysis was on the intercept only (no fixed effects). If this differed from zero than there was a treatment effect for seeding rate. Following this other categorical variables where explored.

A similar method was used for exploring the effect of increasing seeding rate from the recommended rate to 50% greater than recommended.

This analysis was also conducted assuming that each site-year was a random independent experiment. The rationalization for this approach was that this approach would not penalize experiments that had multiple site-years in which the responses differed between site-years. It is the opinion of the author that differences between site-years reflect environmental differences and not differences in experimental precision. i.e. having one site-year where there is a large yield increase from increasing the seeding rate and another site year where there was not a difference probably reflects a difference in random environment differences between the site-years and not a difference in experimental precision. It is therefore not prudent to penalize experiments that have sampled multiple site years which differed in their response.

Regression analysis

For studies that had more than two target seeding rates or plant populations, a regression analysis approach was used. In most cases the yield density response for given site years followed an asymptotic response where the yield increased with density then leveled off at a maximum yield after which the yield was independent of plant density or seeding rate. The simplest form of this nonlinear equation is as follows:

$$Yield = \frac{Yield_{max} * d}{D_{50} + d}$$

where $Yield_{max}$ is the maximum yield as density or rate (d) approaches infinity and D_{50} is the rate or density at 50% maximum predicted yield (Baird et al. 2009). The mixed nonlinear procedure of SAS cannot model the error structure of this analysis so a transformed form of the Michalis Menten equation was used instead to linearize the function:

$$\frac{1}{Yield_{plant}} = 1/Yield_{max} * d + Yield_{max}/(1/D_{50})$$

where the slope = $1/Yield_{max}$ and the intercept is equal to $Yield_{max}/(1/D_{50})$. The regression metaanalysis was conducted using the mixed procedure in SAS according to the methods described by St. Pierre (2001). Briefly, the above linear regression was fit to individual site years and a common relationship was calculated. Individual site-years were considered random effects as the proportion of canola emergence and therefore the subsequent plant population varies greatly between site-years because of the environment. The effect of hybrid versus OP seed as well as the year of the study was considered. The statistical model was fit in a *hierarchical* fashion with main effects and interaction removed if not significant.

A problem arose that many of the site years had no data at low plant densities. This caused some of the regressions to fit a negative intercept to the above model which would describe a yield density function that had negative yield at some site-years. Clearly this is an erroneous result and it was associated with site-years that did not have any treatments with low canola emergence. This problem was overcome by limiting this

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analysis to site-years which had at least one treatment with plant population densities less than 25 plants m^{-2}.

Results and Discussion

Study Selection

Greater than 50 experiments were examined for inclusion in this analysis. Those excluded often did not present the data by site-year (they combined the data) or only conducted the experiment for one year. Studies that did not use replication within the field (strip trials) were also excluded. Overall 35 experiments were included in the dataset comprising 176 site-years of experiments (Table 1). Most of the experiments (27 of 35) measured the effect of seeding rate on a weight per area basis on yield. The remaining experiments measured the effect of target plant population or actual density (thinned to the target density) on yield. Several experiments included other agronomic factors of interest. Four experiments varied nitrogen, twelve had both hybrid and open pollinated canola, three varied row spacing and four varied seeding date. Where the level of agronomic input varied greatly only those values that were somewhat normal were included in the analysis. In several cases the means of several treatments were analyzed where the individual treatment means were not available. For example in one row spacing trial the 60 cm row-spacing treatment was not included as farmers would never seed canola in rows that wide.

Qualitative analysis 3 versus 5 kg ha^{-1}

A total of 26 studies comprising 150 site years were used to compare the yield of canola seeded at 3 versus 5 kg ha^{-1}. Of the 26 studies examined, 22 showed higher average yields at 5 compared to 3 kg ha^{-1}. On average the log response ratio (LnRR) for canola seeded at 3 versus 5 kg ha^{-1} was -0.0418 indicating that canola seeded at 3 kg ha^{-1} yielded 4% lower than canola seeded at 5 kg ha^{-1} (Figure 1). This difference is not considered statistically significant as the 95% confidence intervals include 100% (95% C.I. ranges from 89% to 102%). However this difference is significant at the 0.2 level. Normally one would discount such a low level of significant; however, in the case of this analysis there are factors which can make an argument for accepting it as valid. Firstly, it is not unusual to not find significant differences between two adjacent rate variables that are analyzed as categorical variables. As mentioned previously this analysis was done categorically because of the large amount of experiments that only evaluated two seeding rates. Secondly, site-years are considered as replicates for experiments in this analysis. This approach reduces the weight placed on individual site-years and instead considers only the average for a given experiment (composed of multiple site years) as a random effect. Because of this the results of this analysis are very conservative.

A second analysis was conducted assuming that every site-year was independent. Analyzing the data in this way found that the average yield of 3 kg ha^{-1} was 95% of that of 5 kg ha^{-1} ($P < 0.001$; 95% confidence intervals 94-97%). This analysis also found a significant regression for year that the study was performed but the year to year variability was very high and the r^2 was very low (0.027) (Figure 2).

The emergence at 3 kg ha^{-1} was found to have a relationship to the LnRR ($P<0.0001$). Examination of the relationship indicated that there is a segmented linear relationship in which site-years that have a plant density in the 3 kg ha^{-1} treatments of less than 46 plants m2 (s.e. 6.7) experience yield loss relative to the 5 kg ha treatment (Figure 3.). In contrast those site years which have emergence in the 3 kg ha^{-1} treatment greater than 46 plants m^{-2} have close to the same yield as the 5 kg ha^{-1} treatments. This relationship

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suggests that growers who are able to achieve densities greater than 46 plants m^{-2} at 3 kg ha^{-1} should not have yields that are greatly reduced when compared to 5 kg ha^{-1}. The risk of seeding at a reduced rate is also illustrated by this analysis.

There was no effect of hybrid (H) or open pollinated (OP) seed production on the LnRR for both the data analyzed by experiment and siteyear (P = 0.44). This indicates that both OP and Hybrid respond similarly to the 3 and 5 kg ha^{-1} treatments. Furthermore, an additional analysis examining the covariance of absolute yield revealed that the LnRR was not affected by the absolute yield of the site-year or trial. Thus low yielding crops of canola seeded at 5 kg ha^{-1} compared to 3 kg ha^{-1} had the same relative yield increase compared to high yielding crops.

Qualitative analysis 5 versus 9 kg ha^{-1}

Nine studies had rates of approximately 5 or 9 kg ha^{-1} as seeding rate treatments. Analysis of the LnRR with experiment as a random effect revealed that there was a non-significant (P=0.32) effect (Figure 4). However, when siteyears were considered as random independently effects, there was a 5% yield advantage to growing canola at 9 versus 5 kg ha^{-1}. The results of the 5 versus 9 kg ha^{-1} analyses should be viewed with caution as three of the four experiments that showed the greatest yield response to increased seeding rate were weed control studies that seeded extra weeds and included reduced herbicide rates in the treatments (Blackshaw eta al, 2005; Harker et al. 2003 and O'Donovan, 2004) (Figure 4). This may explain the large yield increase in these specific trials. Eliminating these "weedy" trials would result in little yield advantage for growing canola at 9 versus 5 kg ha^{-1}.

Regression Analysis

As each experiment in this analysis consisted of individual experiments conducted at different locations, each "site-year" was analyzed by regression as if it were an independent experiment. Although absolute yield is presented in the figures the analysis adjusted the yield between locations in order to remove this source of variation.

The effect of genetic system, year of experiment and plant density was modeled iteratively to determine which factors should be included in the model. Based on Akaike's Information Criteria (AIC), it was determined that there was a genotype effect as well as a genotype by density effect. This indicated that there was a separate intercept and slope for hybrid and open pollinated canola. Including year also resulted in a better model fit, however inspection of the results revealed that the year effect was mostly related to the change from open pollinated to hybrid studies over time and it resulted in erroneous predictions. Thus year was not included in the final analysis.

Overall there was a very good relationship between the inverse yield per plant and observed plant density for all the site-years that had at least one density less than 25 plants m^{-2} (Figure 5). The transformation of this relationship into the non-linear form reveals that both hybrid and open pollinated canola follow asymptotic yield density relationship (Figure 6). As expected there was an overall yield increase (300 kg ha^{-1}) in the hybrid cultivars. Hybrid canola was less responsive to canola low canola densities than open-pollinated canola (Figure 6). Transformed the linear parameters described the maximum theoretical yield (Ymax) as well as the density at which 50% of maximum yield was achieved (D50). The D50 parameter

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describes the shape of the curve; a low D50 will have a very square curve with maximum yield achieved at a very low density. Hybrid varieties showed a lower D50 (7 plants m^{-2}) than open pollinated varieties (19 plants m^{-2}) indicating that lower densities of plants are required for optimum yields. In practical terms 90% of the yield at 250 plants m^{-2} was achieved at 45 plants m^{-2} in hybrid varieties versus 95 plants m^{-2} in open pollinated varieties. With hybrid varieties even plant populations as low as 15 plants m^{-2} provided a yield of 70% of the maximum achievable yield. The yield response of hybrid canola at very low plant densities should be treated with caution as there were only 5 site-years that had at least one treatment with canola populations below 10 plants m^{-2}.

Based on the average 4% increase in yield that canola seeded at 5 kg ha^{-1} had over canola seeded at 3 kg ha^{-1}, an economic simulation was conducted that varied the price of canola seed and harvested canola (Figure 7). Economically it is almost always more profitable to seed canola at 3 kg ha^{-1} compared to 5 kg ha^{-1}. At higher yields, higher canola prices and lower seed costs it became more profitable to plant canola at higher rates. At $8 per pound seed cost canola farmers would need a yield of 40 bushels per acre and a selling price of $10 per bushel to cover the cost of seed. As average yields in Saskatchewan are usually lower than this growers may be advised to reduce seeding rates to save costs. However, growers in high yielding areas may be able to successfully achieve higher returns when canola selling prices are high.

There are good reasons why growers would not lower their seeding rate. Emergence rates in canola are often low. The majority of the studies that were accessed in these trials were conducted using small plot equipment (the exception to this is the Canola Production Centre (CPC) trials). Small plot seeders are usually operated at lower speeds than farm scale equipment and there small size probably allows them to seed more uniformly at shallow depths. Because of this one would expect higher emergence with small plot equipment. That said recent advances in air drill technology allow for much more precise seed placement and depth control than with air seeders constructed out of converted field cultivators. The average economic analysis does not include a provision for the variance. The 95% confidence intervals for the 3 versus 5 kg ha^{-1} analysis reveal that 1 in 20 times the 3 kg ha^{-1} seeding rate will yield at least 10% lower than the 5 kg ha^{-1} seeding rate. Most times that lower yield of the low yield were associated with low emergence (Figure 3). Therefore, if producers can exercise care during seeding to ensure good emergence by seeding shallow (Hanson et al. 2008), driving slowly, and using precise air seeders that seed accurately to the required seeding depth (Canola Council of Canada, 2005) they may be able to reduce seeding rates with little yield or financial penalty.

The yield loss from reducing the seeding rate of canola to 60% of recommended (i.e.) from 5 to 3 kg ha^{-1}) depends on the field emergence. At high field emergence rates and therefore higher canola populations the yield loss caused by reducing the seeding rate is not great (Figure 8.) For example if the emergence of the canola at the 60% recommended seeding rate is 80 plants m^{-2}, then this resulted in a predicted yield loss of only 3% or on average 59 kg ha^{-1}. However when the emergence of canola is low, reducing seeding rates results in greater yield losses. If only 20 plants emerge at the reduced seeding rate then the predicted yield loss of from reducing the seeding rate is 10% or on average 170 kg ha^{-1}. Thus growers who reduce seeding rates must ensure that there is adequate field emergence of canola.

The seed weight of canola seed affects how many seeds are planted per unit area when canola is seeded on a weight per area basis. The seed weight of hybrid canola is greater than open pollinated canola so hybrid canola seeded at the same weight per unit area will have a reduced number of seeds

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per area. For example the hybrid canola variety Hyola 401 had a seed weight of 5.4 mg seed^{-1} whereas the open pollinated variety Hudson had a seed weight of 3.5 mg seed^{-1} (Hanson, 2008). The average reported seed weight for Pioneer open pollinated varieties was 2.9 mg seed^{-1} whereas hybrid varieties averaged 4.2 mg seed^{-1} (Pioneer, 2004). The seed weight of hybrids can vary within varieties as Pioneer 45H21 was reported to average 4.5 mg seed^{-1} and ranged from 3.7 to 5.3 mg seed^{-1}.

Canola emergence in farmer's fields is often low with typical field emergence being 50% (Canola Council, n.d.). Furthermore the high seed weight of hybrid canola varieties means that producers seeding on a weight per area basis will seed less seed than they would if lighter seed were used. This large seed size can result in low plant populations. In cases where emergence is low this can result in plant populations below target levels. For example a canola variety with a seed weight of 5.5 mg seed^{-1} seeded at 3 kg ha^{-1} and 50% emergence will result in only 27 plants m^{-2}. At this density there is an 8% or 145 kg ha^{-1} yield loss predicted by reducing the seeding rate (Figure 8). Had that farmer had 30% emergence the yield loss would have been 12% or 190 kg ha^{-1}. Clearly, reducing seeding rates increases production risk.

Spatial variability of emergence is a further complicating factor when choosing a seeding rate. The author has observed that emergence in canola fields varies drastically across landscapes in dry springs such as those experienced in 2008 and 2009. In these springs it has been observed that canola emergence on dry knolls has been very low and in many cases well below 1 plant m^{-2}. The yield loss caused by reduced emergence in such areas is complex for there is reduced canola yield potential on knolls. Pennock et al. (2001) found that canola yields on knolls (convex landscape areas) were on average 55% lower than other areas in the field. The yield differences were partially attributed to differences in soil moisture. So although canola emergence is lower on knolls, the yield potential in these areas is much lower. Therefore the actual yield losses caused by reduced emergence on knolls may be lower than anticipated.

Canola seeded at higher seeding rates and populations is less affected by yields and sustains reduced yield losses when weeds are present. In several cases it was found that canola seeded at higher than recommended rates had less yield loss when seeded into fields with high weed densities (Blackshaw eta al, 2005; Harker et al. 2003 and O'Donovan, 2004; Figure 4). The critical timing of weed removal in canola is the four leaf stage (Martin et al; 2001) so in years when weeds are not controlled in canola by this stage or when weed densities are high growers should not reduce seeding rates.

Crop maturity can also be affected by seeding rate. Although this study did not explicitly examine this effect (only a few studies measured it), very low plant populations are associated with delayed maturity in some cases (Canola Council of Canada, 2002b). Whether the slight difference in plant population from a reduced seeding rate would have a significant effect on maturity will be addressed in a future analysis.

Astute readers will recognize that there may be a contradiction between the categorical analysis and that of the regression analysis. The categorical analysis found a 4% yield increase by increasing the seeding rate from 3 to 5 kg ha^{-1} (Figure 1). In contrast the regression analysis predicts that there would be at least a 4% yield reduction for 3 kg ha^{-1} anytime the emergence is below 57 plants m^{-2}. This difference is probably due to the data that was used for the specific analysis. Different data sets were used to analyze the categorical and regression analysis depending upon how the experiments were done and the variables. The regression analysis was only based on 40 site years (for hybrid canola) as those siteyears that had either not measured plant density or not had plant densities as low as 25 plants m^{-2} were not included. However both

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studies show similar trends. All analyses indicate that yields of canola begin to decrease substantially as plant densities get lower than approximately 45 plants m^{-2} (Figs 3, 6 and 8).

Conclusions and Recommendations

Producers who wish to maximize the yield of hybrid canola as well minimizing seed cost can consider reducing seeding rates provided they can ensure good emergence. Stands of canola below 45 plants m^{-2} (4 plants ft^{-2}) will often have lower yields than more dense stands. That said the high price of hybrid canola seed does make it tempting to reduce seeding rates.

So can producers reduce seeding rate of canola? If they can establish a stand of 50 plants m^{-2} with certainty at 3 kg ha^{-1} then they should be able to reduce seeding rates without economic penalty. In most cases this will mean that they achieve > 50% emergence with hybrid canola. Is this possible? There are numerous factors that influence emergence. The largest under the control of the farmer are seeding depth and seeding speed. Using an accurate air drill with precise seed depth control operated at low field speeds will ensure that farmers can achieve the best possible emergence. However dry seedbed conditions as well as seedling blights and insect attack can reduce canola emergence.

There have been very few studies that have investigated the yield response of hybrid canola at very low plant densities. Only 5 % of the site-years with hybrids had plant populations below 10 plants m^{-2}. At this density the regression analysis predicts that the yield should be 60% of the maximum achievable for hybrid canola. However the response at this density is unsure because of the low number of environments (siteyears) that were sampled. Given that there are often populations of canola below this level in producers fields there clearly needs to be more research in this area. Such research would canola farmers concerns about the viability of reseeding a canola stand with low plant densities.

In summary canola seeded at below recommended seeding rates will on average have lower seed yield. On average canola seeded at 5 lbs $acre^{-1}$ yielded 4% greater than canola seeded at 3 lbs $acre^{-1}$. However reducing seeding rates can result in much greater yield losses; in years where plant emergence is below ~50 plants m^{-2} yield loses were much higher. Economic analysis reveals that in years with low yield potential and low canola selling price the extra yield from seeding at the recommended rate was not enough to cover the additional cost of hybrid seed. Although there was no difference between hybrid and open pollinated canola in the response to seeding rate, hybrid canola reaches its maximum yield at lower plant populations than open pollinated canola. This probably occurs because of the larger seed weight of hybrid canola. Hybrid canola can maintain a high yield potential even when plant populations are very low; on average the yield at 1 plant per square foot is only 30% lower than the yield at 5 plants per square foot. Canola farmers seeking to maximize returns should target populations greater than 50 plants m^{-2} (5 $foot^{-2}$).

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Table 1. Characteristics of studies used in the metaanalyses.

Study	Year started	Years	Site-years	Locations						Seeding rate (kg/ha)				Hybrid /OP
Degenhart et al. 1981	1976	2	4	Edmonton, Ellerslie						3	6	12		OP
VanDeyzne et al. 1992	1986	2	4	Winnipeg (two sites)					1.5	3	4.5	6	9	Both
Morrison et al, 1990	1985	2	3	Winnipeg (two sites)					1.5	3	6	12		OP
Clarke et al. 1978	1975	2	6	Saskatoon rainfed, low and high irr						2.5	5	10	20	OP
Papworth, 1999	1999	1	3	Alberta (3)						2.8	5	7.3		H
Canola Council, 2002b	2000	3	13	CPC sites across prairies					0.9	2.7	5.7			H
Canola Council, 2001a	2001	2	2	Lethbridge					0.9	2.7	5.7			H
Brandt et al. 2007	1999	3	8	Scott, Indian Head, Melfort						2.8	5.6	8.4		Both
Christensen et al. 1984	1981	2	2	Beaver Lodge					1	2	4.5	9	18	OP
Turkington et al. 2005	2002	3	6	Lacombe, Melfort						3	6	9		Both
Gateway, 2005	2005	1	3	Colinton, Stony Plain, Westloc						2.7	5.7	6.1	8	H
Canola Council, 2001b	2001	1	5	CPC sites across prairies						2.7	5.7			H
Canola Council, 2002a	2002	1	4	CPC sites across prairies						2.7	5.7			OP
Jurke et al. 2006	2001	3	3	Winnipeg						2.2	6.7	13	20	?
Monsanto 2003	2003	1	6	Across Prairies						3	4	5	6	Both
Monsanto 2004	2004	1	5	Across Prairies						3	4	5		Both
Monsanto 2005	2005	1	5	Across Prairies					3	3.4	4	4.5	5	H
Monsanto 2006	2006	1	16	Across Prairies						3	4	5		H
Dosdall et al. 2004	1998	4	4	Lacombe						2.6	5.3	8	11	Both
Irvine, 1993	1991	3	3	Outlook						3	6	9		OP
Halford 2002	2001	2	2	Indian Head						2.7	5.4			OP
Hanson et al. 2008	1999	3	8	North Dakota	Rates diff. H and OP					1.8	3.6	5.4	7.2	Both
Kondra et al. 1977	1972	2	4	Parkland, Ellerslie						3	6			OP
Kondra et al., 1975	1971	2	4	Parkland, Ellerslie						3	6			OP
Blackshaw et al. 2005	1998	4	7	Lethbridge, Scott							6	9		OP
O'Donovan et al. 2004	1997	2	2	Vegreville							6	9	12	OP
Hawkins-Bowman 2006	1999	3	3	Winnipeg						4	8			?
										Target Densities (plants/m^2)				
McGregor, 1987	1977	3	3	Saskatoon	Thinned to dens.				3.6	7.2	22	108	200	OP
Angadi et al, 2003	1999	4	4	Swift Current					5	10	20	40	80	OP
Elliot et al. 2004	2001	3	6	Saskatoon				50	100	150	200	250	300	Both
Harker et al. 2003	1998	3	5	Lacombe, Lethbridge						100	150	200		Both
Linde, 2001	1999	2	5	Brandon	Actual Plant density					38	75	150	300	Both
Chen et al. 2005	2002	3	5	Moccasin MT, Conrad, MT						11	32	65	97	Both
Pioneer, 2004	2004	13	13	Across Prairies		20	40	60	80	100	120	140	160	Hybrid

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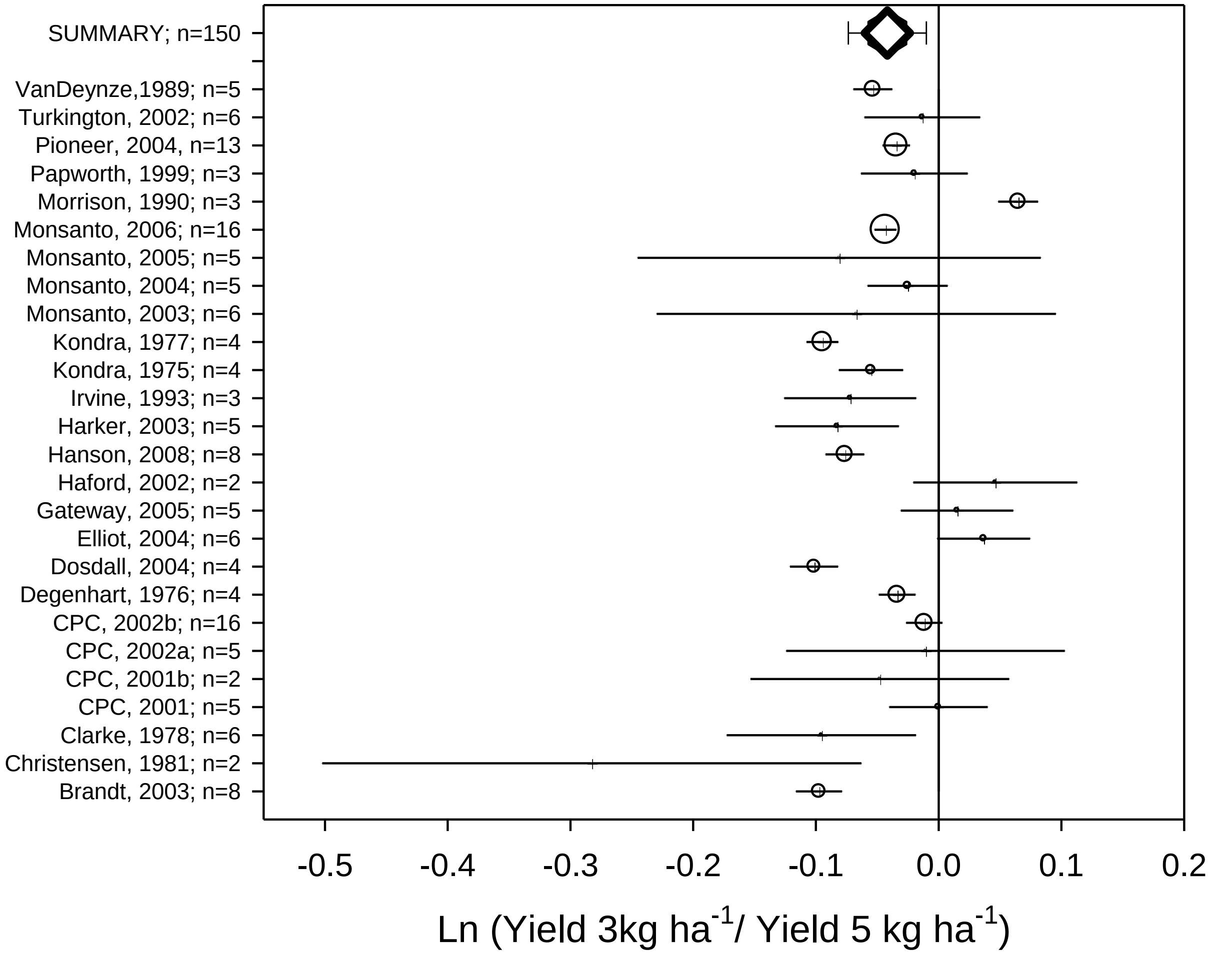

Figure 1. Log response ration of the yield of canola seeded at 3 kg ha^{-1} over the yield at 5 kg ha^{-1}. The crosses indicate the average response for each site year. The size of the circle indicates the weight of each study and the horizontal bars are the standard error. The letter n refers to the number of site years for each experiment. A response ratio of 0 indicates that the yield of both seeding rates is equal.

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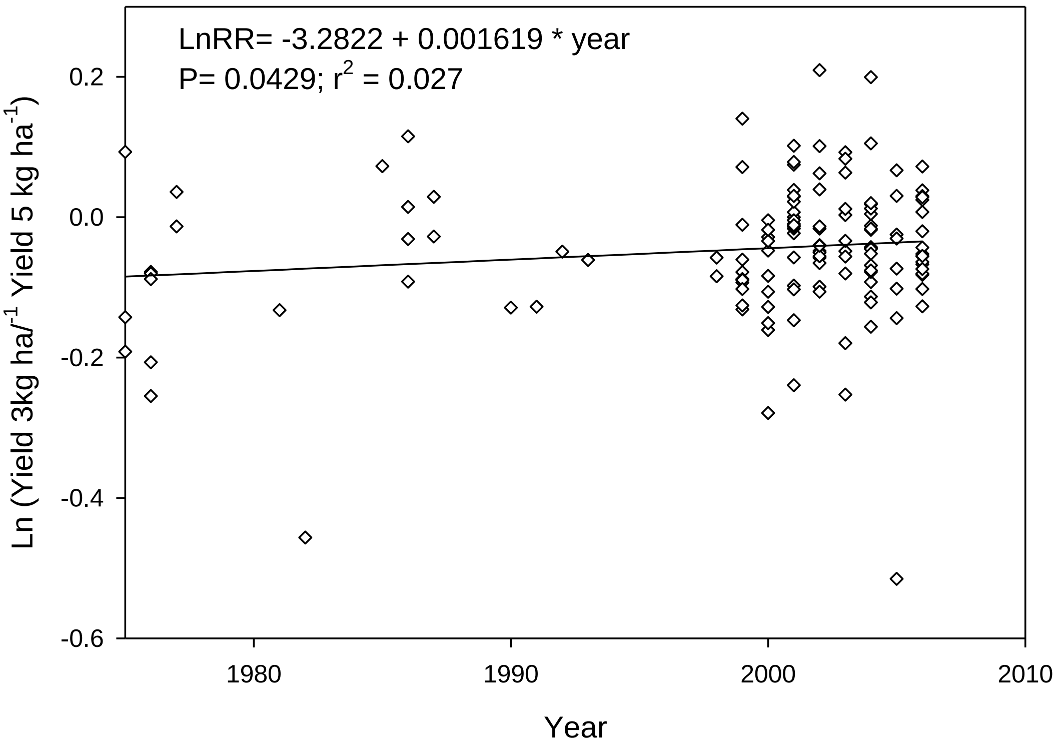

Figure 2. The change in the Log response ration of the yield of canola seeded at 3 kg ha^{-1} over the yield at 5 kg ha^{-1} over time.

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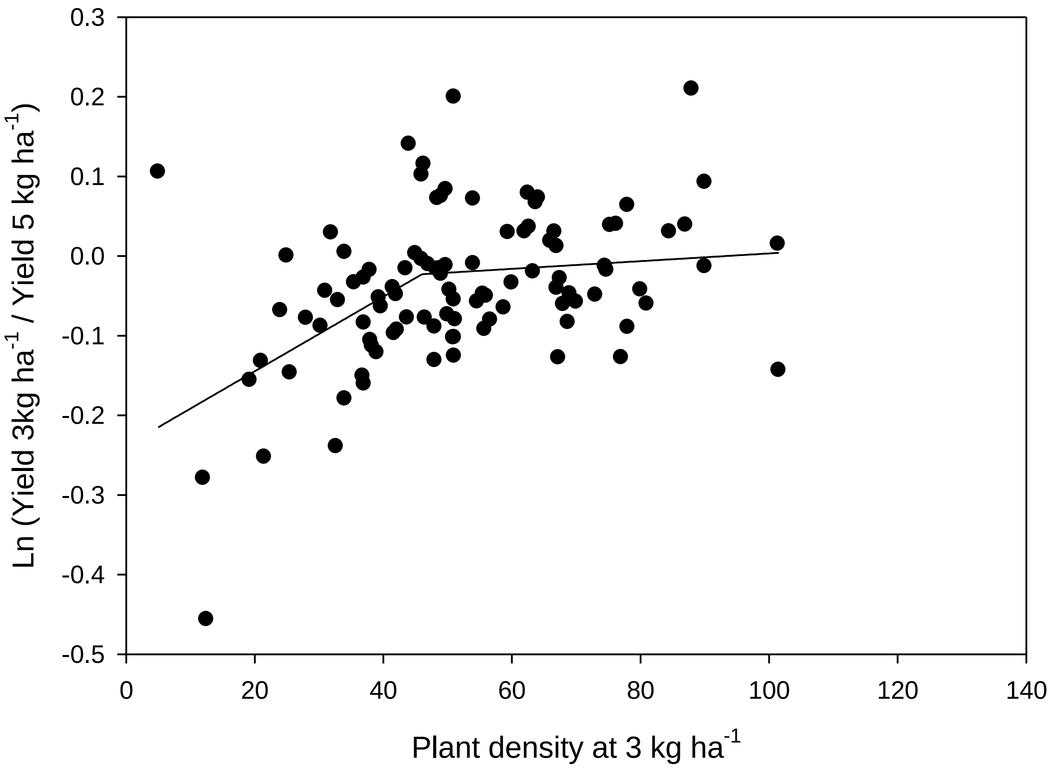

Figure 3. The effect of plant density at 3 kg ha^{-1} on the Log response ration of the yield of canola seeded at 3 kg ha^{-1} compared to 5 kg ha^{-1}.

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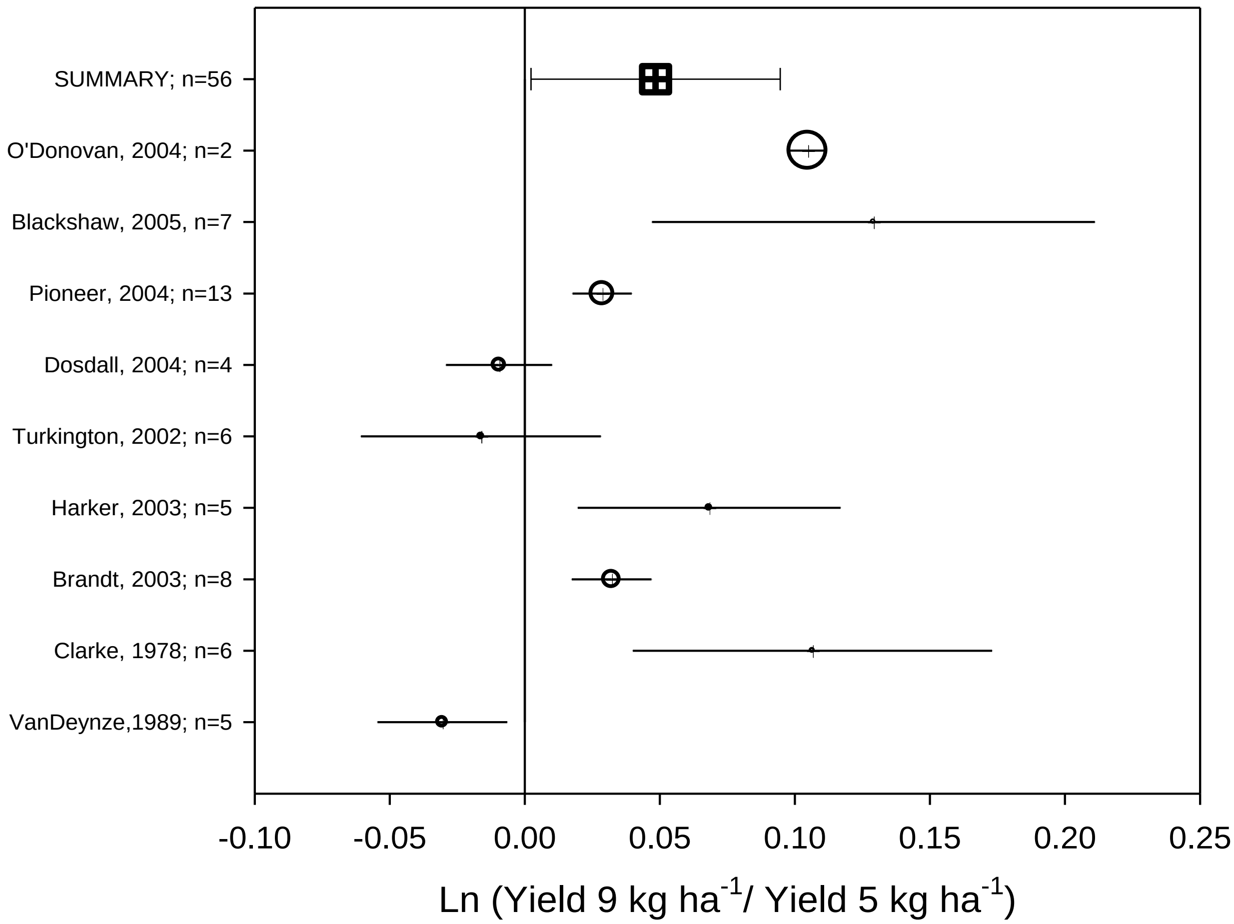

Figure 4. Log response ration of the yield of canola seeded at 9 kg ha^{-1} over the yield at 5 kg ha^{-1}. The crosses indicate the average response for each site year. The size of the circle indicates the weight of each study and the horizontal bars are the standard error. The letter n refers to the number of site years for each experiment. A response ratio of 0 indicates that the yield of both seeding rates is equal.

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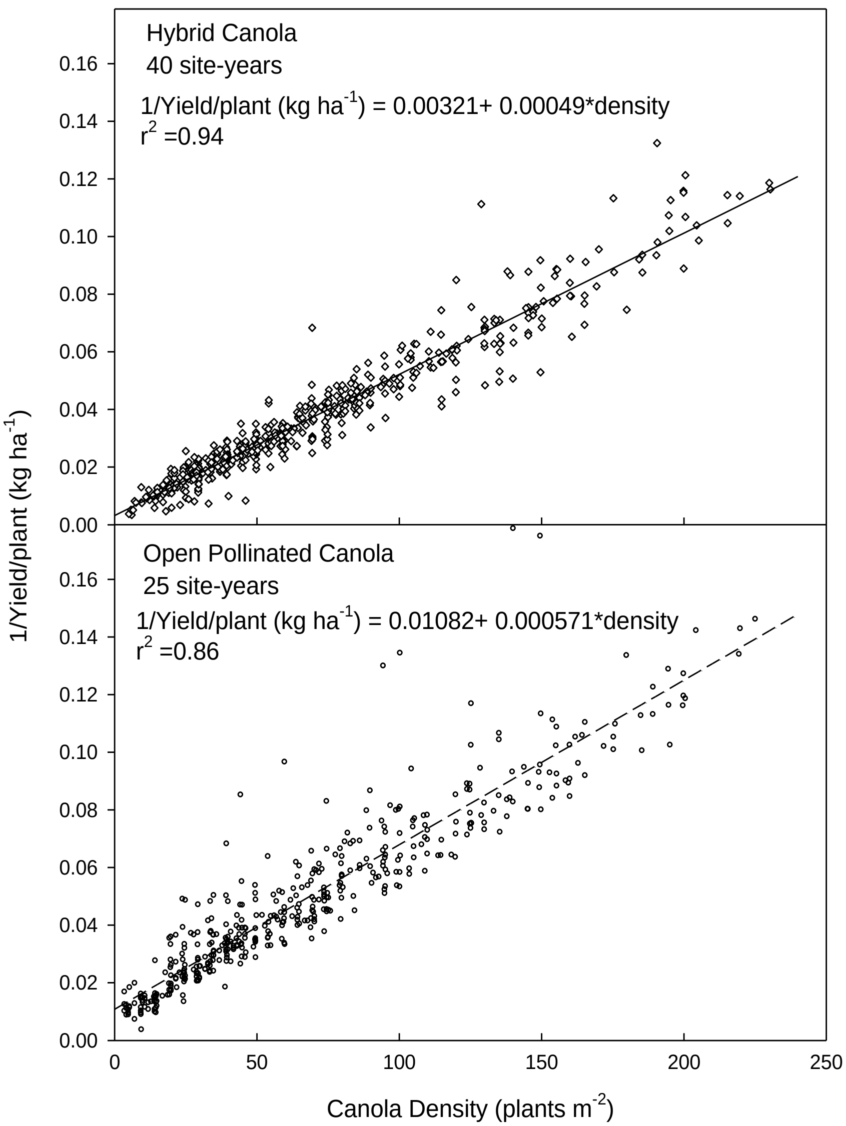

Figure 5. The effect of canola density on the inverse of the yield per plant for hybrid and open pollinated seed. Plot is of adjusted means after removing random variance due to site year.

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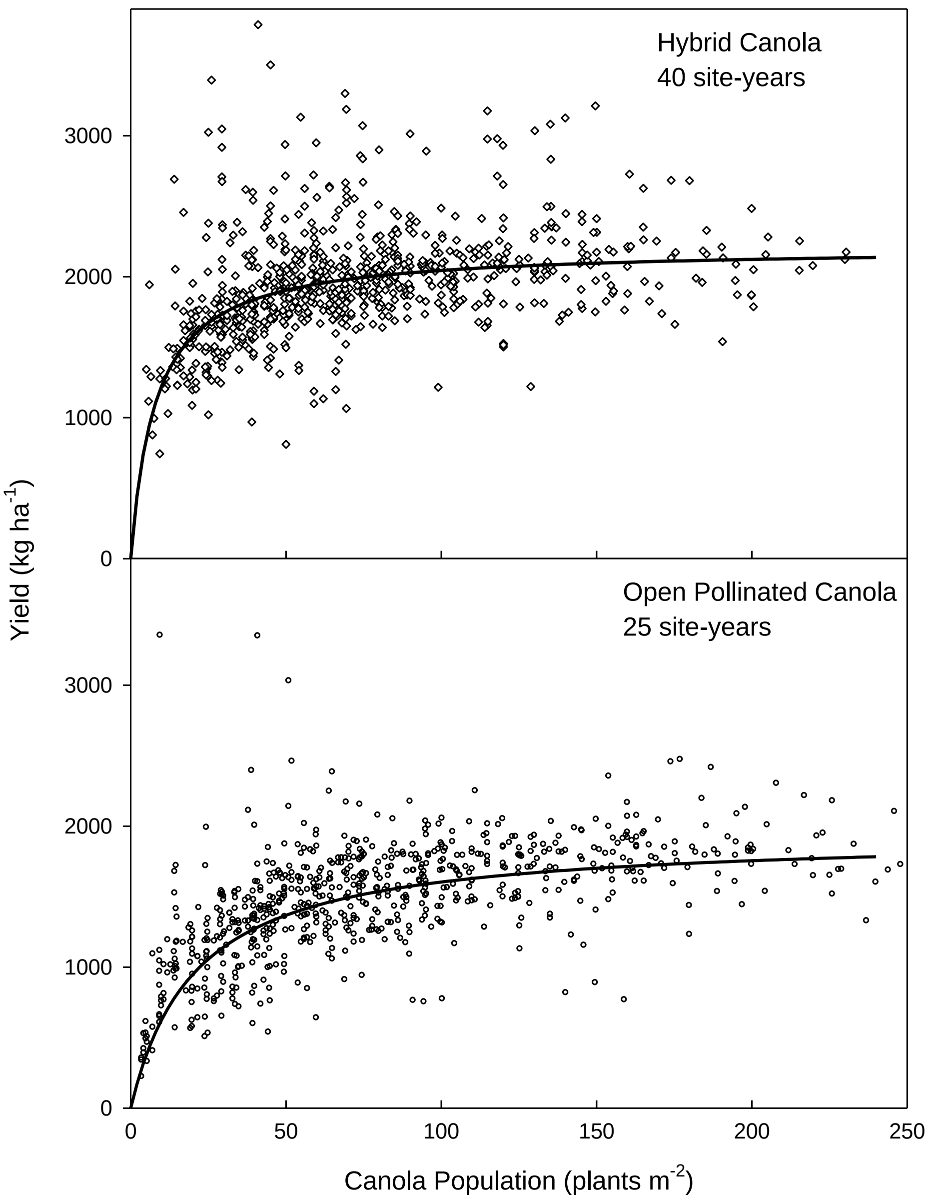

Figure 6. The effect of canola density on yield for hybrid and open pollinated seed (data transformed from Figure 5). Plot is of adjusted means after removing random variance due to site year

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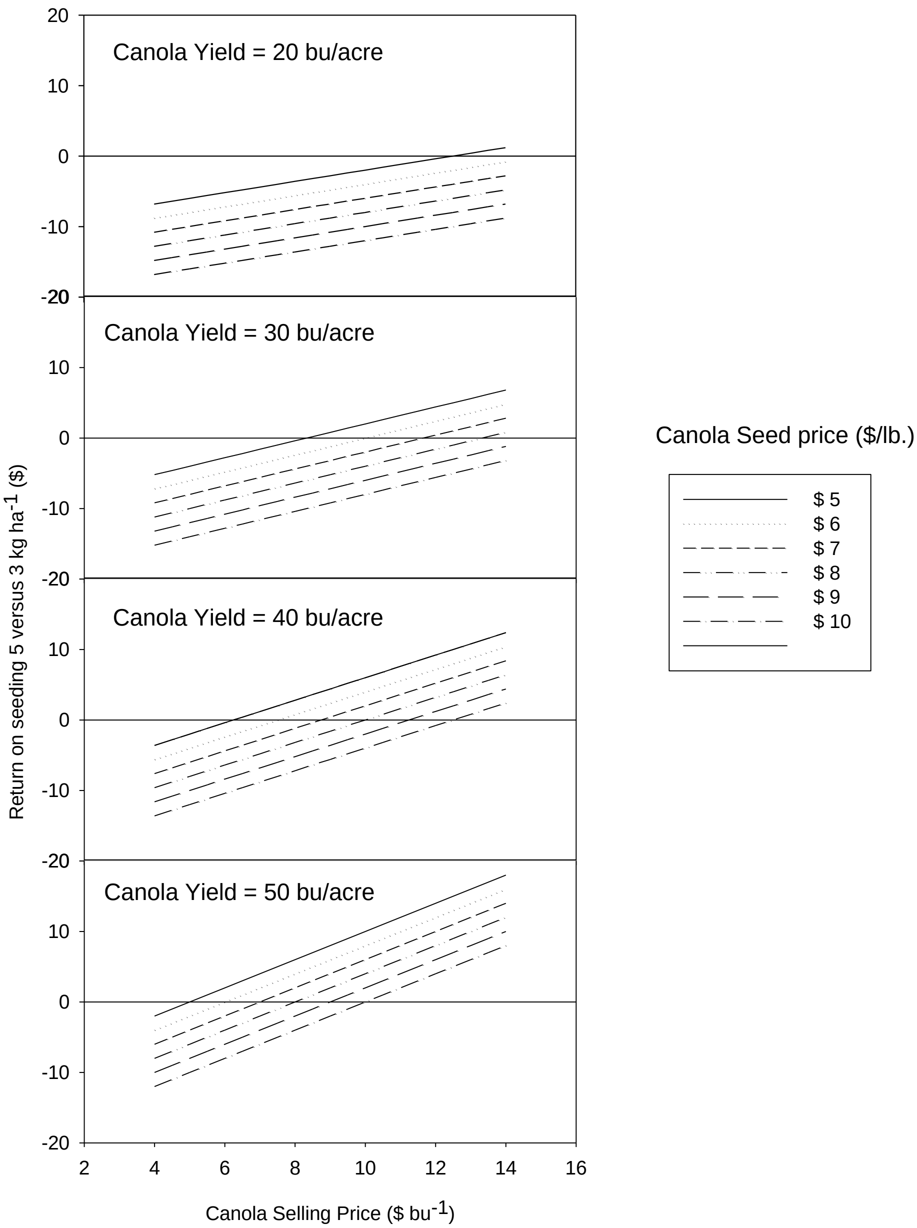

Figure 7. The effect of canola selling price, seed cost and yield potential on the financial return of seeding at 5 versus 3 kg ha^{-1}. This analysis assumes an average yield increase of 4% for seeding at 5 kg ha^{-1} compared to 3 kg ha^{-1}.

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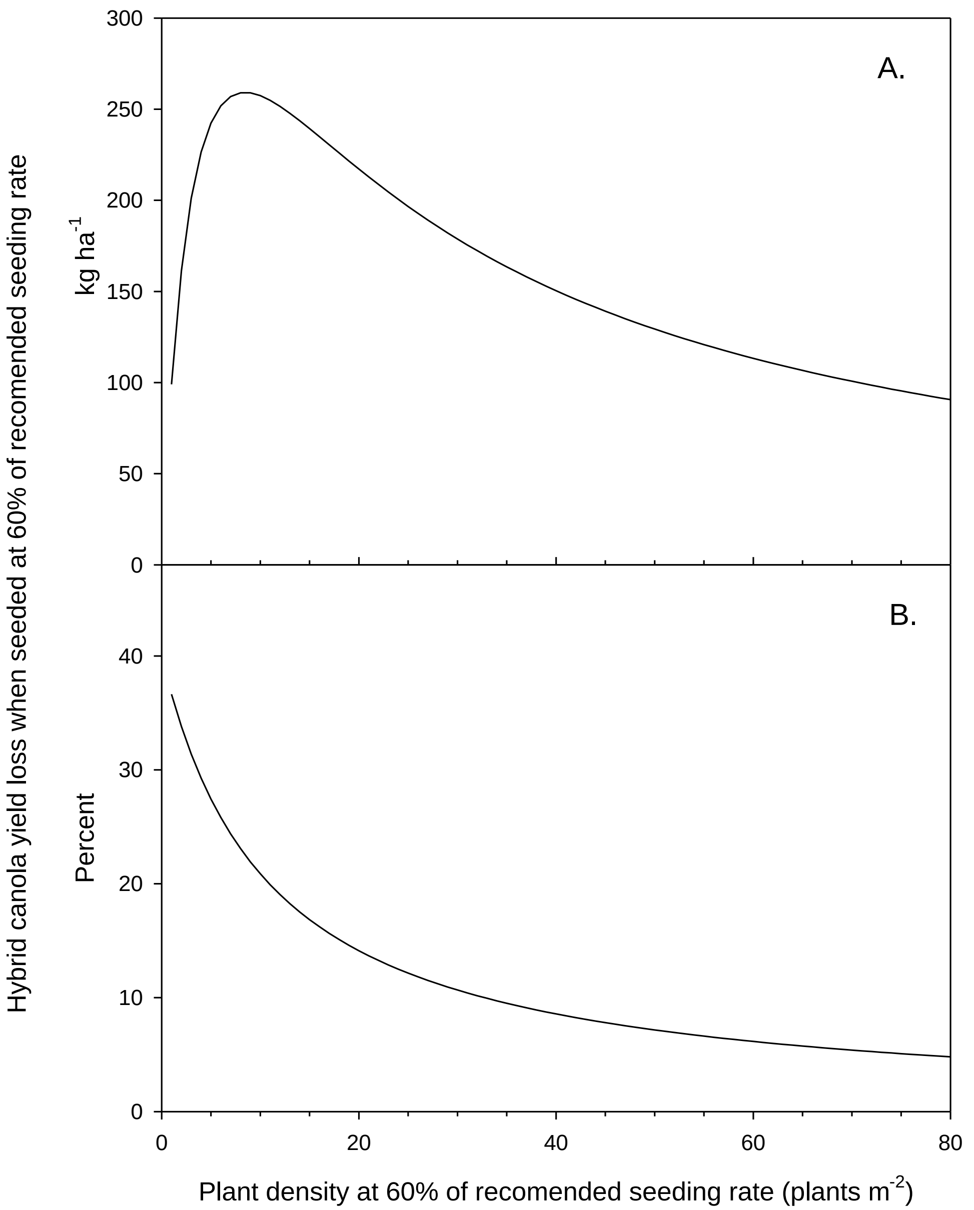

Figure 8. The average yield loss (A.) and percent yield loss (B.) caused by reducing hybrid canola seeding rate to 60% of the recommenced rate as affected by the canola emergence. Values calculated using the regression in Figure 5.

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