Optimizing the production of *Brassica juncea* canola, in comparison with other *Brassica* species, in different soil-climatic zones

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EXECUTIVE SUMMARY

Brassica juncea canola is a relatively new oilseed species that is developed from *Brassica juncea* mustard with its oil and meal quality equivalent to conventional canola species. Some agronomic research projects have been conducted in western Canada in the past, but information on the yield responses to diverse environmental conditions in the different agroecological regions or soil-climatic zones in western Canada is still lacking. Also, nitrogen (N) accounts for the largest energy input in oilseed production, but little is known about how this juncea canola would respond to N fertilization under various growing conditions. Yield potential, response to stress, yield stability, and N input and use efficiency are some of the key issues about this species. Knowing these characteristics will help producers to improve crop adaptability and N use efficiency and thus minimize production costs and environmental impacts. Also, information on the phenological characteristics of this crop under diverse environments will allow the crop to be better adapted to target production areas in western Canada.

The objectives of this project were (i) to determine the responses of the *juncea* canola to various soil-climatic conditions in comparison with *napus* canola, *rapa* canola, *juncea* mustard, and *Sinapis alba* mustard; (ii) to determine N use efficiency and N uptake of *juncea* canola in comparison with *napus* and *rapa* canola species and *alba* and *juncea* mustard under varying soil and climatic conditions with low-, average-, and high-yielding potentials; and (iii) to evaluate the difference in the degree of resistance to seed and pod shattering among five canola/mustard species/cultivars under straight combine versus swathing management regimes. Two field experiments were conducted at four sites (Melfort, Scott, Saskatoon, and Swift Current), in Saskatchewan over the course of 2003-2006 growing seasons. Experiment 1 had two objectives: (1) - Yield potential and response to environmental conditions of *Brissica juncea* canola in different soil-climatic zones; and (2) - Nitrogen use efficiency and N uptake of *juncea* canola under diverse environments. Experiment 2 evaluated five canola/mustard species/cultivars under straight combine versus swathing management for seed shattering.

In Experiment 1, the five oilseed species/cultivars were grown under various N fertilizer rates (0, 25, 50, 100, 150, 200, and 250 kg N ha^{-1}) at four sites from 2003 to 2005. On average, flowering began 40 days after seeding (DAS) for *alba* mustard and *rapa* canola (earliest), 49 DAS for *napus* canola (latest), and 44 DAS for *juncea* canola (intermediate). Flowering duration was longest for *juncea* canola (30 days) and shortest for *napus* canola (22 days). The *napus* canola and *juncea* mustard produced higher (1684 kg ha^{-1}) seed yields than the three other oilseeds (1303 kg ha^{-1} on average). For all oilseed species, the seed yield was highly responsive to N fertilizer rates from zero to about 100 kg N ha^{-1}, and thereafter, the rate of yield responses declined. The amount of N fertilizer required to achieve the maximum seed yield was 106 kg N ha^{-1} for *rapa* canola, 135 kg N ha^{-1} for *alba* mustard and *napus* canola, and 162 kg N ha^{-1} for the two *juncea* spp.

Overall, *juncea* canola had lower seed yield than more popular hybrid *napus* canola, and the yield stability of *juncea* canola was lowest among the five oilseed species when examined across diverse environments. Earlier flowering, longer flowering duration, and greater tolerance to drought stress exhibited by *juncea* canola make the crop best adapted to the drier areas of the northern Great Plains. The improvement of seed yield and yield stability is the key to potentially adapt this new oilseed species to a wider range of environmental conditions.

Nitrogen use efficiency (NUE; defined as seed yield produced per unit of N supply), N fertilizer use efficiency (NFUE; defined as seed yield produced per unit of fertilizer N), and crop N uptake were determined for the five oilseed crops/species. At sites with low soil N supply or low rainfall, *alba* mustard, *juncea* canola, and *rapa* canola had lower NUE and NFUE than *juncea* mustard and *napus* canola. At sites with high soil N supply or rainfall, *napus* canola had the greatest NUE and was the most sensitive to the gradient of productivity among the five oilseeds. All oilseed species responded to N fertilizer rates in a similar manner; both NUE and NFUE decreased as N fertilizer rate increased. The minimum NUE and NFUE were obtained with N fertilizer rate greater than 150 kg N ha^{-1}.

At sites with low soil N supply or rainfall, *alba* mustard had the least NUE or NFUE response to increasing N fertilizer rates and *napus* canola the greatest. At sites with high soil N supply or rainfall, *juncea* mustard had the least NUE and NFUE response to increasing N fertilizer rates and *rapa* canola the greatest. On average, seed N uptake was greatest for *juncea* canola and *juncea* mustard and least for *alba* and *rapa* canola. The five oilseed species had similar response patterns of seed N uptake to N fertilizer rates, while the magnitude of response varied among species. Improving NUE in oilseed production systems requires optimizing rates of N fertilizer which vary depending on environmental conditions, and soil N supply and rainfall during the critical growth period of the oilseed crops play an important role in affecting NUE.

In Experiment 2, under adverse harvesting conditions, all oilseed species/cultivars tested in the study had seed yield losses ranging from 2.4 to 7.7%, which was significantly higher than when harvesting conditions were favourable. Under high shattering conditions, there were large differences in yield loss among species during straight combining. *Brassica juncea* mustard had the greatest seed yield and also had the greatest percent yield loss. *Brassica rapa* canola had the lowest seed yield with lowest percent yield loss. It appears that resistance to shattering is more inherent to oilseed species. To minimize harvest loss of seed yield in crucifer species, one should consider selecting species and cultivars with pods having favourable morphological and physiological traits for pod shattering resistance in combination with the adoption of straight combining practices.

INTRODUCTION

Canola quality *Brassica juncea* is a relatively new oilseed crop that has been developed from *Brassica juncea* mustard (Woods et al., 1991). This crop differs from conventional, condiment (high glucosinolates) mustard, because the quality of the seed oil and meal is equivalent to canola, and thus, the term "*juncea* canola" is used to distinguish these differences. The *juncea* canola seed has low levels of erucic acid and glucosinolates, a moderate level of oleic acid, and produces a product equivalent to that of more commonly-grown *B. napus* and *B. rapa* canola species (Burton et al., 2003).

The advantages of *juncea* canola compared to *napus* and *rapa* canola include more vigorous seedling growth, quicker ground covering, and enhanced resistance to blackleg, a serious disease of canola, caused by *Leptosphaeria maculans* (Desm.) Ces. Et de Not. (Woods et al., 1991; Burton et al., 1999). Other advantages of *juncea* canola over *napus* or *rapa* canola are less seed shattering at maturity, which facilitates direct combine of the crop. In addition, there is potential for higher yields of oil and protein because the seed of *juncea* canola usually has a thinner coat than other canola species. The benefits of growing *juncea* canola have been recognized in the northern Great Plains where this non-genetically modified canola can provide growers with an opportunity to diversify their oilseed production systems (Potts et al., 2003).

In the semiarid regions of the northern Great Plains such as northern Montana, southwestern Saskatchewan, and southeastern Alberta, *napus* or *rapa* canola often suffers from heat and drought stresses during flowering (Miller et al., 2001). These stresses can cause flower abortion (Morrison and Stewart, 2002) and failure to fill developing pods (Gan et al., 2004), which results in decreased seed yield (Angadi et al., 2000). Under stressful environmental conditions, *juncea* canola produces more flowers, resulting in a greater number of seeds per plant than *napus* or *rapa* canola species (Gan et al., 2004). However, there is little information available regarding the relative performance of *juncea* canola in comparison with *napus* canola, *rapa* canola, or condiment mustard species over a wide range of soil-climatic conditions.

Oilseed crops require adequate N supply for maximum productivity (Miller et al., 2001). In the sub-humid environments of western Canada, for example, canola crops responded positively to N fertilizer up to application rates of 180 kg N ha^{-1} (Brandt et al., 2002). Some hybrid cultivars of *napus* canola have a greater response to soil N supply than open-pollinated cultivars under more favorable environments (Brandt et al., 2002; Malhi and Gill, 2004). However, it is unknown whether a similar response can be expected between canola and mustard species in areas with low- and high-yielding potential. Little information is available regarding the yield response of *juncea* canola to nitrogen fertilization. We hypothesized that *juncea* canola would perform better than conventional canola and mustard species under more stressful conditions and that under more favorable growing conditions different canola and mustard species may perform similarly. The objectives of this study were to: 1) understand how *juncea* canola interacts with varying soil and climatic conditions in comparison with commonly-grown canola and mustard species, and 2) determine the effect of N fertilization on plant establishment, start and duration of flowering, seed yield and biomass production among various canola and mustard species under conditions with different yield potentials.

1. OBJECTIVE 1 - YIELD POTENTIAL AND RESPONSE TO ENVIRONMENTAL CONDITIONS OF *BRISSICA JUNCEA* CANOLA IN DIFFERENT SOIL-CLIMATIC ZONES

1.1. Site Description and Experimental Design

Field experiments were conducted at four locations: Melfort, Saskatoon, Scott, and Swift Current, in Saskatchewan, Canada, from 2003 to 2005. Crops at Scott in 2005 were destroyed by hail during late flowering, thus no results from this location-year were obtained. The characteristics of the trial locations, soil types and field conditions are summarized (Table 1). Prior to seeding, residual soil available N, P, and S were determined for each of three depths (0–15, 15–30, and 30–60 cm) at each of the 11 sites (the term ‘site’ refers to location by year combinations and is used throughout the entire text of the paper). Soil samples of 8 to 12 cores were taken from plot areas, and were analyzed for NO_3-N, bicarbonate extractable P, and sulphate-S (Hamm et al., 1970). Soil nutrient concentrations were determined using bulk densities that were previously determined at each site (Table 2).

(Crop management practices made a significant difference in the growth and yield of juncea canola, Swift Current, Saskatchewan, 2005, Photo by Y. Gan).

The five oilseed species examined were *Sinapis alba* yellow mustard (cv. AC Base); *Brassica juncea* canola (cv. Amulet); *Brassica juncea* condiment mustard (cv. Cutlass); *Brassica rapa* canola (cv. Hysyn 110); and *Brassica napus* hybrid canola (cv. InVigor 2663). These cultivars were representative of each species and were popular among growers in the northern Great Plains during the period of this study. The five oilseeds were evaluated in a factorial combination with seven rates of N fertilizer (0, 25, 50, 100, 150, 200, and 250 kg N ha^{-1}) using a randomized complete block design with four replicates. The size of the plot (experimental unit) was between 4.8 and 12 m^{2}, varying among the four experimental locations due to equipment. Plots were seeded between 30 April and 30 May varying among sites, and seeding rates were adjusted for seed size and pre-seed germination of the species/cultivars to target a plant stand of 80 to 100 plants m^{-2}.

Fertilizer N was applied following recommended practices for placement of fertilizer and seed to minimize seedling damage (Malhi and Gill, 2004). At Melfort, ammonium nitrate was incorporated into soil 38 to 40 mm deep using a shallow rotary tillage prior to seeding. The tillage operation was oriented the length of the plots to minimize possible inter-plot movement of fertilizer. Immediately after tillage, plots were seeded 15 to 20 mm deep using a disc press drill with 17.8 cm row spacing. The seeding rows were between the fertilized rows. At the three other locations, no-till management practices were used to seed directly into wheat stubble 15 to 20 mm deep using a hoe press drill with 25.4 cm row spacing. Urea nitrogen fertilizer was mid-row banded to a depth of 38 to 40 mm. Blends of monoammonium phosphate (11-51-0 of N-P-K) or triple superphosphate (0-45-0 of N-P-K) and potassium sulphate (0-0-50-17 of N-P-K-S) were applied at the same time as N fertilizer (Table 2). The amount of N from the blend fertilizer application was accounted in the N rate treatments. Weed control was achieved with a pre-seeding and a pre-emergent burn-off treatment of glyphosate, along with recommended post-emergent sprays of grassy and broadleaf weed herbicides applied following label recommendations.

Table 1. Soil type and description for the field experimental sites in Saskatchewan, Canada, from 2003 to 2005.

Site /Location	Latitude / Longitude	USA soil description	Canadian soil classification	Texture				Organic matter	pH (water paste)
				Class	Sand	Silt	Clay		
					———— % ————				
Melfort (2003)	52° 18N; 104° 30’ W	Mollic Cryoboralf	Dark Gray Luvisol	Silt loam	20	56	26	3.3	7.1
Melfort (2004, 2005)	52° 79 N; 104° 30’ W	Typic Cryoboralf	Gray Luvisol	Loam	40	44	16	3.1	6.6
Saskatoon	52° 09’ N; 106° 32’ W	Typic Boroll	Dark Brown	Clay loam	21	40	39	4.3	7.3
Scott	52° 21’ N; 108° 50’ W	Typic Boroll	Dark Brown	Silt clay loam	31	42	27	4.0	6.0
Swift Current	50° 15’ N; 107° 44’ W	Aridic Haploboroll	Brown	Silt loam	28	49	23	3.0	7.3

Plant population was determined by counting seedlings 10 to 14 days after initial seedling emergence in 2 to 4 one-meter rows (or 0.5-1.0 m^2) per plot. Plant stand was assessed a second time at physiological maturity to determine the rate of plant survival during the period from emergence to maturity. Calendar dates were recorded for the start of flowering (the first flower was visible in a plot), completion of flowering (>95% of flowers had pods in a plot), and physiological maturity (seed moisture content of approximately 20%). Days to first flower, duration of flowering, and duration of maturity were calculated based on the records of calendar dates. Aboveground plant biomass was determined by harvesting one 0.5- to 1.0-m^2 area of each plot at maturity. The plant samples were oven dried at 50 to 70°C for 7 to 10 days, and weighed. Entire plots were swathed or desiccated at physiological maturity with an application of glyphosate at label rates. After 7 to 10 days of drying in the field, the swathed windrows were combined with plot-scale equipment, and seed yields were adjusted to 11% moisture content.

Table 2. Pre-seeding soil tests, N application and seeding operations for field experiments conducted at 11 sites (location by year combinations) in Saskatchewan, Canada, from 2003 to 2005.

Site	Soil test nutrients[†]			Fertilizers applied			N fertilization date	Seeding date
	N	P	S	P	K	S		
	kg ha^{-1}							
Melfort								
2003	30	24	83	30	58	24	May 14	May 23
2004	124	26	38	30	58	24	May 17	May 25
2005	60	33	34	30	58	24	May 16	May 30
Saskatoon								
2003	50	14	45	36	35	11	May 23	May 20
2004	36	24	29	36	35	11	May 27	May 27
2005	20	25	16	36	35	11	May 27	May 27
Scott								
2003	22	71	33	36	35	11	May 21	May 21
2004	17	16	11	36	35	11	May 25	May 25
Swift Current								
2003	17	25	20	25	11	9	May 3	May 3
2004	30	35	30	15	11	9	Apr 30	Apr 30
2005	23	26	34	25	11	9	May 4	May 4

[†] N and S levels were measured from 0-60 cm, and P levels from 0-15 cm soil.

1.2. Statistical Analysis

Data were analyzed using the PROC MIXED model of SAS (SAS Inst., Inc., 1999) where N fertilizer rate and crop type (i.e., various canola and mustard species/cultivars) were designated as fixed effects, and blocks and sites were considered random effects (Littel et al., 1996). In the analysis, N fertilizer rate was considered a continuous variable rather than a class variable. Therefore, all interactive responses of crop types and sites to the various N rates were determined by incorporating the intercept and slope coefficients of linear regressions in the analysis of variance. Variance estimates and P values were used to determine the relative importance of these interactions. The quadratic (N x N) regression coefficients were excluded in variance estimates because exploratory analysis indicated that the quadratic coefficients were too small to be important. With sites designated as random effects, inferences on optimum oilseed crop management could be extended to the other canola and mustard growing regions with similar environmental conditions as those in the northern Great Plains. Treatment effects were declared significant at $P < 0.05$.

Significant responses of the various oilseeds to N fertilizer rates were investigated by regressing seed and straw yield against N fertilizer rates using a segmented quadratic-plateau model as follows:

$$W = \begin{cases} a_0 + a_1\mathrm{N} + c\mathrm{N} & \mathrm{N} \leq \mathrm{N_{join}} \text{ (quadratic part)} \\ plateau & \mathrm{N} \geq \mathrm{N_{join}} \text{ (plateau part)} \end{cases}$$

where W is the yield (kg ha^{-1}), N is fertilizer rates (kg N ha^{-1}), $\mathrm{N_{join}}$ is the join point or the N fertilizer rate at which the *plateau* begins, and *a*, *b*, *c*, and *plateau* are model coefficients. The *plateau* of the regression estimated the maximum yield, and the join point of the regression estimated the N fertilizer rate at which the maximum seed yield was achieved. These non-linear regression coefficients were estimated using the PROC NLMIXED model of SAS (SAS Inst., Inc., 1999). Similar to the linear model described in the previous paragraph, the non-linear regression model variance estimates were determined for site by intercept coefficient and site by linear slope coefficient interactions.

Preliminary analysis revealed that the five oilseed crops did not respond to N fertilizer rates in a similar manner when examined across diverse environments. To further categorize their responses for a given treatment (i.e., crop type) or treatment combination (i.e., crop type x N rate combination), a grouping methodology, as described by Francis and Kannenberg (1978), was used to explore random variability or stability. Means and coefficients of variation (CV) for each crop by N rate combination were estimated across the various levels of yields and N rates. Each yield-related variable was plotted against its corresponding CV, producing a biplot. The biplot, together with the scatter of data points, was used to identify four response categories: Group I: High yield, low variability (optimal); Group II: High yield, high variability; Group III: Low yield, high variability (poor); and Group IV: Low yield, low variability. These biplots give an indication of the relative variability or stability of a crop type across the various environments.

Because of the complex nature of the interactive responses for crop type by various N rate combinations across the 11 diverse environments, more complex analysis was employed to further determine the intensity or magnitude of the variability associated with contrasting environmental sites for each of the five oilseed crops. This was achieved by determining variance estimates for the intercept and linear slope coefficients separately for each crop type or group of crop types. A trial-and-error/elimination process was used to obtain a stable model fit (corrected Akaike's information criterion) that was close to that achieved through linear analysis of variance. Best linear unbiased predictor (BLUP) estimates for the intercept and linear slope coefficients were considered as deviations relative to the overall means of coefficient estimates across sites. The BLUP estimates were outputted for each crop type when there were significant differences between crop types, or the BLUP estimates were outputted for group of crop types when the estimates were similar for more than two crop species/cultivars.

1.3. Results of Experiment 1

The overall performance of the five oilseed crops was assessed by comparing their means of the 11 sites for yield-related variables at 80 kg N ha^{-1}, an N rate typically recommended for oilseed production in the northern Great Plains. Responses to various N fertilizer rates were determined using linear and non-linear regressions for each crop or group of crop types. Yield variability (or stability) across diverse soil-climatic environmental conditions was assessed using biplot methodology, while the interactive effects of crop type by N rate combinations across environments were examined using variance estimates for the intercept and linear slope regression coefficients and their deviations from overall means.

1.3.1. Plant Stand and Development

Seedling emergence and plant survival were greatest for *alba* mustard, followed by *napus* canola, while the three other oilseeds had significantly lower seedling emergence and plant survival (Table 3). Nitrogen fertilizer rate did not affect seedling emergence or the percentage of plants that survived after emergence for any of the oilseed crops.

The date of first flowering varied as follows: *alba* mustard < *juncea* mustard = *rapa* canola < *juncea* canola < *napus* canola. The difference in the time to first flowering was 9 days between the earliest (*alba* mustard) and the latest (*napus* canola) flowering crops (Table 3). The duration of flowering also varied among the oilseeds, with the shortest duration for *napus* (23 d), intermediate for *rapa* canola and the two mustard species (26 d), and the longest for *juncea* canola (30 d). The time to maturity varied by 14 days between the earliest (*rapa* canola) and the latest (*napus* canola) maturing oilseeds. On average, *rapa* canola matured first, mustard species approximately 4 to 6 days later, and *juncea* and *napus* canola 13 to 14 days after the *rapa* canola.

Nitrogen fertilizer rate affected flowering responses and time to maturity, and interacted with the effect of crop types (Table 3). However, the preceding interactions were marginal because additional N fertilizer (i.e., 0 vs. 80 kg N ha^{-1}) delayed the start of flowering and time to maturity by about one day for *napus* canola but it had no effect on the other crop types (data not shown). Increasing rates of N fertilizer shortened the duration of flowering by approximately one day for *alba* mustard, lengthened it approximately one day for *napus* canola, and had no effect on the other crop types. Obviously, the effect of N fertilizer rate on flowering and maturity of oilseed crops was not of practical importance, despite statistical significance in most cases.

Table 3. Summary of analysis of variance and means of yield-related variables for five oilseed crops tested at 11 sites (location by year combinations) in Saskatchewan, Canada, from 2003 to 2005.

	Plant stand		Flowering			Yield		Harvest index
Effect / Level	Emergence	Survival	Start	Duration	Maturity	Seed	Straw	
				Analysis of variance (*P* value)				
Crop type (C)	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**0.022**
N fertilizer rate (N)	0.309	0.788	**0.010**	0.533	0.148	**< 0.001**	**< 0.001**	**0.013**
C x N	0.719	0.296	**0.003**	**0.020**	**0.004**	0.504	0.811	0.077
N x N†	0.336	0.423	0.650	0.177	0.633	**< 0.001**	**< 0.001**	**0.045**
C x N x N	0.595	0.282	**0.004**	**0.005**	**0.042**	0.842	0.770	0.454
				(Variance estimate)‡				
Site x Crop type	22**	25**	2.1**	8.0**	14.5**	54720**	86864**	0.00045**
Site x Intercept	201*	198*	35.9**	56.0*	52.7*	239759*	1393109*	0.00408*
Site x Slope (x 10^4)	—	0	—	—	—	3.9*	11.4*	0
				Means§				
	(%)		(DAS)¶	(days)	(DAS)	(kg ha^{-1})		
AC-Base	76.0	71.8	39.9	26.4	86.3	1230	3477	0.238
Amulet	57.9	54.2	44.3	30.4	94.5	1415	3920	0.244
Cutlass	61.0	54.8	42.5	27.0	88.2	1648	3962	0.269
Hysyn 110	60.3	52.4	41.1	25.6	81.9	1263	3431	0.263
InVigor 2663	69.7	67.4	48.7	23.0	95.7	1720	4584	0.251
LSD$_{0.05}$	5.6	6.9	1.3	3.0	3.4	216	419	0.023

† The quadratic component of the polynomial regression.

‡ The statistical significances of variance component are indicated as follows: '*' = $0.05 \geq P$ value ≥ 0.01; and '**' = P value < 0.01. The site x intercept effect represents variability among sites for intercept. The site x slope effect represents variability among sites for linear slope coefficient, the effect of N fertilizer rate. '—' represents instances where the site x slope effect was omitted because it was small and improved model convergence/fit. '0' variance estimates reflects exceedingly small estimates very close to zero.

§ Crop type means were estimated at an N fertilizer rate of 80 kg N ha^{-1}.

¶ Days after seeding.

Table 4. Variance estimates for yield-related variables for five oilseed crops tested at 11 sites (location by year combinations) in Saskatchewan, Canada, from 2003 to 2005.

	Plant stand		Flowering			Yield		
Effect / Crop type	Emergence	Survival	Start	Duration	Maturity	Seed	Straw	Harvest index
				(Variance estimate)†				
Site x Crop type	—	6	1.8*	1	3*	28370**	34356	0.00024**
Site x Intercept								
AC-Base	218*	294*	33.7*	38*‡	39*‡	115125*‡	613552‡	0.00447*‡
Amulet	147*	125*‡	41.2*	135*	108*	269171*§	1050267*§	0.00589*§
Cutlass	203*	193*	45.0*	48*	68*	282681*	1050267*§	0.00447*‡
Hysyn 110	252*	213*	30.4*‡	38*‡	39*‡	115125*‡	613552‡	0.00447*‡
InVigor 2663	154*	125*‡	30.4*‡	56*	64*	269171*§	2066345*	0.00589*§
Site x Slope								
AC-Base	—	—	—	—	—	2.13*	11.2	0
Amulet	—	—	—	—	—	2.66*	5.6	0
Cutlass	—	—	—	—	—	5.61*	4.4	0
Hysyn 110	—	—	—	—	—	3.18*	5.8	0
InVigor 2663	—	—	—	—	—	8.24*	38.8*	0

† The statistical significances of variance component are indicated as follows: ‘*’ P value ≥ 0.05; and ‘**’ = P value ≥ 0.01. The site x intercept represents variability among sites for intercept. The site x slope effect represents variability among sites for linear slope coefficient, the effect of N fertilizer rate. An attempt was made to fit a variance estimate for each crop type for the site x intercept/slope effect. '—' represents instances where a particular effect was omitted because it was small and improved model convergence fit. '0' variance estimates reflects exceedingly small estimates or close to zero.

‡/§ Crop types that had similar variance estimates were grouped to improve model fit.

1.3.2. Crop Yield

Seed yield differed significantly among the five oilseed crop types, with *napus* canola and *juncea* mustard achieving the highest seed yields (Table 3); both producing about 35% greater yields than the lowest yielding oilseeds, *alba* mustard and *rapa* canola. The seed yield of *juncea* canola was intermediate among the other crops. The differences in straw yield among the five oilseeds followed a similar trend to seed yield, with the exception that straw yield was intermediate for the two *juncea* species (Table 3). The difference between the lowest and highest yielding crop types was 490 kg ha^{-1} for seed yield and 1153 kg ha^{-1} for straw yield. The preceding differences among crop types for seed and straw yields meant that harvest indices were greatest for *juncea* mustard and *rapa* canola, lowest for *alba* mustard and *juncea* canola, and intermediate for *napus* canola (Table 3).

Both seed and straw yield responded to N fertilizer rates in a curvilinear manner, and the responses were consistent among the five oilseed crops (Table 3). Similarly, harvest indices also responded to N fertilizer rates in a curvilinear manner, but only a small change (about 0.01 harvest index units) occurred between N fertilizer rates. The segmented quadratic-plateau model revealed that seed yield increased sharply with increasing N fertilizer rates up to 100 kg ha^{-1} (Fig. 1A). Beyond 100 kg N ha^{-1}, the yield response to fertilizer N rates was generally leveled off or the rate of increase in yield declined. The rate of N fertilizer at 100 kg N ha^{-1} was greater than the current recommendation of 80 kg N ha^{-1} (the vertical dashed line in Fig. 1). The responses of straw yield to N fertilizer rates followed a similar trend as that in seed yield, although sharp increases in straw yield occurred between 0 to 50 kg N ha^{-1} (Fig. 1B). Thereafter, the rate of increase in straw yield was either slowed or declined before the straw yield curves leveled off at about 100 kg N ha^{-1}.

The intercept (*a* value), linear slope (*b* value), and quadratic slope (*c* value) coefficients were used to assess the responses of seed and straw yields to N fertilizer rates for each crop (Fig. 2). The intercept of the regression indicated the minimum yield, which in most cases occurred when no N fertilizer was applied. The join point of the regression estimated the N fertilizer rate at which the maximum seed yield was achieved, while the *plateau* of the regression estimated the maximum yield. There were large differences in the linear and quadratic slope coefficients among the five oilseed species. The *rapa* canola was the most responsive crop to additional N fertilizer (highest *b* value) in terms of seed yield, and the maximum seed yield was achieved most rapidly (reflected by the more negative quadratic slope coefficient) compared to the other crop types. The *rapa* canola and the two *juncea* species achieved maximum straw yield more rapidly than the other crops. The differences in the *b* and *c* slope coefficients resulted in the differences in the join point among the five oilseeds. The join point for seed yield was lowest for *rapa* canola, intermediate for *alba* mustard and *napus* canola, and highest for the two *juncea* species. The join point for straw yield was greatest for the *napus* canola and *alba* mustard among the five crop types.

1.3.3. Variability

The variability of a yield-related variable was assessed using biplots where the mean values were plotted against CVs with each data point being the crop type by N rate combination (Fig. 3). For example, the data point "jm50" means *juncea* mustard at 50 kg N ha^{-1}. For each of the yield-related variables, the biplots categorized variability responses into four groups (i.e., Group I - high yield with low variability; Group II - high yield with high variability; Group III - low yield with high variability; and Group IV - low yield with low variability). The biplots revealed that variability in plant stand was lowest for crops with the greatest percent emergence and plant survival, which were *napus* canola and *alba* mustard (as indicated by data points in Group I). Among crop types, *napus* canola had the latest start of flowering with lowest variability across different growing conditions. Crops with the longest (*juncea* canola) and shortest (*napus* canola) duration of flowering had the greatest variability in flowering. Similarly, crops with the longest duration of maturity had the greatest variability in maturity. The maturity of *juncea* canola was the longest with greatest variability among the five crop species. Despite statistical significance in maturity among crop types, the differences in the variability of maturity were marginal in most cases.

Large variability in seed yield was observed among crop type by N rate combinations (Fig. 3). The lowest yielding treatments, which in most cases were those receiving no N fertilizer, had the greatest variability, and the highest yielding treatments had the lowest variability. The *juncea* mustard had the greatest seed yield with the lowest variability (Group I), while the seed yield of *juncea* canola was highly variable (Group III). The seed yield of *napus* canola was high, similar to *juncea* mustard, but its yield variability was nearly as great as *juncea* canola. The seed yield of *alba* mustard was low with low variability.

There was a clear effect of crop type by N fertilizer rate on straw yield variability (Fig. 3). In general, *napus* canola had the highest straw yields with lowest variability (Group I), along with *juncea* mustard and *juncea* canola under higher N rates. Crops receiving the lowest (0 to 25 kg N ha^{-1}) rates of N fertilizer had the highest variability in straw yield. In general, straw yield variability due to N supply was greater than the variability among crop types. There was a weak association between the values of harvest indices and their corresponding variability. The most prominent trend was that *napus* canola had the lowest variability in harvest index and *alba* mustard the greatest.

1.3.4. Interactive Responses to Environmental Conditions (Sites)

Analysis of variance revealed significant site by crop type and site by intercept coefficient (*a* value) interactions for all the yield-related variables (Table 3). Also, there were significant site by linear slope coefficient (*b* value) interactions for seed and straw yields. Variance estimates indicated that site by intercept interactions for plant stand responses were lowest for *juncea* and *napus* canola and greatest for *alba* mustard (Table 4). For the start of flowering, variance estimates for the site by intercept interactions were similar among crop types. However, for the duration of flowering and time to maturity, the variability for the site by intercept interaction was greatest for *juncea* canola, followed by *juncea* mustard and *napus* canola. For seed yield, variance estimates for site by intercept were greatest for *juncea* and *napus* canola and lowest for *juncea* mustard. Similar differences were apparent for straw yield, with a few exceptions. Variance estimates for the site by slope interaction for seed and straw yields indicated that the responses to N fertilizer rates ≤ 150 kg N ha^{-1} (i.e., within the linear portion of N fertilizer effect) were the most variable for the highest yielding crops, *juncea* mustard and *napus* canola.

Deviations from the means of the 11 sites were determined for the intercept coefficients of linear regressions for seed and straw yields for each crop or group of crops (Fig. 4). Intercept deviations were to examine the difference in the magnitude of variability among the five oilseed crops when no fertilizer N was applied. A more positive or negative value in the deviation of intercept for seed yield represented greater variability in seed yield when no fertilizer N was applied. For seed yield, more negative intercept deviations were found at Melfort in 2003 and 2004 than at other sites, which were probably associated with hot, dry conditions (Table 5). In contrast, at Saskatoon in 2003 and 2005 there were more positive intercept deviations (Fig. 4), possibly due to cooler and wetter conditions than those at Melfort (Table 5). There were significant differences among crop types for intercept deviations for seed yield at Melfort and Saskatoon with the greatest deviations in the highest yielding crops, namely *napus* and *juncea* canola (Fig. 4). Intercept deviations did not differ among crop types at Scott or Swift Current. Straw yield intercept deviations followed a similar trend to seed yield intercept deviations.

Similarly, deviations for the slope coefficients of linear regressions were determined for seed and straw yields for each crop or group of crops (Fig. 4). Slope deviations were to examine the difference in the magnitude of variability among the five oilseed crops in response to various rates of fertilizer N applied. There were large differences in the deviation of slope coefficients for seed yield among sites. The slope coefficient deviation was usually positive in all years at Melfort and at Swift Current in 2004, while they were more negative at Saskatoon and Scott. For the slope coefficient deviation in straw yield, there was no consistent trend among sites, but the sites with positive slope coefficient deviations corresponded to those sites with the least precipitation and greatest residual N (Table 5). In general, more negative slope deviations for seed and straw yield occurred at sites with the greatest precipitation and least residual soil N (Fig. 4). Among the five oilseed species, slope coefficient deviations were most prominent for *napus* canola seed and straw yields and to a lesser extent *juncea* mustard seed yield.

Table 5. Overall productivity and environmental conditions of the 11 experimental sites (location x year combinations) in Saskatchewan, Canada, from 2003 to 2005.

Location / Year	Seed yield	Residual N	Rainfall†	GDD†
	(kg ha^{-1})	(kg N ha^{-1})	(mm)	(□ >5°C)
Melfort				
2003	953	30	118	943
2004	1552	124	170	603
2005	2222	60	175	410
Saskatoon				
2003	2036	50	254	990
2004	1677	36	513	752
2005	2532	20	173	463
Scott				
2003	1139	22	100	849
2004	1287	17	121	698
Swift Current				
2003	1372	17	87	945
2004	1868	30	127	766
2005	1227	23	123	454
Mean	1622	39	178	716

† Averaged across the months of critical growth (June and July).

1.4. Discussion of Experiment 1

In the present study, only one cultivar was selected for each of the five oilseed species, mainly because of the consideration of the size of the experiment. Although the cultivar selected was the best representative for each species, the results from the specific cultivars may not applicable to other cultivars if the traits are substantially different. However, previous studies have shown that the differences between cultivars within a species are always smaller than differences between species (Angadi et al., 2000; Gan et al., 2004). Therefore, in the discussion below, we tended to discuss differences among species.

1.4.1. Plant Establishment

Among the five oilseed species/cultivars tested, *alba* mustard and *napus* canola had significantly greater seedling establishment and plant survival than the three other species/cultivars. The *alba* mustard had largest seed size (5.8 mg seed^{-1}), while the *napus* canola was a hybrid with high seed vigor, both of which have strong influence on seedling establishment (Steppuhn and Raney, 2005). Nitrogen fertilizer rates did not have any effect on seedling emergence or plant survival for any of the oilseed crops in this study. Nitrogen fertilizer was applied using either middle-row banding (at 8 sites) or pre-seeding soil incorporation (at 3 sites); these fertilization practices have been proven to be safe for canola and mustard crops (Malhi and Gill, 2004).

In the present study, the average plant density was 65 plants m^{-2} which was lower than planned target, but it was within the range recommended for optimum plant population of oilseeds in the northern Great Plains (Angadi et al., 2000). Seed and straw yields were poorly associated with either percent seedling emergence, plant survival, or the variability of these factors. For example, the *napus* canola and the *alba* mustard had greatest percent emergence with lowest variability in plant stand, but the *napus* canola produced the highest seed yield while the *alba* mustard the lowest. Canola and mustard species have a strong ability to compensate for low plant density (Degenhardt and Kondra, 1981). The compensatory effect is achieved mainly through production of additional primary and secondary branches (Angadi et al., 2003) and more pods per plant (Kirkland and Johnson, 2000). Due to the strong compensatory effect of canola and mustard, a crop with a plant population of 50 plants m^{-2} can produce similar seed yield per unit area as a crop with a population of 80 plants m^{-2} (Angadi et al., 2003).

1.4.2. Yield and Yield Stability

The *napus* canola and *juncea* mustard produced the highest seed yields with the greatest yield stability (i.e, lowest variability) among the five oilseed species, while the *juncea* canola produced moderate seed yield with the lowest yield stability (i.e., greatest variability) when were tested across various rates of N fertilizer and diverse environments. These results indicate that *juncea* canola can be adapted to some environments but may be challenged when grown under other environmental conditions. In contrast, the *napus* canola and *juncea* mustard can be adapted to more diverse environments. Furthermore, variance estimates revealed that the two highest-yielding oilseed species (*napus* canola and *juncea* mustard) had the most pronounced intercept deviations from the means (indicated by more negative intercept deviations at Melfort and more positive intercept deviations at Saskatoon) relative to other oilseed species. The wide range of intercept deviations indicates that the high-yielding *napus* canola and *juncea* mustard are more sensitive than the other oilseed species/cultivars to conditions where no N fertilizer is applied (note that the intercept of the linear regression to N fertilizer rates was obtained when N rate was zero). This sensitivity was probably influenced by growing season rainfall, heat units, and residual soil N, among other factors.

Coincidently, the *napus* canola and *juncea* mustard had large linear slope coefficients when seed yield was plotted against various rates of N fertilizer. Also, these two high-yielding oilseed species/cultivars had the greatest deviations in the linear slope coefficients when the seed yield responses were assessed across diverse environments. For example, at Melfort and Swift Current, the *napus* canola and *juncea* mustard had more positive slope coefficient deviations while at Saskatoon and Scott, they had more negative slope coefficient deviations than the other species. These results indicate that the high-yielding *napus* canola and *juncea* mustard are the most sensitive of the oilseed species tested to the supply of N fertilizer, and that more pronounced responses to N fertilization can be expected under more favorable growing conditions.

1.4.3. Responses to N Fertilizer

In the present study, the responses of the oilseed species/cultivars to N fertilization was assessed under two scenarios; (i) at the rate typically recommended (80 kg N ha^{-1}), and (ii) at rates increasing from 0 to 250 kg N ha^{-1}. At the typical rate of recommendation, the seed yield of *juncea* canola was similar to that of *alba* mustard; both approximately 300 kg ha^{-1} (18%) less than seed yield produced by *napus* canola. The seed yields of *juncea* canola and *alba* mustard were less responsive than other species/cultivars to various rates of N fertilizer while the *napus* canola had the greatest response in seed yield to increased N fertilization. These results indicate that *juncea* canola is grown with a yield penalty under the typical N recommendation (i.e., 80 kg N ha^{-1}), and that this penalty is not alleviated with an adjustment of the N fertilizer rate. It is unlikely that an improvement of N fertilizer management schemes can help enhance yield potential for *juncea* canola more effectively than for the more popular *napus* canola. Furthermore, our results revealed that the extremes of fertilizer rates (0 vs. 250 kg N ha^{-1}) changed flowering duration and maturity by no more than a few days, suggesting that adjustment of N fertilizer rates is unlikely to be an effective tool to altering phenological differences among the oilseed species.

Overall, seed and straw yield responded to N fertilizer rates in a curvilinear manner for all the oilseed species/cultivars studied. Seed yield increased sharply with increasing N fertilizer rates up to 100 kg ha^{-1}. The rate of increase in seed yield peaked as fertilizer N rates approaching 100 kg ha^{-1}, which was higher than the current recommendation of 80 kg N ha^{-1}. The magnitude of the responses to N rates varied among the species/cultivars. Increasing the supply of N increased the straw yield more prominently than for seed yield in *juncea* canola, as reflected by the lower harvest index (0.244), compared to the high-yielding *juncea* mustard (0.269) or *napus* canola (0.251). More N fertilizer was required to maximize seed yield in *juncea* canola relative to *napus* canola under the same growing conditions. It is speculative that the *juncea* canola has a more structured physiological response to N fertilizer rates compared to a more flexible response in *juncea* mustard and *napus* canola. Structured physiological responses to growth resources limit the ability of crop plants to convert extra photosynthetic biomass associated with additional N fertilization into seed yield (Angadi et al., 2000). In practice, one may expect that the impact of nitrogen application on seed yield will be less for the new oilseed species, *juncea* canola, than for the conventional canola and mustard species, because of less sensitivity of *juncea* canola to addition of N fertilization.

1.4.4. Interactive Responses to Diverse Soil-Climate Conditions

The five oilseed species/cultivars varied in their response to diverse environments encountered in this study. The sensitivity of these responses was partly reflected by large random variance estimates for flowering and maturity among other phenological traits. For example, *juncea* canola flowered four days earlier than *napus* canola and the duration of flowering lasted seven days longer averaged across diverse environments. Earlier flowering increased the likelihood of longer flowering duration, which increased the capacity of *juncea* canola plants to buffer high temperature and drought stresses during the reproductive period. In the northern Great Plains, high temperature and drought stresses often occur during the latter part of the growing season (historical records, McCaig, 1997). Earlier flowering and the longer flowering duration exhibited by the *juncea* canola is probably the key mechanism responsible for high production in the dry areas of the northern Great Plains. Kirkland and Johnson (2000) recognized the promoting early flowering in oilseed crops was one of the key management strategies to avoid hot weather during the reproductive period. However, variance estimates for the duration of flowering and time to maturity were greater for *juncea* canola than for other oilseed species; this partly explained the larger variance in seed yield for the *juncea* canola across diverse environments. In contrast, *napus* canola exhibited a consistent time for the start of flowering and time to maturity across various environments; this also partly explained the consistently higher seed yield of the *napus* canola than other oilseed species/cultivars. Because of the close association among the start of flowering, time to maturity, and the stability of seed yield in oilseed species, one might expect that management of these factors in oilseed species, particularly in *juncea* canola, may have great potential of improving yield potential and stability.

Among the five oilseed species/cultivars tested, the high-yielding *napus* canola and *juncea* mustard were the most sensitive to variation in growing season rainfall, growing degree-days, and residual soil N availability. This was indicated by the larger variance estimates and the greater intercept deviation in seed yield when none to lower rates of N fertilizer (0-25 kg ha^{-1}) were applied. Overall, residual soil N had a more negative effect on straw yield than on seed yield, while growing degree-days had a greater impact on seed yield than on straw yield. The preceding effects were most notable in *juncea* canola. However, there did not appear to be any consistent pattern in the way that the three factors (i.e., growing season rainfall, growing degree-days, and residual soil N) affected the stability of straw or seed yield. Averaged across the 11 diverse environments, the low-yielding oilseed species/cultivars (namely *alba* mustard and *rapa* canola) appeared to have a high degree of yield stability. However, there was subjective evidence presented in the biplots (Figure 3), which indicated that low N fertilizer rates resulted in the low yield stability (i.e., the greatest variability). Therefore, regardless of the oilseed species/cultivars, the application of adequate N fertilizers will help minimize yield variability and reduce production risks.

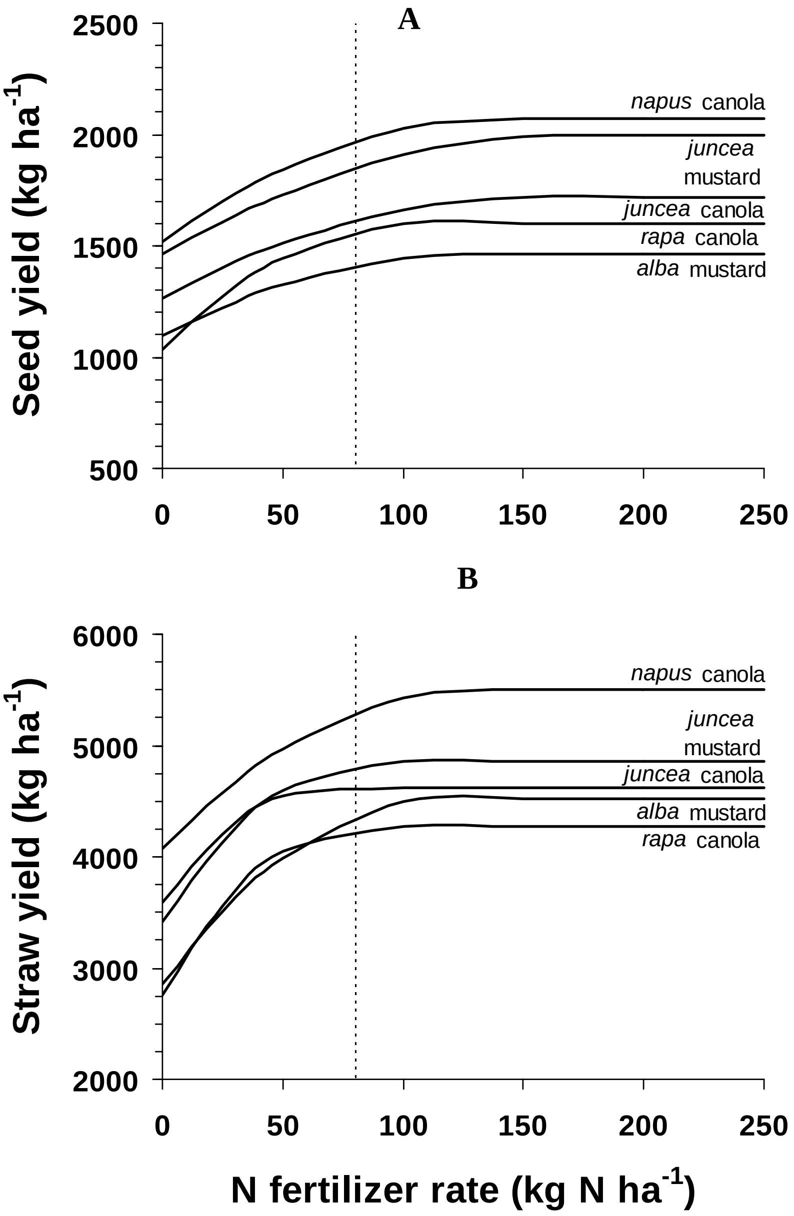


Fig. 1. Non-linear regression output for (A) seed and (B) straw yields produced by *alba* mustard (cv. AC Base), *juncea* canola (cv. Amulet), *juncea* mustard (cv. Cutlass), *rapa* canola (cv. Hysyn 110), and *napus* canola (cv. InVigor 2663). The data were collected from 11 sites (location by year combinations) in Saskatchewan, from 2003 to 2005. The trend lines were derived from predictions associated with the non-linear regression coefficients, and the vertical dash line indicates the recommended rate of N fertilizer (80 kg N ha^{-1}) for oilseed production under normal growing conditions.

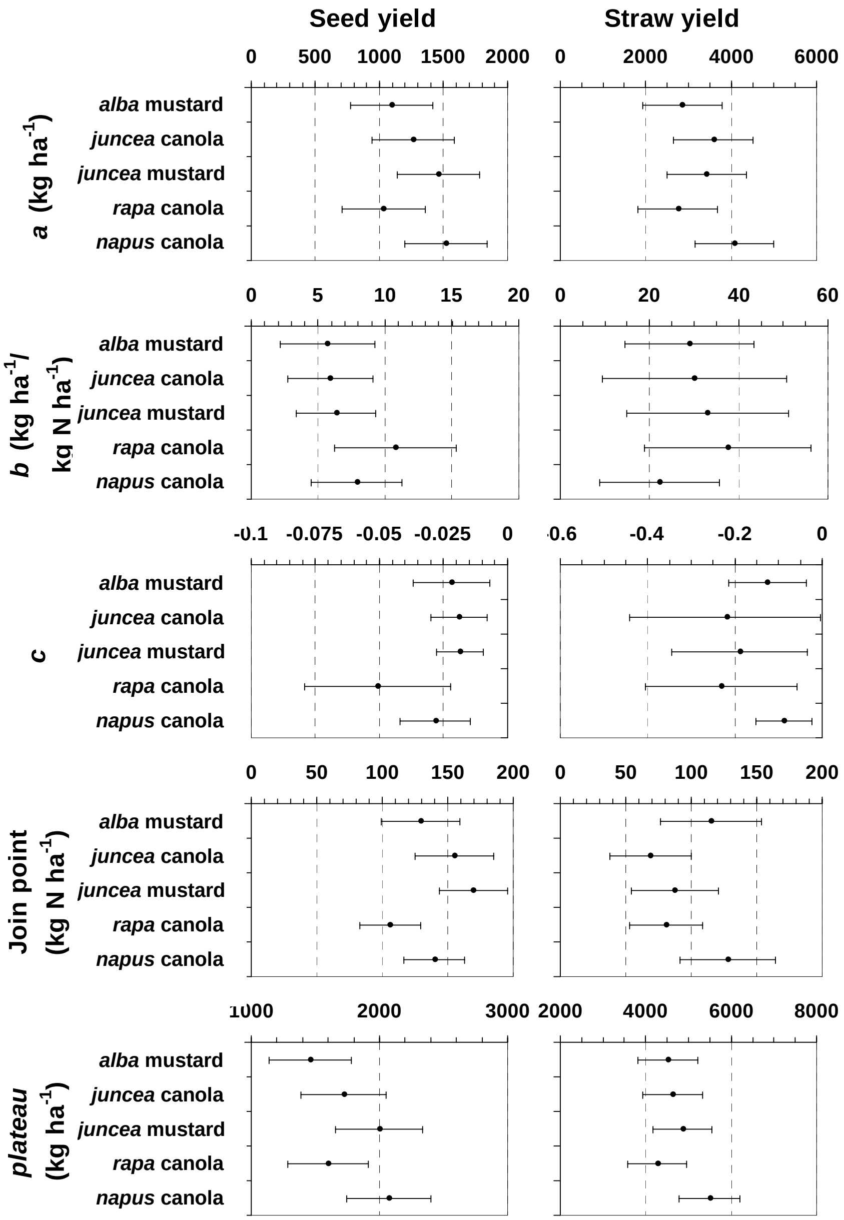
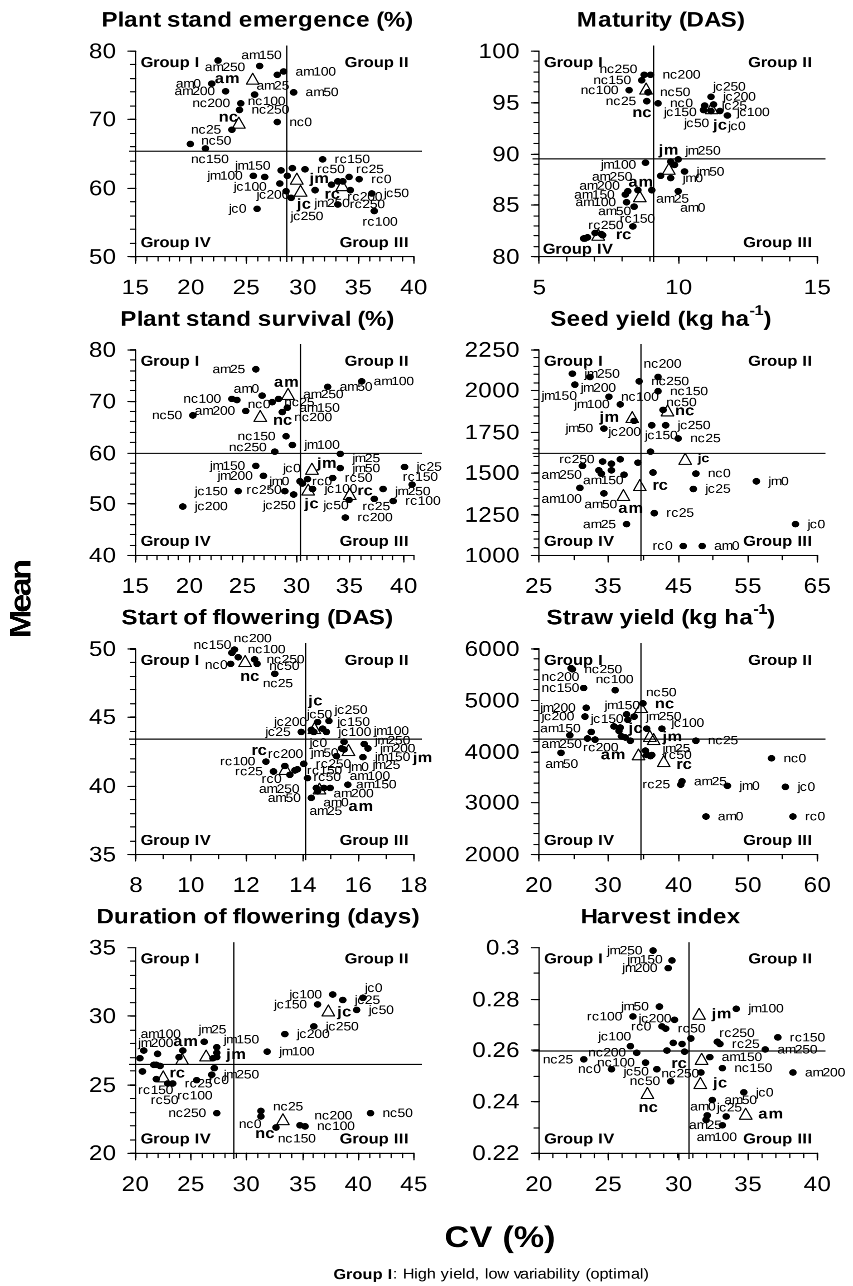


Fig. 2. Summary of the non-linear regression coefficients (*a*: intercept; *b*: linear slope coefficient; *c*: quadratic slope coefficient; join point: N fertilizer rate at which the plateau begins; *plateau*: upper asymptote) for seed and straw yield produced by *alba* mustard (cv. AC Base), *juncea* canola (cv. Amulet), *juncea* mustard (cv. Cutlass), *rapa* canola (cv. Hysyn 110), and *napus* canola (cv. InVigor 2663). The data were collected from 11 sites (location by year combinations) in Saskatchewan, from 2003 to 2005. The horizontal error bars represent confidence intervals for coefficient estimates; error bars that do not overlap are significantly different at ($P < 0.05$).



Group I: High yield, low variability (optimal)
Group II: High yield, high variability
Group III: Low yield, high variability (poor)
Group IV: Low yield, low variability

Fig. 3. Biplot (means vs. CV) of crop type by N fertilizer rate combinations for data collected at 11 sites (location by year combinations) in Saskatchewan, from 2003 to 2005. The first letter of the data point labels indicates crop type (am: *alba* mustard, jc: *juncea* canola, jm: *juncea* mustard, rc: *rapa* canola, and nc: *napus* canola) and the following number indicates the N fertilizer rate. A number closely clustered or clustered near the origin was not labeled. The large open triangle symbols in each graph represent the mean values for each crop averaged across N rates.

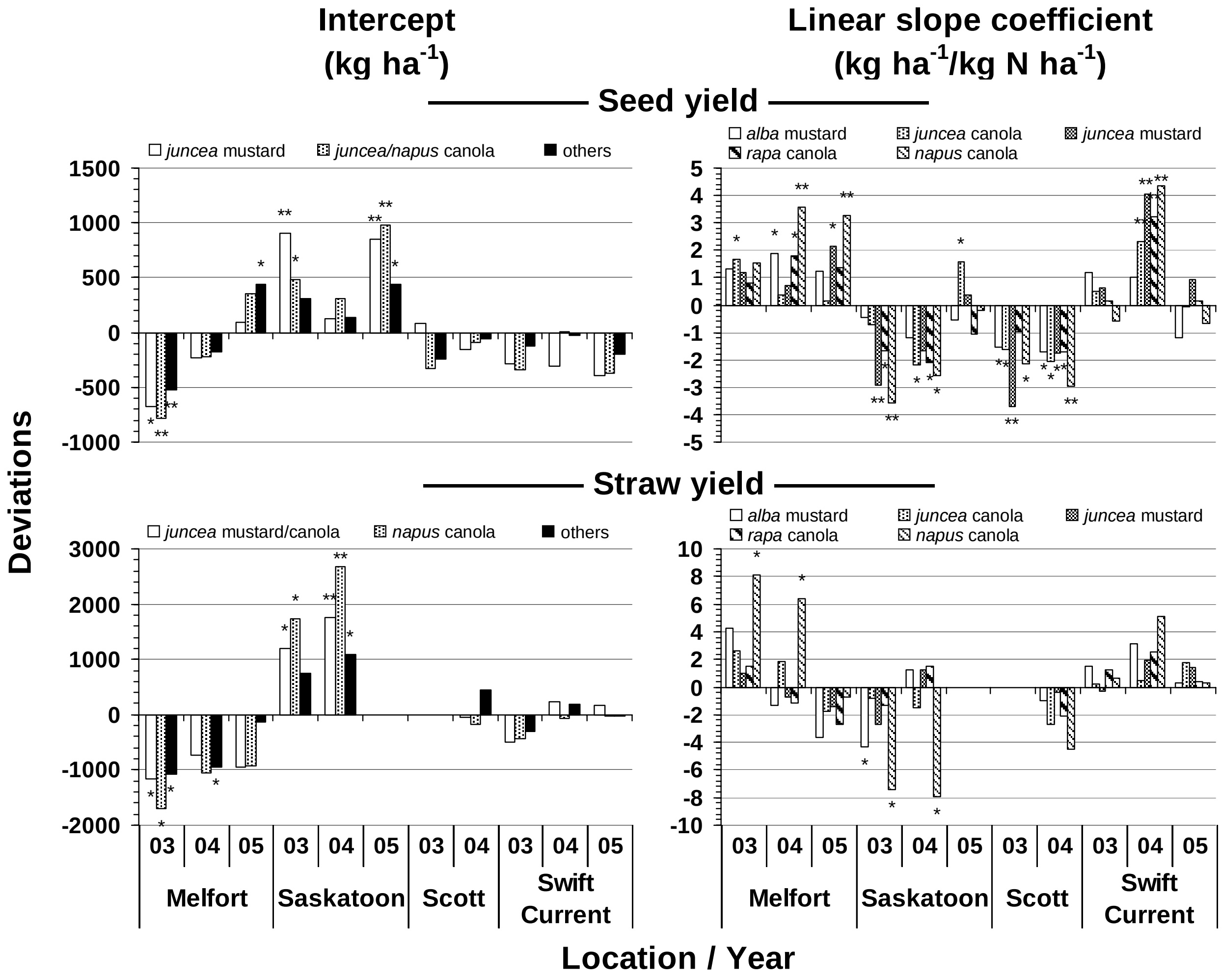


Fig. 4. Best linear unbiased predictor (BLUP) estimates for seed and straw yield deviations of the intercept and linear slope coefficient estimates for each crop type (or crop type group) relative to the overall estimate across sites (location by year combinations). Statistical significance of deviations for each crop type/group at a particular site is indicated as follows: ‘*’ = $0.05 \geq P \geq 0.01$; and ‘**’ = $P < 0.01$.

2. OBJECTIVE 2 - NITROGEN USE EFFICIENCY AND N UPTAKE OF *JUNCEA* CANOLA UNDER DIVERSE ENVIRONMENTS

2.1. Introduction

Brassica oilseed crops respond to N fertilizer positively even when N fertilizer is applied at rates as high as 180 kg N ha^{-1} (Brandt et al., 2002). Amounts of N fertilizer required for maximum yield of oilseed species vary, depending on environmental conditions (Gan et al., 2007). Under environments with low-yielding potential, the N fertilizer required for maximum seed yield was around 160 kg N ha^{-1} for mustard species and 120 kg N ha^{-1} for canola species. As moving to high-yielding environments from the low, the optimum N fertilizer requirement increased by 34 kg N ha^{-1} for mustard species, but stayed the same for hybrid cultivars of *napus* canola. However, information on N responses of *juncea* canola to diverse environments is limited, and little is known about N use efficiency and N uptake of *juncea* canola under various growing conditions.

Nitrogen use efficiency (NUE) may have different definitions (Sowers et al., 1994), but it is commonly defined as seed yield produced per unit of N supplied (Moll et al., 1982). The amount of N supply is quantified as the sum of the N from fertilizer applied (Nf) plus the N uptake of aboveground plant tissues (Nt) in plots with no N fertilizer applied (Limon-Ortega et al., 2000). With this definition, NUE can be used to assess crop management practices that are supposed to affect the amount of residual soil N, mineralized N, and the responses to applied fertilizer N. The NUE typically decreases with progressively greater rates of N fertilizer applied (Fageria and Baligar, 2005). At a level crop plants are approaching physiological inefficiencies of N use, N losses may occur with further increases of N supply (Limon-Ortega et al., 2000). The NUE may interact with crop species and growing conditions. For example, Hocking et al. (2002) demonstrated that extra kg of seed yield obtained from extra N application (relative to unfertilized checks) was greater for mustard than for canola at locations when low rates of N fertilizer were applied. However, this trend of differences between crop species was not shown at locations where high rates of N fertilizer were applied.

In grain cropping systems, N balance is the bookkeeping of N inputs relative to N losses (Racz et al., 1965). Nitrogen losses associated with N exports from harvested grains represent an important component of the N balance (Harbison et al., 1986), and the amount of N exported through grains may vary depending on crop species. For example, N lost through the harvest of *napus* canola was about 34 kg N ha^{-1} (Hocking et al., 2002), whereas it was in the range of 40 (Hocking et al., 2002) to 48 kg N ha^{-1} (Singh and Singh, 1984) for Indian mustard. Greater N removal by Indian mustard was attributable to greater N concentration in the mustard seed compared to *napus* canola. In some cases, the quantity of N lost through grain harvest exceeds the amount of N applied through fertilizer (Hocking et al., 2002), suggesting that N balance in oilseed production is influenced by residual soil N supply.

Nitrogen accounts for the largest energy use and input expenses in oilseed production systems (Zentner et al., 2002). The improvement of NUE is the key strategy for the development of sustainable agricultural systems that allow maximizing productivity with minimum energy inputs and N losses. An understanding of the N use characteristics of *juncea* canola will ensure that this new oilseed species is properly adapted to target production areas. We hypothesized that the N use characteristics of *juncea* canola would be similar to those of more popular *napus* and *rapa* canola as well as *juncea* mustard species. The objective of this study was to determine N use efficiency and N uptake of *juncea* canola in comparison with *napus* and *rapa* canola species and *alba* and *juncea* mustard species under varying soil and climatic conditions with low-, average-, and high-yielding potentials.

2.2. Site Description and Experimental Design

Field experiments were conducted at four Saskatchewan locations: Melfort, Saskatoon, Scott, and Swift Current, from 2003 to 2005. Crops at Scott in 2005 were destroyed by hail during late flowering, thus no results from this location-year were obtained. The characteristics of the experimental locations, soil types and field conditions are summarized in Table 1. Detailed information on the experimental design and crop management practices used in this study has been reported previously (Gan et al., 2007). In brief, five oilseed species, *S. alba* yellow mustard (cv. AC Base); *Brassica juncea* canola (cv. Amulet); *B. juncea* condiment mustard (cv. Cutlass); *B. rapa* canola (cv. Hysyn 110); and *B. napus* hybrid canola (cv. InVigor 2663), were evaluated in a factorial combination with seven rates of N fertilizer (0, 25, 50, 100, 150, 200, and 250 kg N ha^{-1}) using a randomized complete block design with four replicates. Plot size (experimental unit) was between 4.8 and 12 m^2, varying among locations due to equipment. Plots were seeded between 30 April and 30 May varying from year to year, and seeding rates were adjusted for seed size and pre-seed germination of the species/cultivars to target a plant stand of 80 to 100 plants m^{-2}. The amounts of available nutrients in soil were determined (Hamm et al., 1970) before seeding at each location each year (Table 2).

Fertilizer N was applied following recommended practices for placement of fertilizer and seed to minimize seedling damage (Malhi and Gill, 2004). At Melfort, ammonium nitrate was incorporated into soil about 40 mm deep using a shallow rotary tillage before seeding. The tillage operation was oriented the length of the plots to minimize possible inter-plot movement of fertilizer. Immediately after tillage, oilseed crops were seeded 15 to 20 mm deep using a disc press drill with 17.8 cm row spacing. The seeding rows were between the fertilized rows. At the three other locations, no-till management practices were used to seed oilseeds directly into wheat stubble 15 to 20 mm deep using a hoe press drill with 25.4 cm row spacing. Urea N fertilizer was mid-row banded at a depth of about 40 mm. Blends of monoammonium phosphate (11-51-0 of $N-P_2O_5-K_2O$) or triple superphosphate (0-45-0 of $N-P_2O_5-K_2O$) and potassium sulphate (0-0-50-17 of $N-P_2O_5-K_2O-S$) were applied at the same time as N fertilizer. The amount of N from the blend fertilizer application was accounted in the N rate treatments. Other agronomic management practices used in this study have been described previously (Gan et al., 2007).

2.3. Measurements and Calculations

Aboveground plant biomass was harvested from one 0.5 to 1.0 m^2 area per plot at maturity. Plants samples were oven dried at 50 to 70°C for 7 to 10 days and weighed to determine total aboveground dry weight. Entire plots were swathed or desiccated with a preharvest application of glyphosate at label recommendations before being harvested with a plot-scale combine. Seed moisture was near 11% at harvest. Infrared spectroscopy was used to measure total N concentration of seed samples and of straw plus chaff samples. To minimize analytical costs, the total N concentration of each treatment was measured on two sets of subsamples; the first set was assembled by bulking the seed samples from replicates 1 and 2, and the second from replicates 3 and 4.

Nitrogen use efficiency (NUE) was calculated as seed yield (kg seed ha^{-1}) produced per unit of N supply (kg N ha^{-1}), i.e., NUE = seed yield / (Nt + Nf), where Nt equals N derived from soil as determined by N uptake in seed + straw in control plots where zero-N fertilizer was applied, and Nf equals amount of N from fertilizer. The NUE was further partitioned into: (a) N fertilizer use efficiency (NFUE) which was defined as seed yield produced per unit of fertilizer N [(seed yield with applied fertilizer N) – (seed yield in zero-N control)]/ Nf, and (b) N utilization efficiency (NUTE) which was defined as seed yield produced per unit of N derived from soil without fertilizer N (NUTE = seed yield/ Nt). These different determinations of N use characteristics allow better understanding the responses of oilseed crops to various sources of N under diverse environmental conditions.

2.4. Statistical Analysis

Data were analyzed using the PROC MIXED procedure of SAS (Littel et al., 1996) with applied treatments (i.e., crop type, N rates) as fixed effects, and replicates and sites (the term *site* refers to location x year combinations and is used throughout the entire text of the paper) as random effects. With sites designated as random effects, inferences regarding the N management of different oilseed crops can be extended to the other similar areas of canola-mustard growing regions. Because of the complex nature of the interactions between crop, N fertilizer rate, and diverse environments encountered in this study, an extension of the statistical model was used to further explore important site x treatment interactions (Littell et al., 2002). The analysis included three covariables (i) overall mean response for seed yield, (ii) overall mean response for Nt, and (iii) the effect of rainfall during the June–July period. Rainfall during the June-July period was most critical for canola and mustard crops in the northern Great Plains (Angadi et al., 2000; Miller et al., 2001). The weather data were retrieved from Environment Canada weather stations near plot areas at each location. The three covariables were incorporated in the statistical model to determine the effects of crop type, N fertilizer rate, and crop type by N rate interactions. The most ‘informative’ interaction was the one that was: (i) statistically significant, (ii) provided greatest reduction for variance estimate of the site x crop x N rate interaction, and (iii) resulted in an improved model fit (AICC: corrected Akaike’s information model fit criterion) relative to standard analysis of variance. Means were estimated for the treatment effect associated with the ‘informative’ interaction at low (mean seed yield at 1196 kg ha^{-1}), average (1700 kg ha^{-1}), and high (2263 kg ha^{-1}) levels of productivity. Treatment effects and variance estimates were declared significant at $P < 0.05$.

A grouping methodology, as described by Francis and Kannenberg (1978), was used to explore random variability or stability for the responses of a given treatment (i.e., crop type) or treatment combination (i.e., crop type x N rate combination) to diverse environments. Means and coefficients of variation (CV) for each crop x N rate combination were estimated across the various levels of treatment means. Each variable was plotted against its corresponding CVs, producing a biplot. The biplot, together with the scatter of data points, was used to identify four response categories: Group I: high means (i.e., NUE or NFUE) with low variability (optimal); Group II: high means with high variability; Group III: low means with high variability (poor); and Group IV: low means with low variability. These biplots gave an indication of the relative variability or stability of a crop type across various N rates and diverse environments.

2.5. Results of Experiment 2

Straw and seed yields differed significantly among the five oilseed species and the magnitude of the difference was influenced by environmental conditions (Table 6). Also, there were significant linear and quadratic responses of yields to varying rates of N fertilizer for all oilseed species. Detailed results on the yield responses to N fertilizer rates and their variability across diverse environments have been discussed in a previous report (Gan et al., 2007). In the present paper, yield data were used only for determination of N use efficiency and N uptake characteristics as well as variance estimate for treatment and random effects (Table 7).

2.5.1. Nitrogen Use Efficiency

Nitrogen use integrates seed yield responses to different sources of N including available N deriving from soil (Nt, measured as total N uptake in zero-N control), from fertilizer N (Nf), and the sum of soil- plus fertilizer-N (Nt + Nf). Analysis of variance revealed that the oilseed crops had significant ($P < 0.001$) effects on all three N use variables: (i) nitrogen use efficiency [i.e., NUE, seed yield / (Nt + Nf)], (ii) nitrogen fertilizer use efficiency (NFUE, seed yield / Nf), and (iii) nitrogen utilization efficiency (NUTE, seed yield / Nt) (Table 6). Also, N fertilizer rates had significant effects on NUE and NFUE, and the magnitude of the effects varied among crop species and environmental conditions.

Crop Species and Sites

Averaged across 11 sites, the *napus* canola and *juncea* mustard had the greatest NUE, NFUE, and NUTE, the *alba* mustard the lowest, and the *juncea* canola intermediate (Table 6). The difference among crop species in N use characteristics was closely linked to seed yield. At high-yielding sites, all oilseed species had greater NUE and NFUE compared to low-yielding sites. Among the three N use variables, NUTE > NFUE > NUE, and the ranking was similar for all crop species.

There were significant crop species x site interactions for NUE and NFUE (Table 7). The interaction was explored using covariance analysis where yield, Nt, and June-July rainfall were considered as covariables (Table 7). The analysis revealed that at sites with low- to average-yielding potentials, the *alba* mustard, *juncea* canola, and *rapa* canola had a similarly lower NUE than the *juncea* mustard and *napus* canola (Table 8). At sites with high-yielding potential, the *napus* canola had the NUE value that was 5.5 kg ha^{-1} per kg N ha^{-1} greater than the NUE obtained for the *juncea* mustard; both being greater than the three other oilseed species. The hybrid cultivar of the *napus* canola was the most sensitive to the gradient of productivity. The response of NFUE to the gradient of productivity followed a similar trend as the responses of NUE with a few exceptions (data not shown).

N Fertilizer Rate and Sites

Nitrogen fertilizer rates had significant linear and quadratic effects ($P < 0.001$) on NUE and NFUE (Table 8). Therefore, the curvilinear polynomial regression model was used to describe the N use responses of crop species to N fertilizer rates. There were clear trends that the NUE decreased significantly as the rates of N fertilizer increased averaged across crop species (Fig. 5). This effect was interacted with the levels of N deriving from soil (i.e., Nt, Fig. 5A) as well with June-July rainfall (Fig. 5B). The interactive effect was reflected on the decreasing linear and quadratic coefficients in size when Nt increased from low (Nt = 20 kg ha^{-1}) to average (Nt = 64 kg ha^{-1}) and to high (Nt = 180 kg ha^{-1}). These regressions were described as follow:

At sites with low (20 kg ha^{-1}) Nt: $y = 23.8 - 0.162x + 0.0004x^2$; $r^2 = 0.98$
At sites with average (64 kg ha^{-1}) Nt: $y = 20.9 - 0.134x + 0.0003x^2$; $r^2 = 0.98$
At sites with high (180 kg ha^{-1}) Nt: $y = 13.4 - 0.059x + 0.0001x^2$; $r^2 = 0.98$,
where y is NUE, and x is N fertilizer rate.

At a given rate of N fertilizer (for example, at 25 kg N ha^{-1}), oilseed crops had a lower NUE at sites with higher Nt compared with sites with lower Nt.

Similarly, the effect of N fertilizer rates on NUE was interacted with the levels of June–July rainfall (Fig. 5B). The regression responses were described as follow:

At low (100 mm) rainfall sites: $y = 23.8 - 0.166x + 0.0004x^2$; $r^2 = 0.98$
At moderate (178 mm) rainfall sites: $y = 19.2 - 0.115x + 0.0003x^2$; $r^2 = 0.98$
At high (250 mm) rainfall sites $y = 15.0 - 0.068x + 0.0001x^2$; $r^2 = 0.99$, where y is NUE, and x is N fertilizer rate.

The five oilseed species exhibited a similar NUE response pattern to N fertilizer rates, while the magnitude of the responses differed among crop species and were interacted with sites (Fig. 6). At sites with low to average soil N supply or rainfall, the *alba* mustard had the least NUE response to the changes of N fertilizer rates and the *napus* canola the greatest. At sites with high soil N supply or rainfall, the *juncea* mustard had the least response of NUE to the changes of N fertilizer rates and the *rapa* canola the greatest.

Overall, response patterns of NFUE to the changes of N fertilizer rates and their interactions with environmental conditions were similar to the NUE response patterns described above (data not presented). Only difference was that NUE decreased all the way as the N fertilizer rates increased to 250 kg N ha^{-1}, whereas the NFUE decreased as fertilizer N rates increased to near 130 kg ha^{-1}, and thereafter, the NFUE response was leveled off or became slightly more positive. For NUTE, the variance estimate for interaction between crop and N rate was statistically not important and the proportion of variance explained by this interaction relative to the overall variation among sites was relatively low (Table 7).

2.5.2. N Uptake

Correlation analysis showed that total N uptake was highly related to seed and straw yields and total N concentrations (Table 9). Also, the N uptake in seed was closely associated with yields and seed N concentrations. However, seed N uptake was not directly associated with straw N concentration. The magnitude of the associations was interacted with both crop species and N fertilizer rates.

Crop Species Effect

Analysis of variance revealed that there were significant differences among crop species in N uptake and tissue N concentrations (Table 10). The magnitude of the effects varied depending on environmental conditions; as reflected by the variance estimates for the random effect of crop x site interactions ranging between 10 and 30% of the total variation. At low- to average-yielding sites, the *juncea* canola and *rapa* canola had significantly lower seed N uptake than the three other crop species (Table 11). At high-yielding site, the *rapa* canola had the lowest seed N uptake and the *juncea* mustard the highest. Straw N uptake followed a similar trend as seed N uptake with a few exceptions (data not shown). Averaged across the five oilseed species, straw N uptake was 15.8, 33.6, and 45.4 kg N ha^{-1}, respectively, at low-, average-, and high-yielding sites.

N Fertilizer Rate and Site Interaction

The effect of N fertilizer rate on crop N uptake was a linear and quadratic relationship, and the seed N uptake increased with increasing N fertilizer rates for all crop species (Fig. 5). This effect was interacted with soil N supply (graphs on the left in Fig. 5) and with June-July rainfall (graphs on the right in Fig. 6). At sites with low (Nt = 20 kg N ha^{-1}) soil N supply, the maximum seed N uptake was about 60 kg ha^{-1}, and the N uptake had great response to N fertilizer rates. At sites with average (Nt = 64 kg N ha^{-1}) soil N supply, the maximum seed N uptake was about 80 kg ha^{-1}, and the seed N uptake response to N fertilizer rate increased when N fertilizer rates were between 25 and 170 kg N ha^{-1} and thereafter the response pattern was leveled off or declined. At sites with high (Nt = 180 kg N ha^{-1}) soil N supply, the maximum seed N uptake averaged around 120 kg ha^{-1} and the response of seed N uptake to N fertilizer rates varied largely among crop species. Under the high soil N conditions, the *juncea* mustard had the greatest seed N uptake and the *alba* mustard the least. The *juncea* mustard seed N uptake also had the greatest response to increasing N fertilizer rates, while the response patterns for the *alba* mustard, and the *rapa* and *napus* canola were relatively flat. The seed N uptake response of the *juncea* canola to increasing N fertilizer rate increased to about 145 kg ha^{-1}, and thereafter, the response declined sharply as N fertilizer rate further increased.

Similarly, the rainfall by N fertilizer rate interaction for seed N uptake was reflected by the declining linear and quadratic coefficients in size when the rainfall increased from low to high (Fig. 7). All crop species showed similar aforementioned trends at sites with low (100 mm) to average (178 mm) rainfall. However, at sites where there was high rainfall (250 mm), the *rapa* and *napus* canola had the lowest seed N uptake responses to increased N fertilizer rates and the *juncea* mustard the highest. For the *juncea* canola and the *alba* mustard, the response of seed N uptake to the increased N fertilizer increased until N rates approaching 150 kg ha^{-1} and then declined.

2.5.3. Variability

The variability of the N use characteristics was assessed using biplots where the mean values of a variable (i.e., NUE) were plotted against their corresponding CVs with each data point being the crop type by N rate combination (Fig. 8). For example, the data point "jm50" means the *juncea* mustard at 50 kg N ha^{-1}. For each variable, the biplot categorized variability responses into four groups (i.e., Group I - high means with low variability; Group II - high means with high variability; Group III - low means with high variability; and Group IV - low means with low variability). The biplots showed clear trends for the NUE, NUTE, straw N uptake, and total N uptake variables. Increasing NUE mean values increased the variability of NUE, with highest NUE values being coupled with highest variability. The variability of NUE was affected mostly by N fertilizer rates and was less affected by crop species. The highest NUE variability was obtained with those treatments receiving none to low rates of N fertilizer. The pattern of NUTE in variability was similar to the pattern of NUE. Conversely, the biplots showed that increasing mean values in straw N and total N uptake decreased their variability. Crops having the highest N uptake had the lowest variability. However, both NFUE and seed N uptake did not show any trend in variability; all data points scattered all over the four variability groups.

2.6. Discussion

Only one cultivar was selectively used for each of the five oilseed species in the present study; this was mainly due to consideration of the size of the experiment. Also, previous studies have shown that differences between cultivars within a canola or mustard species are always smaller than differences between oilseed species (Angadi et al., 2000; Gan et al., 2004). For example, regardless of choice of cultivars, *alba* mustard always matures about one to two weeks earlier than *juncea* mustard under the same growing conditions in the northern Great Plains. Therefore, in this paper, we tend to discuss differences among the five oilseed species rather than specific cultivars. Additionally, fertilizer application was implemented using conventional tillage at Melfort and no-till systems at all other locations. However, preliminary analysis showed no significant interactions of tillage and treatment effects (data not shown), therefore, the difference in tillage was ignored in all statistical analyses.

The *juncea* canola is developed to have the drought tolerance trait of oriental mustard, yet has seed quality attributes of the *napus* and *rapa* canola (Burton et al., 2003), thus allowing producers in the northern Great Plains more options to produce oilseed with a marketing choice of species. Previous studies have shown that nitrogen fertilizer accounts for the most costly inputs in oilseed production, and the reduction of energy input costs is the key in development of sustainable agriculture (Zentner et al., 2002). Considering the relative greater N demands of oilseed crops relative to crops like spring wheat, it is particularly important to understand differences in N use characteristics and corresponding N fertilizer management for different oilseed species.

2.6.1. Nitrogen Use Efficiency

The results of this study showed that there was a general trend of decreasing NUE with increasing N fertilizer rate for all the five oilseed species studied. This is in agreement with previous findings by others (Hocking et al., 2002; Fageria and Baligar, 2005). Our study also showed that the magnitude of decrease in NUE with increasing rates of N fertilizer was interactively affected by soil N supply aside from fertilization. At any given N fertilizer rate less than 100 kg N ha^{-1}, the NUE was high as soil N supply was low. The preceding effect likely reflects better match of soil N supply with physiological N demand of the oilseed plants. It is also possible that soil N losses via denitrification or alike are minimum when fertilizer N is low and that mineral N pool is smaller (Nyborg et al., 1999).

The magnitude of decrease in NUE with increasing rates of N fertilizer was interactively affected by rainfall during the months of June-July when canola and mustard are in their vigorous vegetative growth and flowering period. At any given N fertilizer rate less than 100 kg N ha^{-1}, the NUE was greater at sites where June-July rainfall was lower compared to sites with more rainfall. The preceding trends were consistent among the five oilseed crops, indicating that N use attributes of oilseed crops are largely influenced by environmental conditions rather than by genotypic or phenotypic differences. June-July rainfall was considered as an environmental covariable in this study, because the variance of analysis revealed that this covariable explained a substantially large portion of the site by N fertilizer rate interaction that reflected on seed yield and NUE. Previous studies have shown that water supply during the period of vigorous vegetative growth and flowering is critical for oilseed production (Morrison and Stewart, 2002; Gan et al., 2004).

There was a general trend of decreasing N fertilizer use efficiency (NFUE) with increasing N fertilizer rate. The NFUE improved more when levels of soil N supply were less than 100 kg N ha^{-1}. The hybrid cultivar of the *napus* canola and the *juncea* mustard had the greatest NFUE responses to N fertilizer rate and were the most sensitive to soil N availability. The genetic make up of these two species may allow more elastic responses to environmental and N fertility conditions than the three other oilseed species. Coincidently, the *napus* hybrid canola and *juncea* mustard were the highest yield producers, leading us speculate that there might be some associations between mechanisms controlling yield and NFUE.

2.6.2. N Uptake

Seed N uptake increased with increasing N fertilizer rate in canola and mustard species in most cases; this is in agreement with previous reports (Malhi and Gill, 2004). Our study also showed that the magnitude of changes in seed N uptake among oilseed species varied with soil N supply and rainfall during the June-July period. The maximum N uptake in seed was lowest (60 kg N ha^{-1}) and its response to applied N fertilizer rate was greatest when soils contained available N less than 20 kg N ha^{-1}. This was probably due to less contribution of N from soil towards N uptake in seed, resulting in greatest response of N uptake to applied N fertilizer at low N soils. On the other hand, in soils with available N of 180 kg N ha^{-1}, the maximum seed N uptake averaged about 120 kg N ha^{-1}. The response of seed N uptake to N fertilizer rates was low, although it varied among oilseed species. This suggests that in soils with high N supply, there will be less contribution of N fertilizer towards N uptake in seed because of greater availability of N from soil to the crop, thus reducing N uptake response to applied N fertilizer.

Under high soil N conditions, the *juncea* mustard had the greatest N uptake in seed and also the greatest response to increasing N fertilizer rates. This indicates that *juncea* mustard is the most efficient oilseed species in making best use of both soil and fertilizer N. For *alba* mustard, *rapa* canola and *napus* canola, the lower N uptake in seed and relatively flat response patterns to N fertilizer rate when soil N supply was high, suggesting that these oilseed species are poor users of N both from soil and fertilizer. For *juncea* canola, seed N uptake and response pattern indicated that this oilseed species is intermediate in using soil and fertilizer N between the *juncea* mustard and the other oilseed species. The order of performance of oilseed species in taking up N and their response to fertilizer N can be generated as *juncea* mustard > *alba* mustard > *napus* canola > *juncea* canola > *rapa* canola under average soil N conditions, and while *napus* canola = *alba* mustard = *juncea* mustard > *juncea* canola = *rapa* canola under low soil N conditions. These results indicated that *rapa* canola was the least efficient user of soil and fertilizer N regardless of soil N supply conditions.

Crop N uptake response to increasing rates of N fertilizer decreased and varied among oilseed species when rainfall during June to July increased from low to high. With a few exceptions, all oilseed species showed similar N uptake response trends at sites with low (100 mm) to average (178 mm) rainfall. Under high rainfall (250 mm) conditions, the *rapa* and *napus* canola had the lowest responses to increasing N fertilizer rates, and the *juncea* mustard the highest. These results indicate that *rapa* canola is the poorest user of soil and fertilizer N regardless of soil moisture conditions and *juncea* mustard is the best or near best user of N from soil and fertilizer under high soil moisture conditions.

A reasonable N balance associated with seed N export during harvest is an important attribute of a sustainable cropping system. A system with an inordinate amount of N exported may create a significant ‘N leak’, which has both long-term economic consequences (Nyborg et al., 1999). Our results showed that the two *juncea* species exported up to 28 kg N ha^{-1} more than conventional canola and mustard species when soil N availability was high. Seed N uptake was highly correlated with seed yield, indicating that the practical implications of resolving N losses associated with oilseed crop harvest will not be easy, especially when seed yield is economic cornerstone of canola and *juncea* production. Genetic enhancement and best crop management to minimize N concentration in oilseed seed may decrease N losses via seed export with minimum yield penalty, particularly for the *juncea* canola and *juncea* mustard. However, this may decrease protein concentration in oilseed meal which is often used for animal feed.

Table 6. Mean yield, N use efficiency, N uptake, and N concentration for five oilseed species/cultivars across 11 sites (location by year combinations) in Saskatchewan, Canada, 2003–2005.

Crop type	Cultivar	Yield		N use characteristics †			N uptake			Total N conc.	
		Straw	Seed	NUE	NFUE	NUTE	Seed	Straw	Total	Seed	Straw
		(kg ha^{-1})		(kg seed ha^{-1} / N ha^{-1})			(kg N ha^{-1})			(g kg^{-1})	
alba mustard	AC-Base	4073	1368	9.9	18.8	26.8	69.6	34.3	104	54.6	9.2
juncea canola	Amulet	4358	1592	11.2	21.9	35.2	63.2	34.6	97	43.0	8.6
juncea mustard	Cutlass	4445	1842	12.8	24.9	39.1	75.0	32.2	106	44.8	8.1
rapa canola	Hysyn 110	3915	1433	12.3	20.1	38.7	52.4	31.7	84	39.5	8.5
napus canola	InVigor 2663	5053	1886	14.2	26.4	42.0	69.1	37.1	106	41.5	7.5
$LSD_{0.05}$		252	102	1.2	2.8	3.9	6.0	3.7	8	0.8	0.7

† Definitions are the same as those described in text.

Table 7. Variance estimates for N use efficiency variables of five oilseed crops at 11 sites (location by year combinations) in Saskatchewan, Canada, 2003–2005.

		Yield			Nt†			June-July rainfall		
Variable / Effect	None	Crop type (C)	N fertilizer rate (N)	C x N	C	N	C x N	C	N	C x N
NUE †										
					(Variance estimate)					
Site (S)	5.20	4.63	4.61	4.63	5.21	5.22	5.25	5.62	5.62	5.64
S x C x N	1.47	0.81	1.73	1.88	1.41	0.96	1.36	1.31	0.87	1.18
					(% total variance) ‡					
S	78	85	73	71	79	84	79	81	87	83
S x C x N	22	15	27	29	21	16	21	19	13	17
					(*P* value)					
Covariable§	—	< 0.01	0.947	0.910	0.278	< 0.01	0.442	0.271	< 0.01	0.361
S	0.109	0.154	0.155	0.155	0.113	0.113	0.113	0.110	0.110	0.110
S x C x N	**0.073**	0.204	**0.049**	**0.050**	**0.082**	0.155	**0.097**	**0.097**	0.177	0.128
NFUE†										
					(Variance estimate)					
Site (S)	45.0	< 0.1	0.3	0.3	18.7	19.5	19.5	42.8	43.2	43.1
S x C x N	56.1	55.1	25.7	25.2	46.5	22.4	22.8	56.7	45.5	49.0
					(*P* value)					
Covariable	—	< 0.01	< 0.01	< 0.01	**0.062**	< 0.01	< 0.01	0.793	< 0.01	< 0.01
S	**0.020**	—	0.425	0.422	**0.075**	**0.066**	**0.067**	**0.026**	**0.025**	**0.026**
S x C x N	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
AICC	8669	8684	8523	8711	6512	6402	6476	8702	8654	8781

† The definitions of NUE and NFUE in text..

‡ The variance estimate for a given effect divided by the sum of the variance estimate.

Table 8. Mean nitrogen use efficiency (NUE) of five oilseed species/cultivars at low-, average-, and high-yielding sites (location by year combinations) in Saskatchewan, 2003–2005.

		NUE at environmental sites with seed yield potentials†		
Species	Cultivar	Low	Average	High
			(kg seed kg^{-1} N ha^{-1})	
alba mustard	AC-Base	12.0	18.7	26.7
juncea canola	Amulet	11.8	21.8	33.8
juncea mustard	Cutlass	16.2	24.9	35.2
rapa canola	Hysyn 110	11.6	20.1	30.1
napus canola	InVigor 2663	14.4	26.4	40.7
LSD (0.05)		1.9	1.2	2.9
Covariable level		1000	1684	2500

† Sites with low, average, and high mean seed yields across all treatments.

Table 9. Correlation coefficients between N uptake and yield and total N concentration for oilseed species grown at 11 sites (location by year combinations) in Saskatchewan, 2003–2005.

	Yield		Total N concentration	
N uptake	Straw	Seed	Straw	Seed
	(correlation coefficient)			
Seed	0.69**	0.66**	0.05	0.32**
Straw	0.60**	0.33*	0.75**	0.47**
Total	0.74**	0.61**	0.34**	0.40**

* and ** indicate statistical significance of correlation coefficients at *P*<0.01 and *P*<0.05, respectively.

Table 10. Variance estimates for N uptake of five oilseed species/cultivars at 11 sites (location by year combinations) in Saskatchewan, 2003–2005.

Variable / Effect	None	Yield			Nt[†]			June-July rainfall		
		Crop type (C)	N fertilizer rate (N)	C x N	C	N	C x N	C	N	C x N
Seed N uptake										
					(Variance estimate)					
Site (S)	796	527	527	527	248	248	248	251	250	250
S x C x N	110	112	109	131	83	93	79	86	100	89
					(% total variance)[‡]					
S	88	82	83	80	75	73	76	74	71	74
S x C x N	12	18	17	20	25	27	24	26	29	26
					(*P* value)[§]					
Covariablex	—	0.283	0.281	0.988	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
S	0.040	0.058	0.058	0.058	0.088	0.088	0.088	0.092	0.092	0.092
S x C x N	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
AICC[¶]	8168	8201	8214	8382	8149	8161	8178	8153	8169	8193
Total N uptake										
					(Variance estimate)					
Site (S)	976	666	666	669	73	73	75	191.5	191.2	196.0
S x C x N	189	195	178	220	156	144	106	159.0	150.0	115.0
					(*P* value)					
Covariable	—	0.313	0.047	0.730	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
S	0.056	0.080	0.080	0.080	0.285	0.284	0.281	0.165	0.165	0.162
S x C x N	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
AICC[¶]	7970	8001	8006	8152	7948	7937	7908	7952	7944	7924

[†] Nt equals N derived from soil as determined by N uptake in seed + straw in the zero-N control plots.

[‡] The variance estimate for a given effect divided by the sum of the variance estimate for effects associated with site and multiplied by 100.

Table 11. Mean seed N uptake of five oilseed species/cultivars at low-, average-, and high-yielding sites (location by year combinations) in Saskatchewan, 2003–2005.

		Seed N uptake at sites with seed yield potentials†		
Species	Cultivar	Low	Average	High
		kg N ha^{-1}		
alba mustard	AC-Base	48	69	125
juncea canola	Amulet	36	62	131
juncea mustard	Cutlass	45	74	149
rapa canola	Hysyn 110	37	52	93
napus canola	InVigor 2663	49	69	119
LSD (0.05)		8	6	15
Covariable level		20	64	180

† Sites with low, average, and high mean seed yields across all treatments.

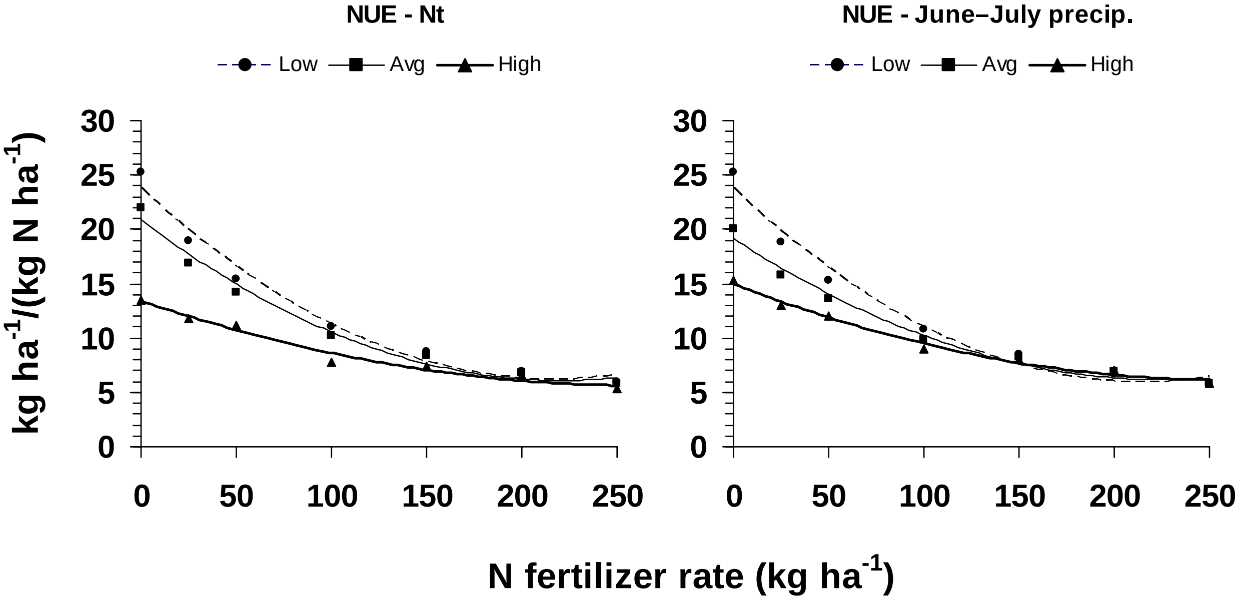


Fig. 5. Polynomial regression trend lines of N use efficiency (NUE = seed yield / (Nt + Nf); where Nt equals N derived from soil as determined by N uptake in seed + straw in zero-N control, and Nf equals amount of N from applied fertilizer) on N fertilizer rates at environmental sites with (A) low, average, and high levels of Nt and (B) low, average, and high June-July rainfall. The unit of yield is in kg seed ha^{-1} and the unit of N supply is in kg N ha^{-1} (this is also applicable to Figs. 2, 3, and 4). The data were averages of five oilseed crops across 11 sites (location x year combinations) in Saskatchewan, Canada, 2003-2005.

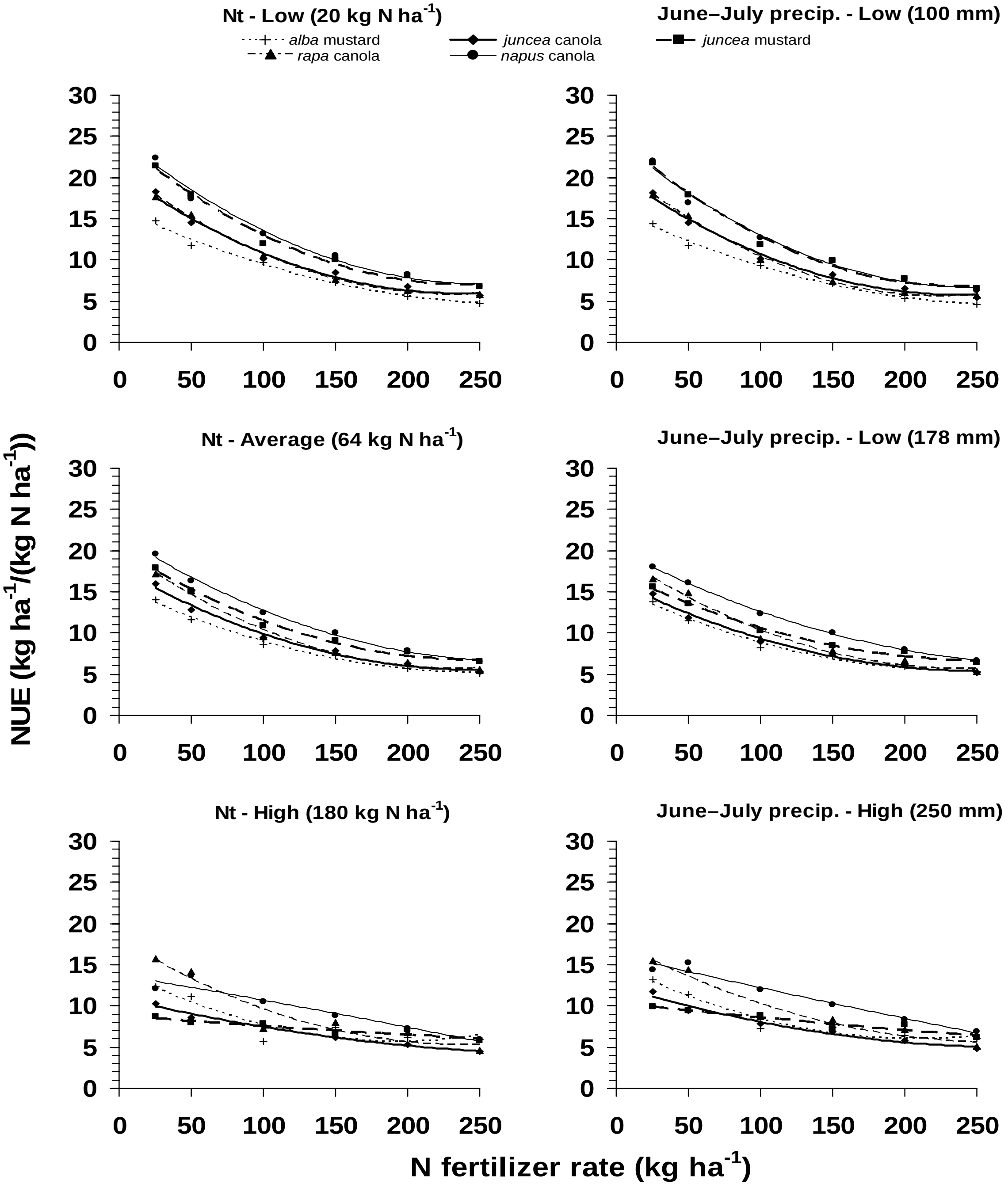


Fig. 6. Polynomial regression trend lines for N use efficiency (NUE = seed yield / (Nt + Nf); where Nt equals N derived from soil as determined by N uptake in seed + straw in zero-N control, and Nf equals amount of N from applied fertilizer) on N fertilizer rates at environmental sites with (A) low, average, and high levels of Nt and (B) low, average, and high June-July rainfall, for the five oilseed crops across 11 sites (location x year combinations) in Saskatchewan, Canada, 2003-2005.

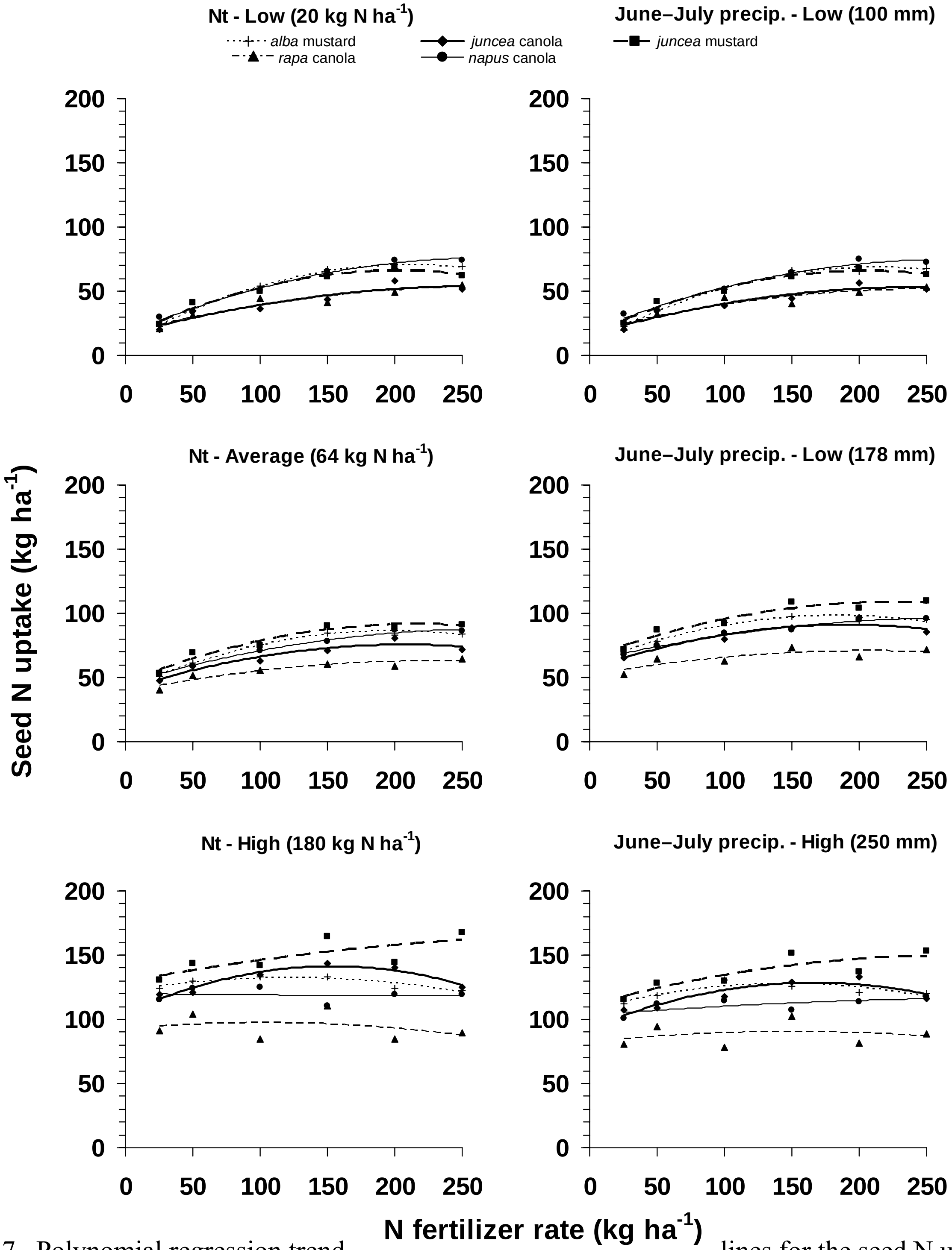


Fig. 7. Polynomial regression trend lines for the seed N uptake variable at sites with low, average-, and high-levels of Nt (graphs on the left) and of June-July rainfall (graphs on the right), for five oilseed crops across 11 sites (location x year combinations) in Saskatchewan, Canada, 2003–2005.

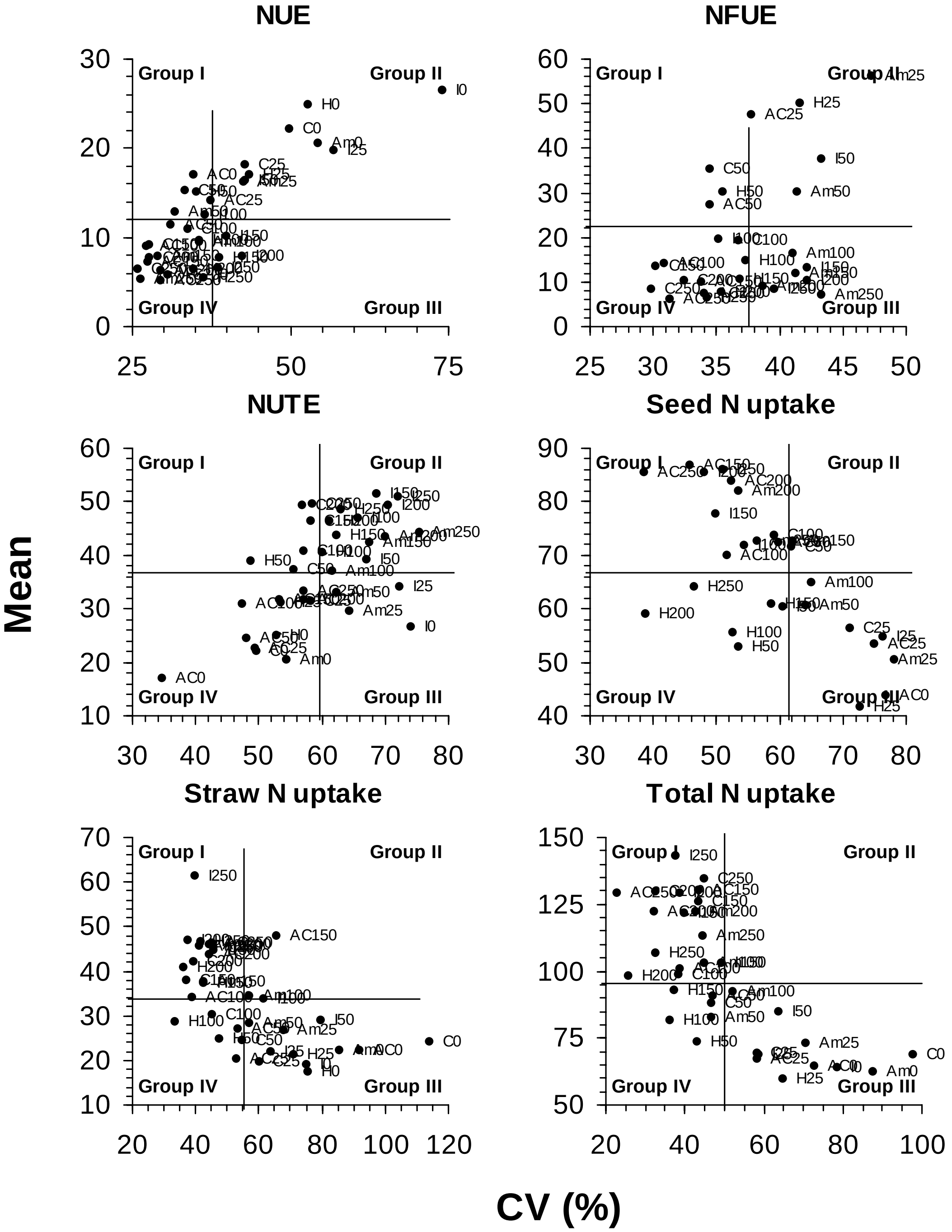


Fig. 8. Biplot (mean vs. CV) for crop species x N fertilizer rate combination treatments for data collected across 11 sites (location x year combinations) in Saskatchewan, Canada, 2003–2005. The letter on the label of the data point indicates crop cultivars (AC = AC-Base *alba* mustard, Am = Amulet *juncea* canola, C = Cultlass *juncea* mustard, H = Hysyn 110 *rapa* canola, and I = InVigor 2633 *napus* canola) and the following number indicates the N fertilizer rate. For example, the data point 'H50' means the cultivar Hysyn 110 at 50 kg N ha^{-1}. A number closely clustered or clustered near the origin were not labeled.

3. OBJECTIVE 3 - STRAIGHT COMBINE VERSUS SWATH HARVEST FOR BRASSICA SPECIES

3.1. Introduction

Seed shattering or pod shed after maturity is a major problem in canola production worldwide and shattering can cause up to 50% yield loss if harvesting is delayed due to adverse conditions (Price et al. 1996). Shed canola seed adds as much as 50 times the normal seeding rate of canola to the soil seed bank (Gulden et al. 2003). Shed seeds persist in the soil giving rise to volunteer plants and increasing weed control problems in subsequent years. Volunteer *Brassica* plants may cause phytotoxic effects on subsequent crops (Vera et al. 1987). Swathing canola before full maturity may reduce yield loss from shattering, but it increases production cost and reduces seed quality due to higher seed chlorophyll content (Vera et al. 2007). On the other hand, if straight combining is delayed and strong winds occur, large seed losses due to shattering may result (Vera et al. 2007). Resistance to pod shattering is variable among crucifer crops like *B. juncea* L., *B. rapa* L., *B. napus* L., and *Sinapis alba* L. (Brown et al. 1997). Screening breeding materials for seed shattering resistance is difficult because pod and seed shattering are characters that are also affected by factors other than genetics such as the degree of pod maturity, timing of pod senescence, and method of harvesting. Little is known about the differences in seed and pod shattering among crucifer species under the environmental conditions of western Canada. The objective of this study was to determine the difference in the degree of resistance to seed and pod shattering among five canola/mustard species/cultivars under straight combine versus swathing management regimes.

3.2. Materials and Methods

Field experiments were conducted at Star City (Gray Luvisol [Cryoboralfs] silt loam soil), Scott (Dark Brown Chernozem [Typic Boroll] silt clay loam soil) and Swift Current (Brown Chernozem [Aridic Boroll] silt loam soil), Saskatchewan from 2004 to 2006. Mean monthly precipitation in the growing season (May-August) in 2004, 2005, 2006 and long-term average, respectively, was 290, 372, 220 and 244 mm at Star City; 200, 306, 190 and 213 at Scott; and 283, 220, 192, and 206 mm at Swift Current.

Five oilseed species/cultivars: *Sinapis alba* yellow mustard 'AC Base', *Brassica juncea* canola 'Amulet', *Brassica juncea* conventional mustard 'Cutlass', *Brassica rapa* canola 'Hysyn 110' and *Brassica napus* hybrid canola 'Invigor 2663' were examined. In this paper, we use terms "alba mustard", "juncea canola", "juncea mustard", "rapa canola" and "napus canola", respectively, for the five species to simplify the presentation. Crops were grown in a randomized complete block design with four replicates with each plot being 8.4 m^2 in size. Oilseed crops were seeded at 20-30 mm depth between 30 April and 20 May at a rate of 240 viable seeds m^{-2} targeting plant stand of 100 plants m^{-2}. Weed control was achieved with a pre-seeding or pre-emergent burn-off treatment of glyphosate, and post-emergent grassy and broadleaf weed herbicides at label recommendations. Fertilizer N was applied at the rate of 100 kg N ha^{-1}, using a shallow rotary tillage prior to seeding at Star City and mid-row banded at Scott and Swift

Current. Triple superphosphate, to supply 16 kg P ha^{-1} at Swift Current and Scott and 30 kg P ha^{-1} at Star City, was applied at the same time as the N fertilizer was applied.

Dates of 1st flower, the end of flowering, and physiological maturity (approximately 20% seed moisture) were recorded. Between the end of flower and harvest, four customized catch trays (15 cm wide, 100 cm long, 15 cm high), were placed between rows at four locations in each plot. A wire screen was mounted 5 cm above the bottom of each tray, allowing the capture of shattered pods and seeds above the screen. Four holes were made on the bottom of the tray, allowing rainwater drainage. At harvest, the trays were removed from plots and taken into the laboratory where number of seeds, number of pods, and weight of seed collected in the trays was determined. Plots were either swathed or desiccated with glyphosate at physiological maturity. Swathed plots were picked up and combined while desiccated plots were straight combined both with a plot scale combine harvester when seed had dried to near 10% seed moisture. The data were analyzed using the PROC GLM procedure of SAS (SAS Institute 1999), where oilseed species was designated as fixed effect and replicate as a random effect. Treatment effects were declared significant at $P < 0.05$. The interaction of location with year was not significant for most variables examined.

3.3. Results and Discussion

Average plant stand was 128 plants m^{-2}, which was higher than the target plant density due to higher than estimated field emergence rate (Table 12), but there was no significant difference in plant stand among the five species/cultivars. Spring seedbed moisture was adequate at all sites, giving rise to excellent plant establishment. Seed yield differed significantly among species/cultivars (Table 12). Napus canola produced highest seed yield (2146 kg ha^{-1}), followed by juncea mustard (1971 kg ha^{-1}). Seed yield of juncea canola and alba mustard was 18% and 28% lower than napus canola, respectively. The rankings of seed yields among the five species/cultivars were similar with swathing and straight-combine harvest regimes. However, in most cases, crops that were straight combined had greater seed yield than crops that were swathed (Table 12). Juncea canola and juncea mustard produced an average of 13.7% greater seed yield when they were straight combined than when swath harvested. Straight combining of rapa canola resulted in 7.0% greater seed yield than swathing, while napus canola did not show difference in yield between the two operation regimes. Alba mustard was straight combined only, as it would be when grown commercially. In commercial production, it is traditionally recommended that both rapa and napus canola be swathed at physiological maturity, and left to dry naturally in the field before combining. The present study showed that swathing may not be better than straight combining, and that straight combining may be adopted in all crucifer oilseed species.

Swathing canola has long been used as a preferred harvest operation (Brown et al. 1999; Vera et al. 2007). Swathing can hasten pod maturity, reduce uneven seed ripening, and minimize seed loss due to premature pod shelling (Brown et al. 1999). Swathing may also help reduce problems associated with green weed undergrowth at harvest (Gulden et al. 2003). However, inappropriate timing of swathing can significantly decrease seed yield (Brown et al. 1999) and seed quality (Vera et al. 2007). Yield loss can be substantial if swathed windrows are exposed to adverse conditions such as excessive precipitation for a long period of time before being combined.

Additionally, early swathing of immature plants may result in chlorophyll retention in the embryo, increasing oil processing costs associated with chlorophyll removal (Bruce et al. 2002).

At site-years where average shattering losses were less that 4 g m^{-2} (low shattering conditions) there were no significant differences among the five species/cultivars in the number of shed pods or shattered seeds, and the overall yield loss was less than 2.5% of the total seed yield (Table 13). Although the seed yield loss was statistically greater for juncea mustard than for alba mustard and rapa canola, the actual seed loss difference was marginal so that it was inconsequential from a practical viewpoint.

Under high shattering conditions (i.e., the overall shattering was greater than 4 g m^{-2}), the differences among species/cultivars were significant in all the shattering-related variables measured (Table 13). Juncea mustard shed near 400 pods m^{-2}, significantly greater than all other species/cultivars. Rapa canola had the lowest number of shed pods. The weight of shattered seeds per unit area followed a similar trend as the number of shed pods, suggesting that either of the two variables can be used for assessing shattering resistance in crucifer crops. Yield loss was greatest for juncea mustard and napus canola; both losing >7% of the total seed yield. Yield loss was lowest for rapa (2.4%) and juncea (3.8%) canola, with alba mustard intermediate (5.2%). Species showing greater pod shattering also had higher seed shatter and yield loss; this suggests that pod shattering is a trait largely controlled by genetic makeup. Additionally, the degree of yield losses due to shattering was also affected by environmental conditions. Dry conditions between physiological maturity and straight combining, coupled with wind movement within crop canopy, resulted in pods breaking off or splitting open and losing seeds readily.

Pod and seed shattering in crucifer species may be related to the morphology of the pods and of the whole plant (Summers et al. 2003). The thickness of the pod wall, length of the pod beak, and the size of pod vascular tissue may influence pod shatter resistance (Child et al. 2003). The degree of these associations depends on their genetic makeup, as pod shattering resistance appears to be related to anatomical (Meakin and Roberts 1990a) and physiological changes (Meakin and Roberts 1990b) that take place in the tissues of the dehiscence zone near maturity, which may differ from one species to another. Species or cultivars with short or thick walls in their pods have lower physical stress in the dehiscence zone (layers of cells separating the replum from the pericarp edge of the two silique valves). The strength of the dehiscence zone reduces the tendency of the pods to split during the progress of maturity (Roberts et al. 2002).

Table 12. Plant density, days to flower and maturity, and seed yield of five species/cultivars that were swathed at physiological maturity versus straight-combined at full maturity in Saskatchewan, 2004-2006

Species/cultivar	Plant density (No. m^{-2})	Days to flower (d)	Days to maturity (d)	Seed yield (kg ha^{-1}) Swathed	Straight combined	Mean [y]	Relative increase in seed yield with straight combining over swathing (%)
AC-Base (Alba mustard)	136.2	44.4	90.7	n/a [z]	1480 [z]	1547	0.0
Amulet (Juncea canola)	120.6	50.4	98.8	1540	1751	1726	13.7 ** [x]
Cutlass (Juncea mustard)	123.4	49.1	92.8	1819	2046	1971	12.5 **
Hysyn (Rapa canola)	124.3	44.8	85.5	1651	1767	1739	7.0 *
I2663 (Napus canola)	135.6	51.1	95.9	2166	2150	2146	-0.7 ns
Mean	128.0	48.0	92.8	1731	1839	1826	6.5 *
LSD (*P* value)	ns	ns	8.6 (0.04)	165 (<0.01)	182 (<0.01)	174 (<0.01)	--

[z] All AC-base were straight-combined, and seed yield for the swathed and straight-combined were averages of four site-years where the two operation regimes were studied in the same tests.

[y] means from seven site-years

[x] single degree of freedom contrast between swathing and straight-combining.

Table 13. Means of shattered pods and seed and the loss of seed yield for five oilseed species/cultivars under low- and high-shattering conditions in Saskatchewan, 2004-2006.

Species/cultivar	Shed pods (No. m^{-2})	Shattered seeds (g m^{-2})	Seed yield loss (g m^{-2})	Percent total seed yield loss (%)
Under low shattering conditions (3 site-years) [z]				
AC-Base (Alba mustard)	107	3.56	4.21	1.40
Amulet (Juncea canola)	110	3.18	4.59	2.25
Cutlass (Juncea mustard)	146	4.75	8.63	1.46
Hysyn (Rapa canola)	104	2.38	3.88	2.21
I2663 (Napus canola)	108	5.03	6.97	1.74
Mean	115	3.79	5.66	1.81
LSD (*P* value)	ns	ns	4.18 (0.04)	ns
Under high shattering conditions (4 site-years) [z]				
AC-Base (Alba mustard)	243	5.89	7.02	5.20
Amulet (Juncea canola)	252	4.50	5.27	3.82
Cutlass (Juncea mustard)	395	6.26	14.16	7.15
Hysyn (Rapa canola)	110	2.73	3.53	2.42
I2663 (Napus canola)	250	8.11	10.03	7.70
Mean	250	5.50	8.00	5.26
LSD (*P* value)	102 (0.03)	3.19 (0.01)	6.62 (<0.01)	1.35 (0.02)

[z] Low- and high-shattering conditions were defined as the site-years where average shattered seeds were below or greater than 4 g m^{-2}, respectively.

CONCLUSIONS

The results of this study indicate that *juncea* canola can be considered as an alternate oilseed crop that is adapted to the semiarid areas of the northern Great Plains where high temperature and drought stresses often limit the productivity of conventional *napus* and *rapa* canola species. It appears that the *juncea* canola cultivars have improved some key phenological traits such as earlier flowering, longer duration of flowering and maturity, and improved drought tolerance during the reproductive growth period. These improved phenological characteristics help improve the adaptation of this new oilseed species to the drought-prone regions of the northern Great Plains.

However, the current cultivars of *juncea* canola do not have the yield potential of the more popular hybrid cultivars of *napus* canola, and the yield stability *juncea* canola is lower than other oilseed species/cultivars when tested across diverse environments. Longer maturity of *juncea* canola crop may be a concern in cooler and short-season areas of the northern Great Plains. Compared to the high-yielding *napus* canola and *juncea* mustard, the seed yield of *juncea* canola had a weaker response to increased rates of N fertilizer, suggesting that N use efficiency of *juncea* canola is low. Further genetic enhancement in conjunction with improved management practices may be able to narrow the gaps in yield potential and N use efficiency between *juncea* canola and *napus* canola. There exist needs to determine if crop management practices such as altering seeding date or adjusting seeding rates would increase seed yield, improve yield stability and N fertilizer use efficiency for *juncea* canola. Further investigation of these factors on *juncea* canola is warranted.

Maximum NUE and NFUE were achieved at N fertilizer rates < 100 kg N ha^{-1}, less than the rates necessary to maximize seed yield which required N fertilizer rates near 130 kg N ha^{-1}. High-yielding hybrid cultivars of *napus* canola and the *juncea* mustard had greater NFUE and N uptake at lower N fertilizer rates (< 50 kg N ha^{-1}) than other oilseed crops, especially under more productive environments. These two oilseed species may be better scavengers of soil and fertilizer N. It was noteworthy that *juncea* canola required more N to achieve optimum seed yield and exported more N via seed harvest especially when soil N availability was high. Therefore, an optimal N fertilizer rate for NUE and seed yield may difficult to reconcile for *juncea* mustard and *juncea* canola species. It may be wise to determine optimal N fertilizer rates for the preceding oilseed crops based largely on economics rather than NUE and N uptake. Additionally, the refinement of N fertilizer management (e.g, split and timing of N applications) may be necessary for *juncea* canola to achieve maximum seed yield while minimizing N losses via seed harvest.

Under adverse harvesting conditions, all oilseed species/cultivars tested in the study had seed yield losses ranging from 2.4 to 7.7%, which was significantly higher than when harvesting conditions were favourable. Under high shattering conditions, there were large differences in yield loss among species during straight combining. *Brassica juncea* mustard had the greatest seed yield and also had the greatest percent yield loss. *Brassica rapa* canola had the lowest seed yield with lowest percent yield loss. It appears that resistance to shattering is more inherent to oilseed species. To minimize harvest loss of seed yield in crucifer species, one should consider selecting species and cultivars with pods having favourable morphological and physiological traits for pod shattering resistance in combination with the adoption of straight combining practices.

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(Field days were held in July each summer where juncea canola was highlighted)

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