Maximizing Yield and Quality of Canola Seed with Optimum Sulphur Fertilizer Management Practices in the Parkland Region of Western Canada

(July 26, 2013)

Sukhdev S. Malhi[1] and Rigas Karamanos[2]

[1]Northeast Agricultural Research Foundation, P. O. Box 1240, Melfort, Saskatchewan S0E 1A0; E-mail: ssmalhica@yahoo.ca (Previous Address: Agriculture and Agri-Food Canada, Research Farm, Melfort, Saskatchewan)

[2]Viterra Calgary, Alberta; E-mail: rigas.karamanos@viterra.com

Canola (*Brassica* oilseed species) is one of the major cash crops in the Prairie Provinces of Canada and most of it is grown in the Parkland region where many soils are deficient or potentially deficient in sulphur (S) for optimum seed yield of canola. Soil texture and organic matter play a role in whether S is typically deficient. Deficiencies of S usually occur on sandy and low organic matter soils. The S deficiency in the Parklands and forest edge of the Canadian prairies occurs most often in Gray and Dark Gray soils, and less frequently in some coarse-textured Black soils. The affected canola plants are stunted, with cupped and reddish leaves; flowers are paler than normal (i.e., whitish yellow as opposed to normal bright yellow) and fail to set seed. The problem usually occurs in patches in fields with insufficient levels of sulphate-S in the soil.

Canola requires high amounts of S, since it is involved in flowering and seed formation. Unlike nitrogen (N), S does not move from older to actively-growing plant parts. If the supply of available S in soil is exhausted prior to pod or seed formation, the resulting yield loss can be devastating. Therefore, canola plants need a constant supply of available S throughout the growing season in order to prevent any seed yield loss due to S deficiency. A number of field experiments were conducted in northeastern Saskatchewan to determine the effects of various rates (0 to 40 kg S ha^{-1}), sources (sulphate S - potassium sulphate, ammonium sulphate, potassium thiosulphate and ammonium thiosulphate; and elemental S – ES 90, ES 95 and RRES [Rapid Release Elemental S, called Vitasul]), times (fall, sowing/seeding, bolting and flowering) and methods (incorporation, sideband, seedrow, topdress and foliar) of S application, N x S fertilizer rate interactions (0 to 150 kg N ha^{-1} and 0 to 30 kg S ha^{-1}), and *Brassica* oilseed species/cultivars on seed yield and quality of canola.

Correcting S Deficiency in Canola in the Growing Season:

Plants feed on sulphate-S, and S deficiency of crops can be prevented by applying sulphate-S fertilizer at seeding time. High yielding cultivars of canola are becoming more popular as their potential for great increases in seed yield is realized. In addition, as producers continue to push up the yields by applying higher rates of N and phosphorus (P) fertilizers, soils are becoming depleted of S and there are more instances of S deficiency on canola in the growing season, even on medium- to fine-textured soils. On soils with mild plant-available S levels at seeding but well fertilized with N and P, the S deficiencies can manifest themselves during peak vegetative growing periods of canola, or later at flowering and seed formation. The S deficiencies at any growth stage can drastically reduce canola seed yield; devastating to the producers.

With little previous research on how to restore high canola yields when S deficiency appears in the growing season, a 3-year study was conducted from 1998 to 2000 to determine the extent to which high canola yields in these situations can be restored. The study focused on the effects of different rates and application methods of sulphate-S fertilizer (potassium sulphate) at various growth stages (seeding, bolting and flowering) of canola grown on S-deficient soils at six locations in northeastern Saskatchewan. The rates of S were 15 and 30 kg S ha^{-1}. Methods of S application were broadcast and incorporated, sidebanded, applied in the seedrow at seeding, and topdressed granular or foliar spray at bolting and flowering.

In all of the six field experiments on soils deficient in both S and N, there was a marked seed yield increase from N and S fertilization. On the other hand, there was a reduction in seed yield in the N alone treatment compared to no fertilizer treatment. On average of six sites, there was a good seed yield response of canola to potassium sulphate at the bolting stage (Table 1), when used as a rescue treatment if S deficiency symptoms show up at this growth stage. There was also correction of S deficiency in canola and moderate restoration of seed yield with potassium sulphate application at early flowering.

Seed yield increase was lower when S fertilizer was applied at flowering compared to that obtained at bolting or seeding. Applications of S fertilizer at seeding gave the greatest increase in seed yield. Foliar application of S was slightly more effective than topdressing in restoring seed yield in S-deficient canola. The findings also suggest that the efficacy of topdressed S fertilizer is dependent on the amount of rainfall after topdress application to move the S fertilizer into the subsoil where roots can intercept it. Application of S fertilizer also increased oil content in canola seed.

In summary, the findings of this study demonstrated that S deficiency on canola can be corrected and seed yield increased with application of potassium sulphate S fertilizer in the growing season, substantially until bolting stage and moderately until early flowering stage. The ideal time for S fertilization is at seeding, but growers should consider applying sulphate-S fertilizer if S deficiencies appear in canola in the growing season.

Table 1. Relative effectiveness of sulphate-S fertilizer, along with 120 kg N ha^{-1} at seeding, applied at different growth stages on the increase in seed yield of canola (average of six sites)

	Seed yield increase (kg ha^{-1}) from applied sulphate-S at rates (kg S ha^{-1})	
Fertilizer treatment	15	30
N + Pre-seedingIncorporated S	934	1088
N + Sidebanded S at Seeding	924	1068
N + Seedrow-Placed S	943	916
N + Topdressed S at Bolting	683	797
N + FoliarApplied S at Bolting	770	862
N + Topdressed S at Flowering	506	626
N + Foliar Applied S at Flowering	648	673

Note: Mean seed yield of canola was 406 kg ha^{-1} in plots receiving no fertilizer, and was 140 kg ha^{-1} in plots receiving only N fertilizer.
Source: Malhi and Gill 2002.

Maximize Canola Seed Yield with Proper/Balance N and S Fertility:
Balance between N and S fertilization is critical for optimum canola yield and seed quality on S-deficient soils. Crop requirements for S and N are closely linked because both are used for

protein and chlorophyll synthesis. Canola has higher S requirement than cereals, because canola has higher protein content and a higher proportion of the amino acids cysteine and methionine. Sulfur enhances the utilization of N, and high oilseed and protein crops require more S. On mild S-deficient soils in the Parkland zone, application of high rates of N and other fertilizers results in faster depletion of S in soil and increases instances of S deficiencies in canola during the growing season. This can cause substantial reduction in seed yield, apparently due to N:S imbalance in canola.

Field experiments were conducted in 1999 and 2000 on soils deficient in both S and N in northeastern Saskatchewan to determine proper fertilizer N:S combinations using four rates of N (0, 50 100 and 150 kg N ha^{-1}) and S (0, 10, 20 and 30 kg S ha^{-1}) for optimum seed yield and quality of canola. In the zero-S treatments, canola exhibited S deficiency in the growing season and S deficiency became more severe at higher rates of N (visual observations), and reduced seed yield when N was applied without S (Table 2, Figure 1). In the absence of N fertilization, however, generally there was a positive seed yield response to S application. This indicated that S was a greater limitation for seed yield than N. In the S treatments, seed yields of canola increased with increasing N rate but maximum yields were attained when rate of S was also increased to 20 or 30 kg S ha^{-1}. For example, maximum seed yield was obtained at 50 to 100 kg N ha^{-1} with 10 kg S ha^{-1} rate and at 100 to 150 kg N ha^{-1} with 20 or 30 kg S ha^{-1} rate. Also, when N rate was increased from 100 to 150 kg N ha^{-1}, seed yield declined at the 10 kg S ha^{-1} rate, but not at the 20 and 30 kg S ha^{-1} rates. These observations show that seed yield responded to higher N rate when S was applied, and up to 20 kg S ha^{-1} benefitted canola seed yield with the N rates of 100 to 150 kg N ha^{-1}. The results suggest that when high rates of N application are used on S-deficient soils to attain high canola seed yield, it is necessary to also increase the rate of S application to meet the S requirements of the crop.

Overall, the use of S fertilizer was critical to achieve any response to N fertilization. In summary, the results suggest that for higher N application rates, there is a need of increased fertilizer S to adequately meet the S requirements of canola for optimum seed yield. Growers who find that their high-yield cultivars are not responding to high rates of N should look deeper into their fertility program and consider balancing N:S applications.

Table 2. Seed yield of canola with different rates of N and S in northeastern Saskatchewan average of four experiments)

Rate of N (kg ha^{-1})	Seed yield (kg ha^{-1}) at four S rates (kg S ha^{-1})			
	0	10	20	30
0	464	612	657	652
50	256	886	969	1025
100	107	904	1202	1286
150	47	741	1289	1313

Source: Malhi and Gill 2007.

Oil concentration declined as N rate was increased, with a steeper decline at a lower rate of S application and the effect of S application to counteract the decrease in oil concentration from increasing N rate was relatively more pronounced at higher N rates (Figure 2). When N rate was increased from 0 to 150 kg N ha^{-1}, the average oil concentration was decreased by 70, 48, 29, and 22 g kg^{-1} at 0, 10, 20, and 30 kg S ha^{-1}, respectively. Probably high N rates delay oil concentration due to an extended phase of pod development, and later ripening seed may fail to reach full maturity and so have lower oil concentration. Thus, an adequate level of S is critical to maximize oil concentration in canola seed.

Protein concentration increased with N rate and attained a maximum at 100 to 150 kg N ha^{-1} in most cases (Figure 3). When S was applied, the protein concentration showed little change at the 50 kg N ha^{-1} rate, but showed a much higher change at higher N levels. This was apparently due to the dilution of protein concentration with higher seed yield as a result of S fertilization. The relatively smaller effect of S than N on protein concentration was probably because N mainly affects protein concentration while S affects protein composition. In conclusion, S fertilization was critical to avoid negative effects from N fertilization and to obtain a positive response of canola from N fertilization on S-deficient soils, especially for seed yield and oil concentration.

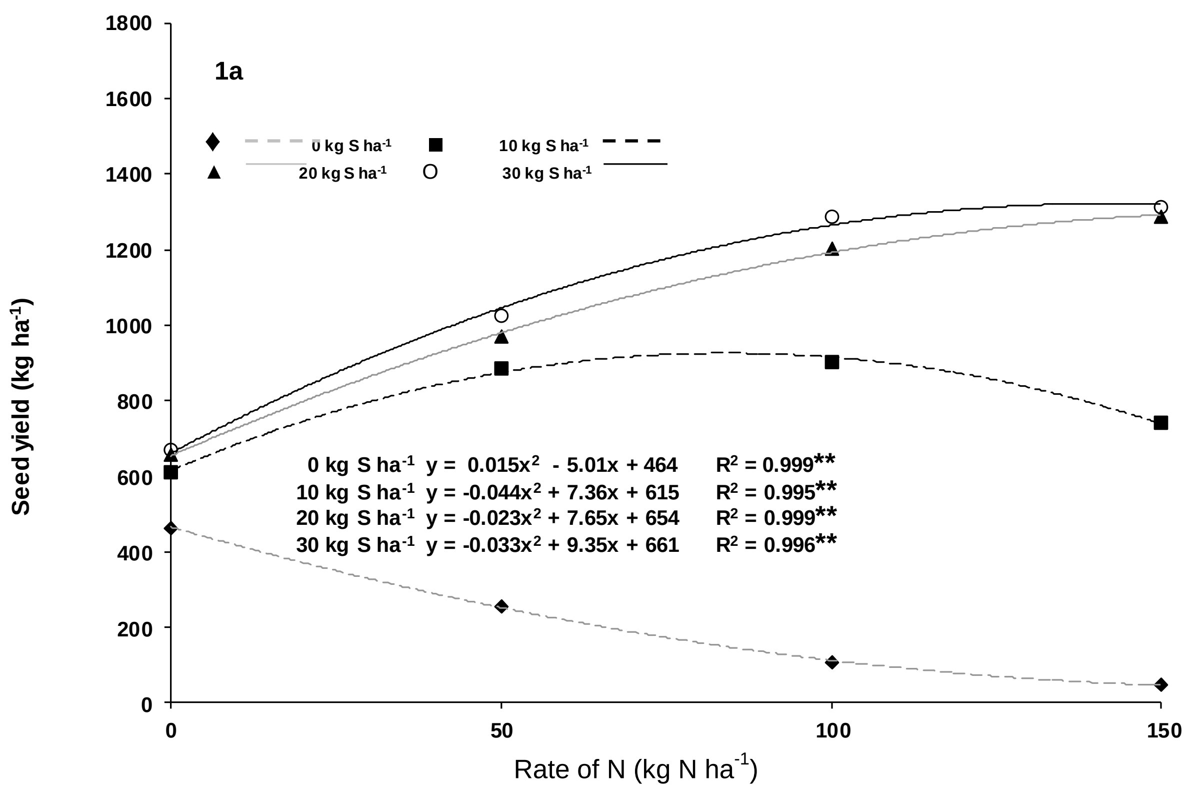

Figure 1. Seed yield of canola at different N rates as influenced by S rate, averaged for the four site-years. Source: Malhi and Gill 2007.

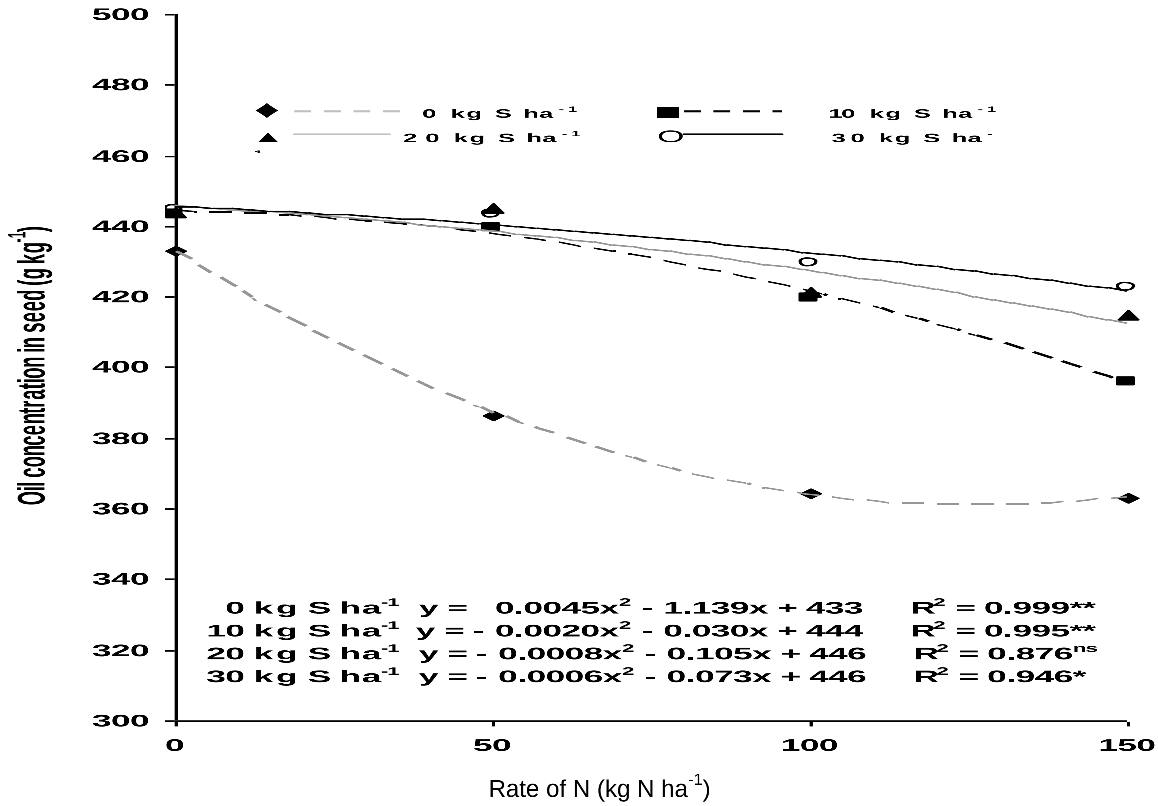

Figure 2. Oil concentration in seed of canola at different N rates as influenced by S rate, averaged for the four site-years. Source: Malhi and Gill 2007.

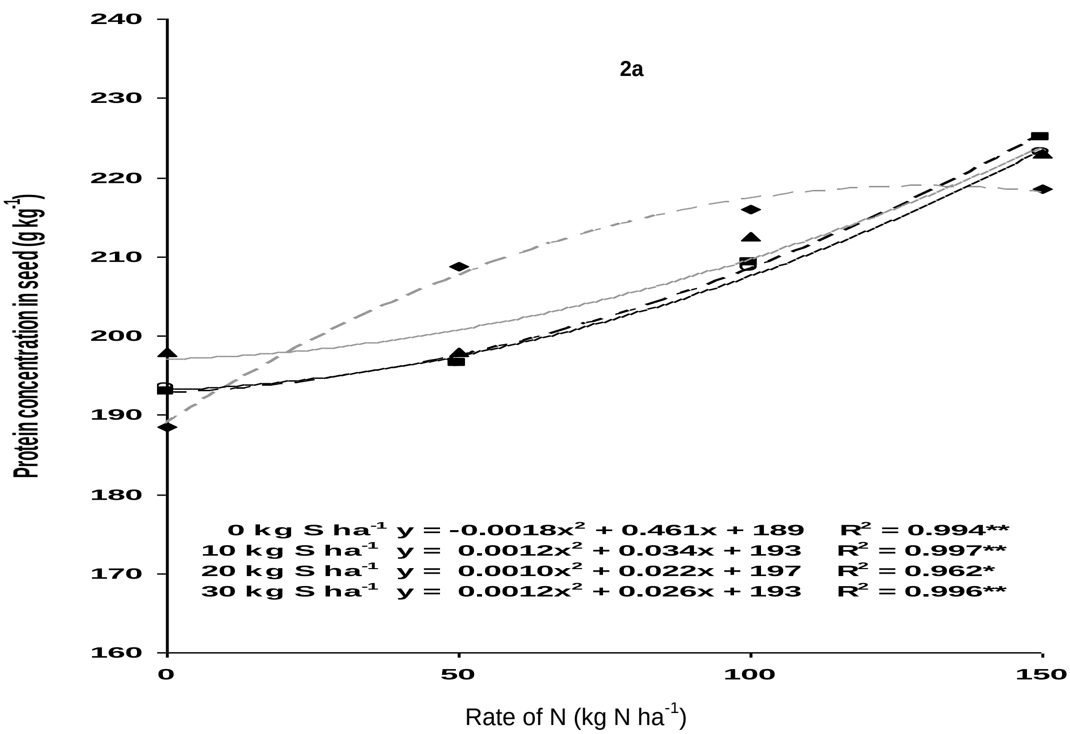

Figure 3. Protein concentration in seed of canola at different N rates as influenced by S rate, averaged for the four site-years. Source: Malhi and Gill 2007.

Sensitivity to S Deficiency and Seed Yield Response to Applied S of Canola Cultivars:
In recent years, many farmers in the Parkland zone have experienced substantial loss in seed yield due to severe S deficiency, particularly at flowering and pod formation. Canola has high requirements for S which may vary with cultivars depending on the differences in growth rate, yield potential, rooting system and genetics. The use of high yielding canola cultivars with high inputs of N and other fertilizers can increase instances of S deficiency in the growing season due to faster depletion of S in soil.

Field experiments were conducted in 1999 and 2000 on S-deficient Gray-Wooded soils in northeastern Saskatchewan to determine differences in the response of some selected canola cultivars (Quantum, AC Excel, Maverick and AC Parkland) to S deficiency and to S fertilizer in relation to seed yield. In the zero-S treatment, some cultivars showed S deficiency more severe than others, and seed yields without and with applied S varied with cultivars (Table 3). In the zero-S treatment, mean seed yield of three experiments was highest with AC Excel and lowest with AC Parkland. In the S-fertilized plots, Quantum produced the highest seed yield, which was closely followed by AC Excel, then Maverick and with the least yield from AC Parkland. In summary, in spite of the differences in actual seed yield without applied S and magnitude of the seed yield response of tested canola cultivars to S fertilization, the similar nature of the response and optimal seed yield at the same S rate indicated that specific S fertilization recommendations for individual canola cultivars are unnecessary.

Table 3. Seed yield of four canola cultivars with different rates of applied S along with 120 kg N ha^{-1} in northeastern Saskatchewan (average of three experiments)

	Rate of S (kg S ha^{-1})			
Cultivar	0	5	10	15
Quantum	329	937	1197	1167
AC Excel	479	722	952	1016
Maverick	332	474	653	711
AC Parkland	169	342	523	570

Source: Malhi and Gill 2006.

Brassica Oilseed Crops Differ in Response to Sulphur Fertilization:
Field experiments were conducted over three years (2003 to 2005) in a combination of four Brassica oilseed crops and five rates of potassium sulfate fertilizer with 0, 10, 20, 30, and 40 kg S ha^{-1}. Cultivars of four *Brassica* oilseed species were: Arid and Amulet for *B. juncea* canola, Cutlass for *B. juncea* mustard and InVigor 2663 for *B. napus* hybrid canola. All *Brassica* oilseed species/cultivars responded positively for seed yield and most other parameters (oil and protein concentration, and total S uptake) to S fertilizer in all three years, but the magnitude of response varied (Figure 4). The findings suggest that S fertilizer application rates for optimum seed yield should be similar for the Brassica species used in this study on S-deficient soil, but higher yielding types would produce greater seed yield by using S more efficiently.

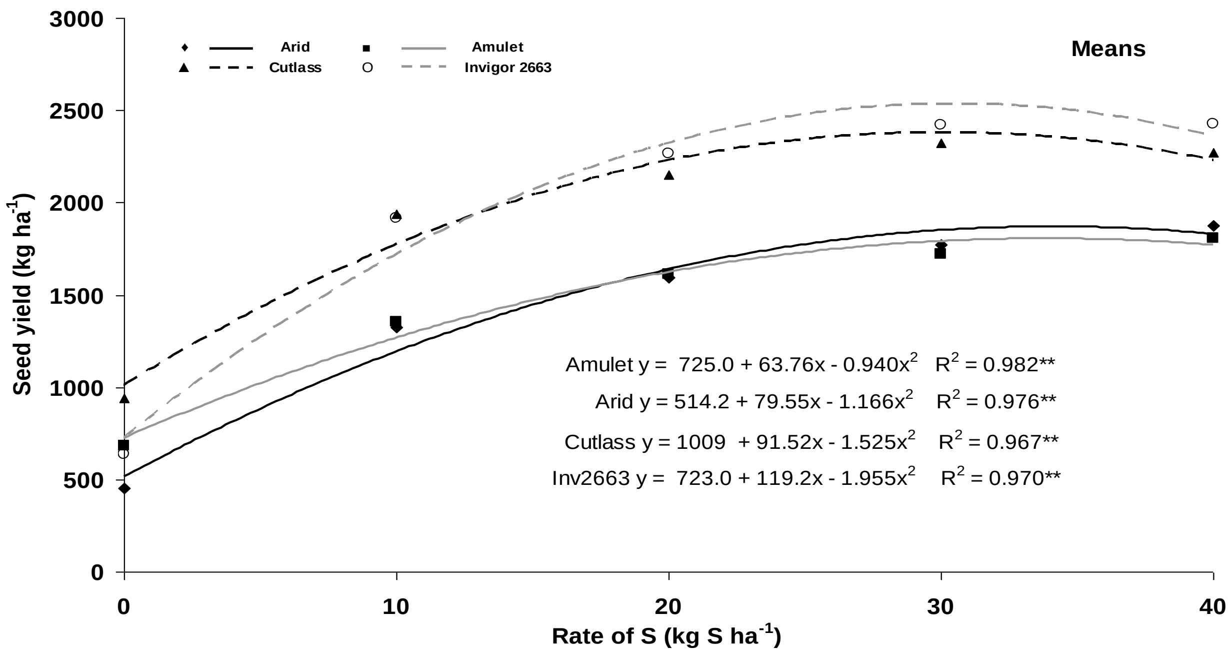

Figure 4. Seed yield response of *Brassica* oilseed species/cultivars to S fertilizer rates at Star City, Saskatchewan (mean of 3 years; Source: Malhi et al. 2007).

Effectiveness of Elemental S vs Sulphate-S Fertilizers on Canola:

Traditionally, S applied in fertilizers was in sulphate form, which is readily available to plants. Now, there are a wide variety of commercial fertilizers that contain S in an elemental form. Elemental S is not plant-available and it must be converted to sulphate by soil microorganisms. Elemental S fertilizers may cost less per unit of S than the sulphate-S fertilizers, but their effectiveness depends on how quickly the S is oxidized to sulphate-S for plant uptake.

Information on the comparisons of repeated annual applications of sulphate-S and elemental S fertilizers in a crop rotation that includes canola is lacking. The question outstanding is… Will annual applications of elemental S provide similar seed yield in canola as annual applications of sulphate-S, and if so how many years it will take?

Two 4-year (1999 to 2002) field experiments using commercial elemental S and sulphate-S fertilizers were established in 1999 in northeastern Saskatchewan to answer these questions. For fall applications, the S fertilizers were surface-broadcast in fall and incorporated into soil at seeding. Spring applications were surface-broadcast and incorporated into soil at seeding.

In 1999, with elemental S fertilizers, there was little or no increase in seed yield in the first year when applied in spring at seeding (Tables 4 and 5). The application of elemental S fertilizers in the previous fall increased canola seed yield moderately at one site which was greater than its application in spring, but the yield increase was still much less than ammonium sulphate. Also, fall-applied ammonium sulphate was less effective in increasing canola seed yield at one site than spring-applied ammonium sulphate. This indicates over-winter loss of sulphate-S from the root zone soil. In 2000 (after second annual application), 2001 and 2002, elemental S fertilizers corrected the S-deficiency in canola, but seed yields were still less than ammonium sulphate (Tables 4 and 5). Fall-applied elemental S was more effective in increasing seed yield of canola than spring-applied elemental S.

In summary, the elemental S fertilizers were not very effective as compared to ammonium sulphate when it came to correcting sulphur deficiencies and increasing canola seed yields in the first year of application. Seed yields were still less than ammonium sulphate after multiple annual applications in most cases.

Table 4. Seed yield increase from various sulphur (S) fertilizers applied at two rates in fall and spring to canola near Tisdale in northeastern Saskatchewan in 1999 to 2002 (Source: Malhi 2005)

	Rate of S	Seed yield increase (kg/ha) from applied S							
		1999		2000		2001		2002	
Source of S	kg S ha^{-1}	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring
ES 90	10	23	0	286	31	208	105	470	148
	20	45	0	572	94	349	196	490	268
ES 95	10	45	10	231	44	159	56	199	90
	20	104	0	612	156	275	109	472	212
Agrium Plus	10	87	77	542	615	292	344	555	500
	20	264	496	885	760	405	420	681	630
Ammonium sulphate	10	106	369	667	747	394	346	543	557
	20	285	851	728	919	368	399	682	813

Table 5. Seed yield increase from various sulphur (S) fertilizers applied at 15 kg S ha^{-1} in fall and spring to canola at Porcupine Plain in northeastern Saskatchewan in 1999 to 2002 (Source: Malhi et al. 2008)

	Seed yield increase (kg ha^{-1}) from applied S									
	1999		2000		2001		2003		2005	
Source of S	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall	Spring
ES 90	602	6	1405	677	498	274	1114	891	1417	1497
ES 95	843	12	865	628	204	85	874	481	1165	769
Agrium Plus	1643	1367	1317	1414	677	561	1367	1115	1247	1438
Ammonium sulphate	1907	2087	1422	1191	675	803	1086	1444	1359	1153

-ES 90 and ES 95 are elemental S fertilizers and Agrium Plus contains both elemental S and sulphate-S.

Influence of Formulation of Elemental S Fertilizer on Yield and Quality of Canola Seed: The effectiveness of elemental S fertilizers depends on the rate at which S is oxidized to sulphate-S in soil for plant uptake. There are many reports on the factors (e.g., soil type - pH, texture; environmental conditions - temperature, moisture, aeration; increasing dispersion of elemental S particles from fertilizer - particle/granule size, tillage, method and time of application) that affect the rate of S oxidation from elemental S fertilizers.

Three field experiments were conducted on S-deficient Gray and Dark Gray Luvisol soils (Typic Cryoboralf) during 2000 and 2001 in Saskatchewan (Experiment 1 at Porcupine Plain and Experiment 3 at Canwood) and Alberta (Experiment 2 at Legal) to determine the effects of formulation of elemental S fertilizers on seed yield, oil and protein concentration, S and N uptake, and percent recovery of applied S and N of canola (*Brassica napus* L. cv. A4573 at Porcupine Plain, and cv. Invigor 2663 at Legal and Canwood). In Experiments 1 (2000 and 2001) and 2 (2000), treatments included five elemental S fertilizers (granular ES-99, ES-95, ES-90 and Biosul-90; and Biosul-50 suspension), granular potassium sulphate and zero-S control. In Experiment 3, treatments included eight elemental S fertilizers (granular ES-99, ES-95, ES-90 and Biosul-90; powder Lab fine ES-99.5, ES Settle-47 and ES SPB571-85.8; and Biosul-50 suspension), 21.7 % elemental S plus 18.7% sulphate-S (Agrium Plus), blend of granular ES-90 and ammonium sulphate (1:1), granular ammonium sulphate and zero-S control. The S fertilizers were surface-broadcast or sprayed at 15 and 30 kg S ha^{-1} rates within 2-3 days after sowing in spring.

Canola plants in the zero-S treatment showed S deficiency in the growing season in all experiments. Seed yield of canola was very low in the absence of S fertilization on S-deficient soils (Table 6). There was a marked increase in seed yield of canola with granular sulphate-S. Seed yield increased with sulphate-S fertilizer by 21.8, 1.4, and 3.6 times in Experiment 1, 2, and 3, respectively. The increase in seed yield with increasing rate of S application was dependent on the severity of S deficiency at a given site. There was a dramatic improvement in seed oil concentration with sulphate-S fertilizer, but it had little effect on protein concentration in seed (data not shown).

In all experiments, granular elemental S fertilizers were not effective in correcting S deficiency in canola in the first year of application. Even after two annual applications in experiment 1, seed yield of canola on S-deficient soils was much less with granular elemental S fertilizers compared to the sulphate-S fertilizers, indicating that granular elemental S fertilizers corrected S deficiency partially only. Seed yield of canola with surface application of suspension and powder formulations of elemental S fertilizers was almost similar to sulphate-S fertilizer, and was more than granular S elemental S fertilizers.

In summary, the findings demonstrate that on S-deficient soils granular elemental S fertilizers are less effective in increasing seed yield and quality of canola than sulphate-S fertilizers, but S deficiency in canola can be prevented by broadcast/spread surface-application of elemental S fertilizers that contain S particles in suspension or powder formulation producing seed yield comparable to sulphate-S fertilizer. Dispersion of elemental S particles from granular elemental S fertilizers in soil to enhance microbial oxidation of elemental S particles to sulphate-S in soil was considered as the major problem for lack of effectiveness of granular S fertilizers in the Parkland region of Canadian Prairies.

Table 6. Seed yield of canola from various S fertilizers applied at two rates near Porcupine Plain, Saskatchewan (Experiment 1), Legal, Alberta (Experiment 2) and Canwood, Saskatchewan (Experiment 3)

Treatment[z]		Seed yield (kg ha^{-1})			
Fertilizer name and formulation	S rate (kg S ha^{-1})	Experiment 1 2000 (yr 1)	Experiment 1 2001 (yr 2)	Experiment 2 2000 (yr 1)	Experiment 3 2001 (yr 1)
ES-99 granular	15	12	4	1533	1244
	30	32	7	1608	1135
ES-90 granular	15	40	50	1758	1913
	30	29	216	1691	2057
ES-95 granular	15	50	44	1783	2009
	30	68	119	1967	2202
Potassium sulphate[z]	15	674	635	1672	2444
	30	1154	539	2041	2509
Biosul-50 suspension	15	739	508	2003	2163
	30	935	690	2123	2633
Biosul-90 granular	15	109	100	1497	1751
	30	284	424	1505	2663
Control	0	53	6	1426	689
ES-90 + AS granular					2474
					2541
Agrium Plus granular					2355
					2506
Lab fine ES-99.5 powder					2198
					2337
ES SPB571-85.8 powder					2372
					2632
ES settle-47 powder					2295
					2300

[z]Ammonium sulphate (AS) in Experiment 3; ES = elemental S.
Source: Malhi et al. 2005.

Feasibility of a New Rapid Release Elemental S (RRES, called Vitasul) Granular Fertilizer in Preventing S Deficiency in Canola:

Our previous research has indicated that granular elemtental S fertilizers were not effective in the year of application and also not as effective as sulphate-S in increasing seed yield of canola, especially when applied in spring, due to poor dispersion of elemental S particles from granules for subsequent oxidation to sulphate-S. A field experiment was established in fall 2010 to compare the relative effectiveness of rapid release elemental S (RRES) and sulphate-S fertilizers on seed yield, straw yield, oil and protein concentration in seed, and N and S uptake of canola on S-deficient Gray Luvisol loam soil at Star City, Saskatchewan. The 11 treatments included two granular S sources (RRES and potassium sulphate) and five application time/placement method combinations (broadcast in fall, broadcast in spring pre-tillage, broadcast in spring pre-emergence, sidebanded in spring and seedrow-placed in spring), plus a zero-S control. In 2011 and 2012, there was a significant seed yield response of canola to applied sulphate-S (Table 7, Figures 5 and 6). Seed yield increased considerably with all sulphate-S treatments compared to the zero-S control, although seed yield tended to be slightly lower in the sideband spring and fall broadcast treatments than the other sulphate-S treatments. Compared to zero-S control, seed yield also increased significantly with all RRES treatments, but the increase was much greater with fall applied RRES than most spring applied RRES treatments. Autumn applied RRES produced only slightly lower and spring applied RRES produced much lower seed yield than the highest yielding spring applied sulphate-S broadcast pre-till or seedrow-placed S treatments. In conclusion, the findings based on two-year results suggest the potential of fall broadcast RRES in preventing S deficiency in hybrid canola, but seed yield was still slightly lower than the spring broadcast/incorporated sulphate-S. The experiment will be continued for one more year in order to make valid conclusions.

Table 7. Seed yield of canola in 2011 and 2012, with various S fertilizer treatments applied in previous autumn and in spring at Star City, Saskatchewan (S-deficient soil)

Treatment		Seed yield (kg ha^{-1})		
No	S source/time/method	2011	2012	2013
1	Control (no S fertilizer)	2021	1361	
2	RRES Broadcast Fall	2836	1860	
3	RRES Broadcast Spring Pre-Till	2451	1666	
4	RRES Broadcast Spring Pre-Emergence	2692	1929	
5	RRES Spring Sideband	2521	1586	
6	RRES Spring Seedrow-Placed	2472	1592	
7	Potassium Sulphate Broadcast Fall	2858	1829	
8	Potassium Sulphate Broadcast Spring Pre-Till	2985	1952	
9	Potassium Sulphate Broadcast Spring Pre-Emergence	2939	1907	
10	Potassium Sulphate Spring Sideband	2830	1948	
11	Potassium Sulphate Spring Seedrow-Placed	2993	1661	
	$LSD_{0.05}$	425	228	
	SEM	146.8**	78.9***	

Source: S. S. Malhi - unpublished results.

References

Grant, C. A. and Bailey, L. D. 1993. Fertility management in canola production. Can. J. Plant Sci. **73:** 651-670.

Grant, C. A., Clayton, G. W. and Johnston, A. M. 2003a. Sulphur fertilizer and tillage effects on canola seed quality in the Black soil zone of western Canada. Can. J. Plant Sci. **83**: 745-758.

Grant, C. A., Johnston, A. M. and Clayton, G. W. 2001. Sulphur fertilizer forms and placements for canola. Proc. Manitoba Agronomists Conference 2000, 12-13 December 2000, Winnipeg, Manitoba, Canada. pp. 51-59.

Grant, C. A., Johnston, A. M. and Clayton, G. W. 2003b. Sulphur fertilizer and tillage effects on early season sulphur availability and N:S ratio in canola in western Canada. Can. J. Soil Sci. **83**: 451-463.

Grant, C. A., Johnston, A. M. and Clayton, G. W. 2004. Sulphur fertilizer and management of canola and wheat in western Canada. Can. J. Soil Sci. **84**: 453-462.

Karamanos, R. E. and Janzen, H. H. 1991. Crop response to elemental sulfur fertilizers in Alberta. Can. J. Soil Sci. **71**: 213-225.

Karamanos, R. E., Hodge, N. and Stewart, J. W. B. 1989. The effect of sulphur on manganese and copper nutrition of canola. Can. J. Soil Sci. **69**: 119-125.

Malhi, S. S. 2005. Influence of four successive annual applications of elemental S and sulphate-S fertilizers on yield, S uptake and seed quality of canola. Can. J. Plant Sci. **85**: 777-792.

Malhi, S. S. and Gill, K. S. 2002. Effectiveness of sulphate-S fertilization at different growth stages for yield, seed quality and S uptake of canola. Can. J. Plant Sci. **82**: 665-674.

Malhi, S. S. and Gill, K. S. 2006. Cultivar and fertilizer S rate interaction on canola yield, seed quality and S uptake. Can. J. Plant Sci. **86**: 91-98.

Malhi, S. S. and Gill, K. S. 2007. Interactive effects of N and S fertilizers on canola yield, seed quality, and uptake of S and N. Can. J. Plant Sci. **87**: 211-222.

Malhi, S. S., Coulman, B. and Schoenau, J. J. 2009. Maximizing timothy forage yield and quality by balanced nitrogen, phosphorus and sulphur fertilization. Agron. J. **101**: 1182-1189.

Malhi, S. S., Gan, Y. and and Raney, J. P. 2007. Yield, seed quality and S uptake response of different *Brassica* oilseed crops to S fertilizer rates on a S-deficient soil in northeastern Saskatchewan. Agron. J. **99**: 570-577.

Malhi, S. S., Schoenau, J. J. and Vera, C. L. 2008. Feasibility of elemental S fertilizers for optimum seed yield and quality of canola in the Parkland region of the Canadian Great Plains. Chapter in N. A. Khan and Singh, S. (eds.). Sulfur Assimilation and Abiotic Stress in Plants, Springer-Verlag, Berlin, Heidelberg, Germany. pp. 21-41.

Malhi, S. S., Solberg, E. D. and Nyborg, M. 2005. Influence of formulation of elemental S fertilizer on yield, quality and S uptake of canola seed. Can. J. Plant Sci. **85**: 793-802.

SAS Institute, Inc. 2004. Online documentation for SAS, version 8. [Online] Available: http://support.sas.com/documentation/onlinedoc/index.html [2005 Jun.30].

Solberg, E. D. 1986. Oxidation of elemental S fertilizers in agricultural soils of northern Alberta and Saskatchewan. M. Sc. thesis. University of Alberta, Edmonton, Alberta, Canada.

Solberg, E. D. and Nyborg, M. 1983. Comparison of sulphate and elemental sulphur fertilizers. Proc. International Sulphur 82 Conference, Vol. 2. A. I. More (ed.). British Sulphur Corporation, London, U.K. pp. 843-852.

Solberg, E. D., Laverty, D. H. and Nyborg, M. 1987. Effect of rainfall, wet-dry, and freeze-thaw cycleson the oxidation of elemental sulfur fertilizers. Proc. Alberta Soil Science Workshop, February 1987, Edmonton, Alberta, Canada. pp. 120-126.

Solberg, E. D., Malhi, S. S., Nyborg, M. and Gill, K. S. 2003. Fertiilzer type, tillage, and application time effects on recovery of sulfate-S from elemental sulfur fertilizers in fallow field soils. Commun. Soil Sci. Plant Anal. **34**: 815-830.

Solberg, E. D., Malhi, S. S., Nyborg, M. and Gill, K. S. 2005. Temperature, soil moisture, and antecedent S application effects on recovery of elemental sulfur as SO4-S in incubated soils. Commun. Soil Sci. Plant Anal. **36**: 863-874.