

Chapter 2

Feasibility of Elemental S Fertilizers for Optimum Seed Yield and Quality of Canola in the Parkland Region of the Canadian Great Plains

S.S. Malhi(✉), J.J. Schoenau and C.L. Vera

Abstract The rate of sulfur (S) oxidation in Canadian prairie soils under incubation is enhanced with increasing temperature (with a maximum close to 40°C) and moisture until lack of aeration above field capacity inhibits S oxidation. Oxidation of elemental S to sulfate-S is positively related to pH, organic matter content, nutrient-supplying power, and microbial activity, while it is inversely related to clay content of soil. Techniques that increase the oxidation rate of elemental S in soil include reducing particle size of the fertilizer product, using tillage to incorporate elemental S fertilizer into the soil to increase contact area between elemental S particles and soil microorganisms, and application in advance of crop demand to allow for oxidation to occur before plants require this element. In a 6-year (1999 to 2004) case study on a S-deficient loam soil in northeastern Saskatchewan, elemental S fertilizers were not effective in increasing seed yield and S uptake of canola in 1999, particularly when applied in spring. From 2000 onward, elemental S fertilizers (ES-90 and ES-95) increased seed yield and S uptake significantly over the zero-S control, but usually not at the same level as with sulfate-S containing fertilizers (ammonium sulfate and Agrium Plus). Autumn-applied elemental S usually had greater seed yield and S uptake than the spring-applied elemental S, and the opposite was true for ammonium sulfate in 3 of 6 years. Oil concentration in canola seed showed trends similar to seed yield, though the effects were smaller and less frequent. The need for greater dispersion of elemental S particles from granular elemental S fertilizers, to enhance microbial oxidation to sulfate-S in soil, was considered to be the main requirement for increasing the short-term availability of S in elemental S fertilizers. Canola seed yield, and N and S uptake with surface application of suspension and powder formulations of elemental S fertilizers were similar to sulfate-S fertilizer. Residual benefit of many successive annual elemental S fertilizer applications on soil S fertility was not cumulative. Residual nitrate-N in soil was much higher in the zero-S control than with applied S, and it also tended to be higher in some elemental S treatments than in spring-applied ammonium sulfate. In conclusion, the amount of elemental S fertilizer, needed to adequately meet crop S requirements, should be adjusted based on environmental conditions, soil properties, microbial activity, dispersion of elemental

S.S. Malhi

Agriculture and Agri-Food Canada, P.O. Box 1240, Melfort, Saskatchewan, S0E 1A0 Canada
malhis@agr.gc.ca

S particles from fertilizer granules, and balance between oxidation and immobilization, leaching, or other S losses in the Parkland region of Canadian prairies.

1 Introduction

Canola is one of the major cash crops in the Prairie Provinces of Canada (Statistics Canada 2002). The majority of canola is grown in the Parkland region, where many agricultural soils are deficient or potentially deficient in plant-available sulfur (S) for high seed yield of canola (Bettany et al. 1983, Doyle and Cowell 1993). Because of canola's high requirement for S (Grant and Bailey 1993), there is faster depletion of plant-available S from soil and increased instances and severity of S deficiency during peak growing periods, especially from the use of high-yielding cultivars and application of high rates of N and P fertilizers. Plants use only sulfate-S, and application of sulfate-S fertilizers has been successfully used to eliminate S deficiency in canola (Malhi and Gill 2002). There is now a wide variety of commercial elemental S fertilizers, which normally cost less per unit of S than sulfate-S fertilizers. However, the oxidation of elemental S to sulfate-S is dependent on soil properties, environmental conditions, and dispersion of elemental S particles from fertilizer granules (Solberg 1986, Solberg et al. 2003). In the Canadian prairie soils, granular elemental S fertilizers have been generally found to be less effective than sulfate-S fertilizers to prevent/eliminate S deficiency in canola (Ukrainetz 1982, Karamanos and Janzen 1991, Nuttall et al. 1993, Grant et al. 2001, Malhi 2005, Malhi et al. 2005). As in most of the earlier field studies, elemental S fertilizers were not applied to the same plots for a number of years, and there is limited information on the effects of long-term annual applications and residual effects of elemental S fertilizers on canola seed yield, quality, and S uptake in comparison to sulfate-S fertilizers. The objective of this paper is to discuss factors affecting the oxidation and availability of elemental S in soil and the feasibility of elemental S fertilizers for optimum seed yield and quality of canola in the Parkland region of western Canada. Selected characteristics of elemental S products are presented in Table 2.1.

2 Factors Affecting Oxidation of Elemental S

In soil, elemental S is oxidized to sulfate-S mainly by autotrophic and heterotrophic microorganisms (Schoenau and Germida 1992). Microbial activity and, consequently, the rate of elemental S oxidation are affected by environmental conditions, soil characteristics, and soil and fertilizer management practices that increase the dispersion of elemental S particles from S fertilizer granules.

2.1 *Environmental Conditions (Temperature, Moisture, Aeration)*

Incubation studies have shown increased rate of S oxidation with increased temperature, with an optimum close to 40 °C (Janzen and Bettany 1987b, Solberg

Table 2.1 Selected characteristics of S sources and their S particles

Name	S source		S particles	
	Characteristics	Sulfur (%) ¹	Size Range (µm)	Weight ((%)
ES-99	Granules	ES: 99	<74	100
ES-95	Granules	ES: 95	74-44	2
ES-90 or Bentonitic S (A)	Bentonite-based	ES: 90	<44	98
	10% bentonite		Not done	
	Granules, 2-4 mm			
ES-90 or Bentonitic S (B)	1979 product	ES: 90	2 000-1 180	17
	10% bentonite		1 180-600	36
	Dome shaped		600-250	20
	2-4 mm long		250-150	13
	1-3 mm wide		150-75	11
	1985 product		75-45	3
			<45	1
ES-90 or Bentonitic S (C)	10% bentonite	ES: 90	>2 000	25
	Granules, 2-4 mm		2000-1180	15
			1180-600	15
			600-250	16
			250-150	13
			150-75	12
			75-45	4
Urea S (A)		ES: 10.4	<45	1
	Urea pallets		25-50	50
	1-3 mm diameter		<25	50
Urea S (B)	Fine S impregnated	ES: 22.4		
	Urea pallets		25-50	50
	1-3 mm diameter		<25	50
Urea S (C)	Fine S impregnated	ES: 20.0		
	Urea pallets		25-50	50
	1-3 mm diameter		<25	50
Biosul-90	Granules	ES: 90	<10	100
Biosul-50	Suspension	ES: 50	<10	100
Sodium sulfate	Reagent grade, crystals	Sulfate-S: 22.5	Not done	
Potassium sulfate	Fertilizer grade, granules	Sulfate-S: 17	Not available	
Ammonium sulfate	Fertilizer grade, granules	Sulfate-S: 24	Not available	
Agrium Plus	Granules	ES: 21.7	90-50	15
		Sulfate-S: 18.7	<50	85
Sulgro-68	Granules	ES: 60	<74	100
	Bentonite-based	Sulfate-S: 8		
Lab fine ES-99.5 or	Reagent grade	ES: 99.5	250-150	22.9
Fine S or Fine sublimed S	Powder		150-75	58.2
			75-53	7.7
			53-45	7.2
			<45	4.2
ES SPB 571-85.8	Powder	ES: 85.8	<10	100
ES settle-47	Powder	ES: 47	<10	100
Flowable S	Suspension	ES: 52.0	1-2	100

¹ES refers to elemental S.

et al. 2005a). Reported Q_{10} values of 3.0 to 4.7 for the relationship between temperature and oxidation indicate that elemental sulfur oxidation is more sensitive to changing temperature than many biological reactions in soil (Wen et al. 2001). Consequently, a larger proportion of applied elemental S is anticipated to be converted to sulfate-S in warmer than in colder regions.

Janzen and Bettany (1987b) reported that the oxidation rate of elemental S is related to soil moisture potential according to a parabolic relationship, and also stated that this relationship is more pronounced with increase in temperature from 3 °C to 30 °C. In their study, optimum water potential ranged from -270 kPa to > -10 kPa when clay content in soil was decreased from 60% to 7%, respectively. In another incubation study, oxidation of elemental S to sulfate-S was enhanced with increasing soil moisture until lack of aeration began to reduce S oxidation rate at soil moisture content above field capacity, reflecting interactive effects of aeration and water availability in soil (Solberg et al. 2005a). In this study, there was reduced oxidation with increase in moisture from 90% to 120% of field capacity in one soil but not in other soils, reflecting differences due to texture.

2.2 Soil Properties (pH, Texture, Microbial Activity)

Research has shown a positive relationship between oxidation of elemental S to sulfate-S and soil pH, organic C concentration, extractable P, or extractable S, while it was negatively related to clay content (Janzen 1984). Rate of oxidation is also affected by the size and activity of microbial populations carrying out the oxidation process. In incubation studies, soils that had received previous elemental S applications usually showed faster S oxidation than soils which had not received any previous elemental S (Bertrand 1973, Janzen and Bettany 1987a, Solberg et al. 2005a) due to increase in the number of S oxidizers and more effective microbial populations (Bertrand 1973). The implications of these observations are that not only soil properties and climatic conditions but also antecedent S application could influence the performance of elemental S fertilizers in a given soil.

2.3 Dispersion of Elemental S Particles from Fertilizer Granules

Being a biological process, oxidation of elemental S in soil is affected by the effective surface area of the S particles exposed to microbial activity. Techniques that increase the oxidation rate of elemental S include reduced particle size of the fertilizer product, tillage to incorporate elemental S fertilizer into the soil and increase contact area between elemental S particles and microbes, and application in advance to allow for oxidation before plants require this element (Janzen 1990). In addition, the effectiveness of these techniques varies with the characteristics of elemental S source and application method (Janzen and Bettany 1987c).

Dispersion of granular ES-95 in water prior to application greatly increased oxidation rate compared to placement of intact granules into the soil (Wen et al. 2001). In an incubation study on Alberta and Saskatchewan soils, there was greater recovery as sulfate-S from Flowable S and Fine S than the Bentonitic S (A, B and C) and Urea S (A and C) products without cultivation (Solberg et al. 2005b). In this study, the low recovery from Urea S (A and C), which had small elemental S particles ($<50\mu\text{m}$), was due to a decrease in the exposed surface area of the elemental S particles because of impregnation in urea pellets of 1-3 mm diameter (Janzen 1984, Janzen and Bettany 1986). In soil, when the urea from Urea S is dissolved, it leaves behind the fine elemental S particles aggregated in approximately the same volume as the original granule, which results in about 40-fold reduction in the exposed surface area, as only the outermost S particles become exposed to microbial action.

Bentonitic elemental S granules are expected to break apart with time, thereby exposing much greater surface area of the finer elemental S particles to soil microbes. However, if the Bentonitic elemental S granules are not disrupted and the elemental S particles are not mixed thoroughly into the soil, the exposed surface area and oxidation potential will be low due to delayed, inadequate, or lack of dispersion of elemental S particles in soil (Noellemeyer et al. 1981, Ukrainetz 1982, Janzen 1990). In incubation studies on Alberta and Saskatchewan soils, the reduction in size of Bentonitic S (C) from 2000-4000 μm to 1500-2000 μm had no effect on recovery as sulfate-S (Solberg et al. 2005b). However, there was high sulfate-S recovery from the incorporation of crushed ($<150\mu\text{m}$) Bentonitic S, and this suggested that if the aggregates of fractured elemental S are thoroughly dispersed into soil, the sulfate-S recovery from this material could be considerably increased.

Earlier research has shown higher oxidation rates when elemental S was mixed into soil rather than banded (Swan et al. 1986). Similarly, in an incubation study by Solberg et al. (2005b), placement of Flowable S and Fine S fertilizers in bands or in nests (point placement) showed much less sulfate-S recovery than their incorporation after broadcasting. Generally, lower sulfate-S recovery from nested than banded S could also be explained by further reduction in exposure of surface in the case of nested S. Also, more mixing by cultivation after incorporation and banding of Urea S did not increase the oxidation. This is supported by field observations, where Urea S pellets could be found four months after incorporation and a subsequent high-speed intensive rotary cultivation.

Under field conditions, the sulfate-S recovery results showed that only up to 44% of the spring-applied elemental S could be recovered during the same growing season (Solberg et al. 2003). Among the elemental S fertilizers, Fine S gave more recovery as sulfate-S compared to Urea S (A), Urea S (B), and Bentonitic S (A). Tillage increased sulfate-S recovery from applied S in one experiment but had inconsistent results in another soil. The substantial differences in the sulfate-S recovery from different soils indicated the influence of soil type on oxidation rate and recovery of applied S at a given time. These results suggest that only a portion of the applied elemental S could be recovered as sulfate-S at any of the sampling times. Partial oxidation of elemental S in the year of application was also observed in other studies on Saskatchewan soils (Janzen and Bettany 1987b, Janzen and

Karamanos 1991, Wen et al. 2001, 2003). Solberg et al. (2003) showed more sulfate-S recovery in soil from October sampling than July sampling. The sulfate-S recovered in October could be considered as the amount of sulfate-S available from an elemental S fertilizer that may be subject to losses during winter and in early spring or become available for crop use in subsequent year.

The recovery of sulfate-S in the following year tended to be lower from elemental S fertilizers (Fine S, Bentonitic S [A]) compared to sodium sulfate (Solberg et al. 2003). Also, Karamanos and Janzen (1991) did not observe any advantage of elemental S over sulfate-S fertilizers during the second and third year after their applications. They attributed the absence of greater residual benefit of elemental S products relative to the sulfate-S fertilizers to the short duration of S uptake period by crops and susceptibility of S oxidized after that period to leaching.

2.4 Balance between S Oxidation and Immobilization, Leaching, or Other Losses

The recovery of sulfate-S from elemental S in soil is affected by a balance between the amount of S oxidized into sulfate-S and the amount of this sulfate-S that is immobilized into organic S pool or lost through leaching, especially in early spring after snow melt. When soil temperature and moisture conditions favor growth of S-oxidizing microbes, they also favor the growth of other microbes that decompose organic matter residues, which may result in immobilization of sulfate-S. Since elemental S is passed through microbial biomass during oxidation, it is possible that a major portion of oxidized S may be immobilized into microbial biomass or organic S pool. At a given time, the net balance of these release-immobilization reactions is expressed as the amount of sulfate-S present in soil and is thus very difficult to predict. Large losses of sulfate-S from the inorganic S pool by immobilization have been observed in incubated soils (Freney and Spencer 1960) and under field conditions (Janzen and Bettany 1987b, Janzen and Karamanos 1991). In addition, previous field research with autumn-applied ammonium sulfate in northeastern Saskatchewan showed downward leaching of sulfate-S in the soil profile in early spring after snow melt (Malhi 2005).

3 Feasibility of Granular Elemental S on Canola: A Case Study

3.1 Materials and Methods

A field experiment was established in the autumn of 1998 on an S-deficient Gray Luvisol (Typic Cryoboralf) loam soil (1.8 mg sulfate-S kg⁻¹ in 0-15 cm) at Porcupine Plain, Saskatchewan, Canada, with annual applications of various S

fertilizers for 6 years (1999 to 2004) and residual effects monitored in 2005 and 2006. Growing season (May to August) precipitation was below the long-term average (244 mm) in 2001 (184 mm) and in 2003 (87 mm). In 2002, the canola crop did not mature prior to severe early frost and no seed yield was recorded. In 2004, seed yield was very low due to frost damage in late August, and the crop was completely destroyed by deer grazing in 2006. Therefore, seed yields for 2002, 2004, and 2006 are not reported.

Each treatment was replicated four times in a randomized complete block design. Individual plots were 1.8 m × 7.5 m. The treatments included two application times (preceding autumn or before seeding in spring) of four S fertilizers (at 15 kg S ha⁻¹) and a zero-S control. The four S fertilizers included ES-90 and ES-95, two bentonite-based elemental S fertilizers containing 90% and 95% elemental sulfur, respectively, Agrium Plus (16-0-0-40), a fertilizer containing both elemental S (21.7%) and sulfate-S (18.7%), and ammonium sulfate (20.5-0-0-24), a sulfate-S fertilizer. Two brands of ES-90 were used, namely, Tiger90™ in the autumn of 1999, and Tiger90CR™ in the remaining years (Tiger Industries, Calgary, Alberta, Canada). The ES-95 was Sulfer95™ brand in all years (Fernz SulFer Works, Crossfield, Alberta, Canada). The S fertilizers were surface-broadcast. Each plot received a blanket annual application of 120 kg N ha⁻¹ (as ammonium nitrate), 30 kg P ha⁻¹ (as triple superphosphate), and 20 kg K ha⁻¹ (as KCl – muriate of potash). In treatments that received ammonium sulfate, the blanket amount of N was adjusted. All the plots were tilled before sowing in May. A double-disc press drill was used to seed canola (*Brassica rapa* L. cv. Fairview) at 17.8 cm row spacing and seed rate of 9 kg ha⁻¹.

Seed yield was determined by harvesting 1.25 m wide and 7.0 m long strips with a plot combine, and straw yield was calculated from hand-harvested samples collected from two 1 m long rows in each plot. The oven dry (60 °C) samples were analyzed for oil, total N and total S in seed, and total S in straw. Oil concentration in canola seed was determined using crude fat method (AOAC 1990). Total S in seed and straw was determined by digestion of samples in nitric acid-hydrogen peroxide and measuring its concentration in the digest by ICP-AES (Huang and Schulte 1985). Total N in seed samples was determined by sample digestion and detection of N by thermal conductivity using a CNS combustion analyzer (AOAC 1995). Protein concentration was calculated by multiplying the total N by 6.25.

Soil samples in each plot were taken from the 0-15, 15-30, and 30-60 cm depths in the spring of 1999 to 2007. Each sample was a composite of four cores (4 cm diameter) per plot. The soil samples were air dried at room temperature, ground to pass through a 2-mm sieve, and then analyzed for sulfate-S. Sulfate-S in soil was determined by extraction with CaCl₂ and measuring its concentration in the extract by ICP-AES (Combs et al. 1998).

The data were subjected to analysis of variance (ANOVA) using GLM procedure (SAS Institute 1993). Selected contrasts and least significant difference (LSD_{0.05}) were used to determine differences between treatment means.

3.2 Results

3.2.1 Yield

Seed yield was very low (4 to 29 kg ha⁻¹) in the zero-S control in all years (data not shown). Annual applications of sulfate-S containing fertilizers (ammonium sulfate and Agrium Plus) increased seed yield significantly over the zero-S control in all years. For elemental S fertilizers, spring application had no effect on seed yield in 1999, but seed yield increased significantly with elemental S fertilizers over the zero-S control in the following years (except most cases in 2001).

Averaged over time of S application, ammonium sulfate had higher seed yield than ES-90 and ES-95 in 1999, 2000, 2001, and 2003 (Table 2.2). Agrium Plus produced lower seed yield than ammonium sulfate in 1999, while seed yields were similar for both sulfate-S sources in the following years. Seed yield was lower with ES-95 than ES-90 in 3 of 4 years (2000, 2001, and 2003). Averaged over S sources, seed yields were higher with autumn application than spring application of S in 1999, 2000, and 2003.

Seed yield with spring-applied elemental S fertilizers was lower than spring-applied ammonium sulfate in all years (Table 2.2). Autumn-applied elemental S fertilizers significantly increased seed yield over the zero-S control in all years (except ES-95 in 2001), but these seed yields were significantly lower than spring-applied ammonium sulfate in 1999, 2001, and 2003 (except ES-90 in 2000 and 2001, when this elemental S fertilizer produced seed yield close to ammonium sulfate). Autumn application of elemental S was more effective in increasing seed yield of canola than spring application, but the differences were significant only in 1999 and 2000 for ES-90 and in 1999 and 2003 for ES-95. Similarly, Agrium Plus also tended to produce more seed yield with autumn than spring application in 3 of 4 years. However, ammonium sulfate tended to produce lower seed yield with autumn than spring application in 3 of 4 years.

Straw yields were recorded in all 6 years from 1999 to 2004 and were moderate (2414 to 6561 kg ha⁻¹) in the zero-S control (data not shown). Averaged over timing of S application, straw yield was significantly higher in 1999 and tended to be higher in 2003 and 2004 with ammonium sulfate than ES-90 and ES-95 (data not shown). Agrium Plus tended to produce lower straw yield than ammonium sulfate in 1999 and 2003. Straw yield tended to be lower with ES-95 than ES-90 in 4 years (2000, 2001, 2002, and 2004), and the opposite was true in one year (2003). Averaged over S sources, straw yields were generally similar for autumn and spring application in most years, with one exception in 2000, when spring-applied S had higher straw yield than autumn-applied S.

In 1999, both autumn- and spring-applied Agrium Plus tended to produce less straw yield than spring-applied ammonium sulfate (data not shown). The elemental S fertilizers increased straw yield when applied in autumn, but the increase was lower or tended to be lower than spring-applied ammonium sulfate. Spring-applied elemental S fertilizers produced significantly lower straw yield than ammonium sulfate. Spring-

Table 2.2 Seed yield of canola with application of 15 kg S ha⁻¹ from various S fertilizers in preceding autumn or in spring of 1999 to 2007 near Porcupine Plain in north-eastern Saskatchewan

Fertilizer Treatment		Seed Yield (kg ha ⁻¹) ^y				
S source ^z	Time	1999	2000	2001	2003	2005
Fertilizer S Source x Time of Application						
ES-90	Autumn	623	1432	502	1143	1421
	Spring	27	704	278	920	1501
ES-95	Autumn	864	892	208	903	1169
	Spring	33	655	89	510	773
AP	Autumn	1644	1344	681	1396	1251
	Spring	1388	1441	565	1144	1442
AS	Autumn	1928	1449	679	1115	1363
	Spring	2108	1218	807	1473	1157
	LSD _{0.05}	548	458	ns	279	ns
	SEM ^w	186 [*]	156 [*]	123 ^{ns}	95 ^{**}	222 ^{ns}
Fertilizer S Source						
ES-90		325	1068	390	1031	1461
ES-95		448	774	149	707	942
AP		1526	1392	623	1270	1347
AS		2018	1333	743	1294	1275
LSD _{0.05}		387	324	255	197	ns
SEM		132 ^{***}	110 ^{**}	87 ^{***}	67 ^{***}	158 ^{ns}
Time of Application						
	Autumn	1270	1279	517	1139	1310
	Spring	889	1005	435	1012	1222
	LSD _{0.05}	274	229	ns	140	ns
	SEM	93 ^{**}	78 [*]	61 ^{ns}	47 [*]	111 ^{ns}
*Contrast (autumn vs spring)						
ES-90		*	**	ns	ns	ns
ES-95		**	ns	ns	***	ns
AP		ns	ns	ns	*	ns
AS		ns	ns	ns	*	ns

^zES refers to elemental S; AP refers to Agrium Plus containing both elemental S and sulfate-S; and AS refers to ammonium sulfate.

^yIn the zero-S control, in 1999, 2000, 2001, 2003, 2005, 2006 and 2007, respectively, seed yield was 21, 27, 4, 29 and 4 kg ha⁻¹.

^xContrast refer to comparison of autumn and spring application means for the given year and S fertilizer.

^wSEM refers to standard error of the mean. *, **, and *** indicate treatment effect being significant at $P \leq 0.01$, $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; and ^{ns} indicate treatment effect not significant.

applied ammonium sulfate produced significantly more straw yield in 1999 and tended to produce more straw yield in 3 years than autumn-applied ammonium sulfate, but the opposite was true in 2001. Autumn-applied ES-90 had higher straw yield than spring-applied ES-90 in 1999, but the opposite occurred in 2000. For ES-95, autumn

application produced higher straw yield than spring application in 1999 and 2002. Application time did not have a consistent effect on straw yield with Agrium Plus.

The residual effects of previously applied S fertilizers from 1999 to 2004 were recorded in 2005 and 2007. In 2005, there was a significant increase in seed and straw yield from previously applied S fertilizers over the zero-S control (data not shown). There were no significant differences in seed and straw yield between the elemental S and sulfate-S fertilizers, and also between autumn and spring application. In 2007, there was a significant increase in seed yield from previously applied elemental S fertilizers but little increase from sulfate-S fertilizers over the zero-S control.

3.2.2 Seed Quality

Oil concentration in canola seed was determined in 4 years, and it increased with application of S fertilizers in all years (Table 2.3). Sulfate-S-containing fertilizers had higher oil concentration in seed than the elemental S fertilizers in 1999, 2000, and 2001. Average oil concentration in seed was higher in 1999 and tended to be lower in 2003 with ammonium sulfate than Agrium Plus. Oil concentration in seed was higher in 2001 and tended to be higher in 1999, 2000, and 2003 with ES-90 than ES-95. Average oil concentration in seed was higher in 2001 and tended to be higher in 1999 with autumn than spring application. The contrasts showed that oil concentration in seed was higher when the elemental S fertilizer was applied in autumn rather than in spring for ES-90 in 1999, 2000, and 2001 and for ES-95 in 1999 and 2001. For ammonium sulfate, autumn application had higher oil concentration in seed than spring application. Application time of Agrium Plus did not have any significant effect on the oil concentration in seed.

Protein concentration in seed ranged between 192 to 304 g kg⁻¹ in different years, and was decreased with S fertilization in 1999, while it increased in 2000 and 2003, and showed no significant effect in 2001 (data not shown). Sulfate-S-containing fertilizers had lower protein concentration in seed than the elemental S fertilizers in 1999, most likely due to a dilution effect of increased seed yield from sulfate-S fertilizers, but there were no differences in seed protein concentration among the various S fertilizers in other years. Autumn application had higher protein concentration in seed than spring application in 2003 for ES-90 and in 2000 and 2003 for ES-95.

In 2005, residual effects of previous 6 annual applications of S fertilizers showed significant increase in oil concentration in seed over the zero-S control for all S fertilizer treatments (data not shown). There was no residual effect of applied S on protein concentration in seed.

3.2.3 Sulfur Uptake

Like seed yield, uptake of S in canola seed was very low in the zero-S control treatment (0.01 to 0.06 kg S ha⁻¹) and the sulfate-S containing fertilizers, particularly ammonium sulfate, increased S uptake most times in all years (Table 2.4). Elemental

Table 2.3 Oil concentration in seed of canola with application of 15 kg S ha⁻¹ from various S fertilizers in preceding autumn or in spring of 1999 to 2007 near Porcupine Plain in north-eastern Saskatchewan

Fertilizer treatment		Oil concentration (g kg ⁻¹) ^y				
S source ^z	Time	1999	2000	2001	2003	2005
Fertilizer S Source x Time of Application						
ES-90	Autumn	367	413	358	374	432
	Spring	339	383	338	355	432
ES-95	Autumn	362	388	320	366	387
	Spring	329	390	293	335	392
AP	Autumn	396	407	373	374	421
	Spring	393	417	367	378	433
AS	Autumn	398	417	376	333	413
	Spring	425	411	379	369	392
	LSD _{0.05}	29	15	ns	ns	ns
	SEM ^w	10.0*	5.1**	6.5 ^{ns}	14.0 ^{ns}	8.3 ^{ns}
Fertilizer S Source						
ES-90		353	398	348	364	432
ES-95		345	389	307	351	390
AP		395	412	370	376	427
AS		412	414	377	351	403
LSD _{0.05}		20	11	13	ns	17
SEM		6.9***	3.6***	0.46***	10.0 ^{ns}	6.0***
Time of Application						
	Autumn	381	406	357	362	413
	Spring	371	400	344	359	412
	LSD _{0.05}	ns	ns	10	ns	ns
	SEM	4.9 ^{ns}	2.5 ^{ns}	3.3*	7.0 ^{ns}	4.1 ^{ns}
*Contrast (autumn vs spring)						
ES-90		•	***	*	ns	ns
ES-95		*	ns	**	ns	ns
AP		ns	ns	ns	ns	ns
AS		•	ns	ns	•	•

^zES refers to elemental S; AP refers to Agrium Plus containing both elemental S and sulfate-S; and AS refers to ammonium sulfate.

^yIn the zero-S control, in 1999, 2000, 2001, 2003, 2005, 2006 and 2007, respectively, oil concentration in seed was 303, 373, 252, 260 and 317 g kg⁻¹.

*Contrast refer to comparison of autumn and spring application means for the given year and S fertilizer.

^wSEM refers to standard error of the mean. •, *, **, and *** indicate treatment effect being significant at $P \leq 0.01$, $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; and ^{ns} indicate treatment effect not significant

S fertilizers increased S uptake in seed with autumn application in all years, except ES-95 in 2001, while the effect of their spring application was significant in 2000 and 2003. Average S uptake in seed was lower with elemental S fertilizers than sulfate-S-containing fertilizers in almost all cases, and it was usually lower with ES-95

Table 2.4 Total S uptake in seed of canola with application of 15 kg S ha⁻¹ from various S fertilizers in preceding autumn or in spring of 1999 to 2007 near Porcupine Plain in north-eastern Saskatchewan

Fertilizer treatment		Total S uptake in seed (kg S ha ⁻¹) ^y				
S source ^z	Time	1999	2000	2001	2003	2005
Fertilizer S Source x Time of Application						
ES-90	Autumn	1.44	4.27	1.66	4.46	5.04
	Spring	0.06	1.83	0.79	2.75	5.04
ES-95	Autumn	1.97	2.42	0.54	2.76	2.95
	Spring	0.07	1.64	0.23	1.34	1.93
AP	Autumn	3.87	4.31	2.45	5.30	3.32
	Spring	3.19	4.80	2.09	4.52	4.44
AS	Autumn	4.87	4.87	2.64	4.67	4.20
	Spring	5.32	4.03	3.17	5.97	3.05
	LSD _{0.05}	1.35	1.53	1.27 ^{ns}	0.85	ns
	SEM ^w	0.46*	0.52*	0.43 ^{ns}	0.29***	0.74 ^{ns}
Fertilizer S Source						
ES-90		0.75	3.05	1.22	3.60	5.04
ES-95		1.02	2.03	0.38	2.05	2.37
AP		3.53	4.56	2.27	4.91	3.88
AS		5.09	4.45	2.90	5.32	3.71
	LSD _{0.05}	0.95	1.08	0.90	0.60	1.54
	SEM	0.32***	0.37***	0.31***	0.20***	0.52*
Time of Application						
	Autumn	3.04	3.97	1.82	4.29	3.94
	Spring	2.16	3.07	1.57	3.64	3.65
	LSD _{0.05}	0.67	0.76	Ns	0.42	ns
	SEM	0.23*	0.26*	0.22 ^{ns}	0.14***	0.37 ^{ns}
*Contrast (autumn vs spring)						
ES-90		*	**	Ns	***	ns
ES-95		**	ns	Ns	**	ns
AP		ns	ns	Ns	*	ns
AS		ns	ns	Ns	**	ns

^zES refers to elemental S; AP refers to Agrium Plus containing both elemental S and sulfate-S; and AS refers to ammonium sulfate.

^yIn the zero-S control, in 1999, 2000, 2001, 2003, 2005, 2006 and 2007, respectively, S uptake in seed was 0.05, 0.05, 0.01, 0.06 and 0.01 kg S ha⁻¹.

*Contrast refer to comparison of autumn and spring application means for the given year and S fertilizer.

^wSEM refers to standard error of the mean. *, **, and *** indicate treatment effect being significant at $P \leq 0.01$, $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; and ^{ns} indicate treatment effect not significant

than ES-90 in 3 of 4 years. Autumn-applied ES-90 had S uptake in seed equal to ammonium sulfate or Agrium Plus in 2000 and 2003. Agrium Plus had lower S uptake in seed than ammonium sulfate only in 1999, otherwise the two sulfate-S-containing fertilizers had similar S uptake in seed. On average, autumn application had higher S uptake in seed than spring application.

Elemental S fertilizers had greater S uptake in seed when autumn-applied compared to their application in spring, with significant differences in 1999, 2000, and 2003 for ES-90 and in 1999 and 2003 for ES-95. For Agrium Plus and ammonium sulfate, application time had significant influence on S uptake in seed only in 2003, when spring-applied ammonium sulfate had greater and spring-applied Agrium Plus had lower S uptake in seed than their corresponding applications in autumn.

There was a significant increase in uptake of S in straw with application of Agrium Plus and ammonium sulfate over zero-S control in all years (data not shown). Elemental S also tended to increase S uptake in straw, with significant effect for autumn and spring applications of ES-90 in 2001, 2002, and 2004, and autumn application in 2003. ES-95 also showed significant effect for autumn and spring applications in 2003. Average S uptake in straw was higher with sulfate-S-containing fertilizers than ES-95 in all 6 years and ES-90 in only 2 of 6 years (2000 and 2003). Sulfur uptake in straw was lower with ES-95 than ES-90 in 3 of 4 years (2001, 2002, and 2004). Uptake of S in straw was lower with Agrium Plus than ammonium sulfate in 1999 and 2003, and tended to be lower in 2000, 2001, and 2002, but the opposite tended to be true in 2004. Ammonium sulfate applied in spring had higher uptake of S in straw than its autumn application in 1999, while the effect of application time of both sulfate-S-containing fertilizers was not consistent otherwise. For the elemental S fertilizers, on the other hand, much higher S uptake in straw occurred from autumn than spring application in 1999 and for ES-90 in 2001, 2002, and 2003. The elemental S fertilizers had less uptake of S in straw than Agrium Plus and ammonium sulfate, except for autumn application of ES-90 in 2001, 2002, and 2003, when there were no differences among the S sources. The differences between elemental S and sulfate-S fertilizers were relatively greater for spring than autumn application.

In 2005, there was a significant residual effect of previously applied S on S uptake in seed and straw (data not shown). A year after the last S application, uptake of S in seed and straw tended to be greatest for ES-90 and lowest for ES-95, with the exception of Agrium Plus applied in spring. Average S uptake in seed was higher with ES-90 and Agrium Plus than ES-95 and ammonium sulfate, while S uptake in straw was lower with ES-95 than the other three S sources. On average, residual effect of spring S application tended to have higher S uptake in straw than autumn application, except for ES-95 and Agrium Plus, where uptake of S in straw was higher or tended to be higher with autumn than spring application.

3.3 Discussion

3.3.1 Canola Yield, Seed Quality, and S Uptake

Severe S deficiency symptoms were observed on canola plants at early growth stages in the absence of S fertilizer application in all years. Under this treatment, seed yields of canola ranged from 4 to 29 kg ha⁻¹, which indicated that soil was very deficient in

plant-available S during the experimental period from 1999 to 2004 and that deficiency of S in soil during the growing season can cause a major reduction in seed yield.

Averaged across 1999 to 2004, seed and straw yield of canola in plots treated with ammonium sulfate were 66.5 and 1.8 times greater than the zero-S plots, respectively. This indicated that response of canola to applied sulfate-S was much greater for seed yield compared to straw yield and that S fertilization was essential to attain optimum canola seed yield. Substantial increase in seed yield from ammonium sulfate suggests that this fertilizer provided S in the form which plants can absorb. These results are supported by earlier observations that S deficiencies in crops can be prevented or eliminated by applying sulfate-S (Malhi and Gill 2002).

Elemental S must be converted to sulfate-S before it can be utilized by a crop (Bettany and Janzen 1984). In our study, there was little or no increase in seed yield from elemental S fertilizers compared to zero-S control in the first year, especially with spring application. Similarly, in earlier studies the availability of sulfate-S from elemental S fertilizers in the year of application was considered minimal (Noellemeyer et al. 1981), and the elemental S fertilizers were inferior to sulfate-S fertilizers on canola in the year of application (Karamanos and Janzen 1991, Malhi 2005).

The amount of available S in soil from elemental S fertilizers is expected to increase with time and to produce seed yield benefit (Bettany and Janzen 1984). Therefore, cumulative effect was assessed in canola seeded with annual applications of elemental S fertilizers for 6 years on the same plots. From the second year onward, elemental S fertilizers significantly increased seed yield and S uptake over the zero-S control, except spring application of ES-95 in 2001. This indicates further dispersion of the S particles to enhance oxidation rate, and increased time for oxidation improves effectiveness of elemental S fertilizers. However, seed yield and S uptake of canola with elemental S fertilizers were lower than ammonium sulfate in many cases. This indicated that elemental S fertilizers were unable to consistently supply sufficient amounts of sulfate-S to canola plants in the growing season for optimum growth and seed yield, even after many consecutive annual applications on the same area.

Agrium Plus (which contained both sulfate-S and elemental S) was effective in correcting S deficiency in canola starting from the first year, but produced less seed yield and S uptake than ammonium sulfate in some years. This indicates that the elemental portion of S in Agrium Plus probably behaved similar to the other elemental S fertilizers and was not as effective as the sulfate-S portion in increasing seed yield of canola.

The granular elemental S fertilizers are probably less effective than granular sulfate-S fertilizers because granules remain intact, and elemental S particles do not disperse from granules resulting in a low rate of microbial oxidation. The conversion of granular elemental S fertilizers to sulfate-S can be improved by increasing the contact area between elemental S particles and the soil by allowing granules to disintegrate on the soil surface prior to their incorporation at seeding (Solberg 1986). Leaving granules of elemental S fertilizers on the surface of soil exposed to frost or rain speeds up the physical breakdown of the granules into fine particles,

allowing faster oxidation to sulfate (Solberg et al. 2003). In order to get maximum conversion of elemental S to sulfate-S, the autumn-applied granulated elemental S fertilizers in the present study were broadcast and left on soil surface until sowing of canola in the following spring. Autumn-applied elemental S fertilizers were more effective than their spring application in correcting S deficiency and improving seed and straw yield and S uptake of canola. This may reflect a greater conversion of elemental S to sulfate-S due to a longer period of exposure to dispersion over the autumn to spring period and then to microbial oxidation during the growing season with autumn application, but little or no oxidation with spring application, particularly in the first year of application. The canola seed yield and S uptake with both autumn and spring applications of elemental S were still less than both application times of sulfate-S-containing fertilizers, particularly ammonium sulfate, except ES-90 autumn application in 2000 and 2003. This suggests that granulated (pelletized) elemental S fertilizers cannot be recommended to correct S deficiency in S-sensitive annual crops (such as canola), because the oxidation rate is not rapid enough to satisfy the S requirements of the crop, even after six consecutive applications on the same area.

Elemental S fertilizers that disperse readily into small particles should improve the effectiveness of elemental S (Janzen 1990). The elemental S fertilizers used in this study contained bentonite or other dispersing agents to absorb water, swell, break down, and disperse into many small particles very quickly, but were still inferior to sulfate-S fertilizer. In another field experiment at same site, water suspension containing very fine elemental S particles sprayed on the soil surface after seeding of canola produced seed yield close to potassium sulfate in the year of application (Malhi et al. 2005). This suggests that physical dispersion of S particles from the elemental S granules for exposure to oxidation to sulfate-S was a major limitation under climatic conditions in the Parkland Region, as also observed by Wen et al. (2001).

Autumn application of ammonium sulfate was somewhat less effective in increasing seed and straw yield and S uptake than spring application in many cases. This was most likely due to overwinter loss of S from the soil sulfate-S pool. Sulfate-S is subject to leaching and possibly gaseous losses under wet conditions. In the Parkland region, soils are normally wet for 7-10 days in early spring after snow melting.

Increased oil concentration in seed above zero-S control was observed with Agrium Plus and ammonium sulfate in all years and with elemental S fertilizers in many cases. This indicates that when S deficiency exists, fertilization with sulfate-S can increase oil concentration in seed. Similar patterns of seed oil concentration response to S fertilizer on S-deficient soils have been obtained in Saskatchewan (Malhi and Gill 2002) and Manitoba (Grant et al. 2003a).

Application of ES-90 and ES-95 (especially when applied in spring) had little and inconsistent effect on oil concentration and S concentration in seed. This lack of consistent increase in seed S concentration and oil concentration reflects the inconsistent effect of elemental S fertilizers in increasing the quantity of sulfate-S available for crop uptake (Grant et al. 2003a, b). Sulfur fertilization decreased or tended to decrease protein concentration in 1999, whereas it increased or tended to increase protein

concentration in 2000 and 2003, and had very little effect in 2001, indicating an inconsistent effect. The increased oil concentration associated with S application could have led to a proportional decrease in seed protein concentration in 1999, as seed protein and oil concentrations tend to be inversely related (Ridley et al. 1972).

In field studies related to crop response of canola to elemental S fertilizers, the performance of elemental S fertilizers was usually inferior to sulfate-S fertilizers in the initial year (Solberg et al. 2007). Exposing the elemental S fertilizers and their particles to microbes for oxidation appears to enhance their availability for plants. Incorporation or broadcast methods are better than banding for the elemental S fertilizers. Application of elemental S fertilizers much in advance of crop use time is another technique to improve their effectiveness. Overall, correction of a severe S deficiency by elemental S alone may be risky in the short term, and thus addition of some sulfate-S in the initial 1 or 2 years to supplement the sulfate-S from elemental S is advisable. Then, annual applications of elemental S alone may be sufficient to supply the S requirements of crops, depending on crop species, soil type, and climatic zone. Increased exposure of elemental S fertilizers to oxidation, either by incorporation and broadcast methods or by application ahead of plant use time, tends to improve crop response.

The residual yield benefit to future crops from S fertilizer application may also occur due to carryover of sulfate-S in soil, from the release of sulfate-S from decomposing high S crop residues, and oxidation of previously applied elemental S fertilizers that did not become available to the crop in the years of application. In a field study on canola near Star City in northeastern Saskatchewan, Grant et al. (2001, 2003a) reported that the residual seed yield benefit from broadcast-applied elemental S was similar to sulfate-S fertilizer. In Alberta, Janzen and Karamanos (1991) also found similar residual response from elemental S suspension, granular elemental S, and sulfate-S on canola, but the residual benefits of these three S sources were small. In a field study on oilseed-cereal-legume rotation in Saskatchewan, Wen et al. (2003) found residual effects of sulfate-S and elemental S fertilizers on uptake of S in the second and third years after application, and S uptake in three years tended to be greater with elemental S than sulfate-S fertilizers. Karamanos and Poisson (2004) found that both ammonium sulfate and a number of elemental S sources had the same residual effect after 3 years in a canola-barley-canola rotation. Similarly in this case study, there was a significant residual effect on canola seed yield and S uptake in 2005 from both elemental S and sulfate-S sources. In 2006, although the crop was completely destroyed by deer grazing, we visually observed much better canola growth in plots that received S fertilizers previously compared to the zero-S control. The canola growth tended to be inferior in ammonium sulfate than elemental S fertilizers.

3.3.2 Residual Sulfate-S in Soil

Compared to zero-S control, preceding autumn application tended to increase the amount of sulfate-S at spring soil sampling of 1999 in the 0-15 cm for ES-90, and in the 15-30 and 30-60 cm depths for Agrium Plus and ammonium sulfate (data not

shown). In the later years, from 2000 to 2004, the residual sulfate-S amount extracted from soil was generally lower with elemental S than Agrium Plus and ammonium sulfate. The increased amount of sulfate-S in the 15-30 and 30-60 cm soil depths in some cases suggested some leaching of sulfate-S from the surface layer to subsoil layers. Autumn application generally tended to show more sulfate-S in soil than spring application, with some exceptions. However, the differences between autumn S application treatments and the zero-S control in terms of sulfate-S amount at spring sampling were always lower than the applied 15 kg S ha^{-1} . This loss from autumn application of sulfate-S probably resulted from immobilization and/or deep leaching. In the case of elemental S, this lesser recovery of S in the sulfate form was probably the result of partial oxidation of the amount applied as well as some loss after oxidation to sulfate-S. Also, larger concentration of sulfate-S was found in the deeper soil layers with autumn over spring applications and with S fertilization over the zero-S control, especially for Agrium Plus and ammonium sulfate. As samples were taken only to 60 cm soil depth, it is probable that some of the sulfate-S may have leached below the 60 cm depth.

The amount of sulfate-S in soil was less with elemental S than sulfate-S-containing fertilizers, especially with spring applications. Also, the increase in sulfate-S over the zero-S control was relatively smaller with elemental S compared to sulfate-S application, indicating more residual effect of consecutive S fertilization from sulfate-S than elemental S. The increase in sulfate-S from S fertilizers was not cumulative with time, but rather fluctuated from year to year, which suggested that S application is needed each year. This was contrary to the expectation of S fertility buildup from residual benefits of elemental S fertilizers. Earlier studies also observed no extra residual effect of elemental S compared to sulfate-S application (Janzen and Karamanos 1991, Grant et al. 2003a, b).

Elemental S sources applied annually for several years were expected to build long-term S fertility, which did not happen in this study. There was not sufficient available S from the elemental S fertilizers, as evidenced by low amounts of sulfate-S in soil at spring sampling, to produce optimum canola yield. The canola production and soil sulfate-S data clearly show that under the conditions of this study physical dispersion of the elemental S granules and their oxidation to sulfate-S were not rapid enough to supply canola plants sufficient amount of S early in the growth stage for optimum canola yield and S uptake when soils were deficient in plant-available S.

3.3.3 Effect of Balanced N and S Fertilization on Residual Nitrate-N in Soil

Because of the critical balance that exists between S and N in the plant, growth and seed production of canola has been shown to be affected by nutrient imbalances in soil, and S must be balanced with N and other nutrients for optimum yield of high-quality canola seed (Janzen and Bettany 1984, Malhi and Gill 2002). The N and S imbalance with too much N and too little S in the plant can impair protein and seed production. In the zero-S treatments, low seed yield indicates N:S imbalance, and

maximum seed yield with application of both N and S fertilizers indicates a proper balance of S with N to optimize seed yield along with high utilization efficiency of nutrients, water, and energy. Nutrient balance is thus essential, as too much N with insufficient amount of S will lead to S deficiency in plants, poor seed yield, and residual N in the soil. Similarly, in the present study, residual nitrate-N in the 0-60 cm soil was considerably higher in the zero-S control (i.e., plots receiving N fertilizer without S) than with applied S (i.e., plots receiving both N and S fertilizers together) (Table 2.5). Residual nitrate-N in soil also tended to be higher in some elemental S treatments than spring-applied ammonium sulfate. The higher amount of nitrate-N in soil in the N only treatment was most likely due to poor growth and N-use efficiency of applied nitrogen alone as compared to N + S fertilizer treatment. This suggests that imbalanced fertilization can result in accumulation of nitrate-N in soil at the end of the harvest season, which is subjected to leaching and gaseous N losses over the winter, especially in early spring after snow melt (Nyborg et al. 1990, Heaney et al. 1992). In other research in Saskatchewan, Malhi et al. (2002) also noticed greater accumulation of nitrate-N in soil under organic input (i.e., no input of fertilizer) in some cases than in soil receiving adequate amounts of both N and P fertilizers due to relatively low plant-available P for optimum crop growth in soil under an organic regime.

Table 2.5 Estimated amounts of nitrate-N in the 0-60 cm soil after growing canola without and with applied sulfate-S and elemental S fertilizers on S-deficient soils in north-eastern Saskatchewan (adapted from Malhi et al. 2005)

Location	Date of initiation	Date of soil sampling	S fertilizer treatment	Nitrate-N (kg N ha ⁻¹) in soil
Porcupine Plain	1999	Spring 2002	Control	194
			ES-90 – autumn	40
			ES90 – spring	50
			ES-95 – autumn	94
			ES95 – spring	73
			Agrium Plus – autumn	24
			Agrium Plus – spring	43
			Ammonium sulfate	50
			– autumn	
			Ammonium sulfate - spring	19
			LSD _{0.05}	76
Star City	2004	Spring 2005	SEM ^y	26.1 ^{**}
			Control	149 ^{**}
Tisdale	1999	Autumn 2002	Ammonium sulfate	106
			Control	179 [*]
			Ammonium sulfate	108

^ySEM refers to standard error of the mean. *, **, and *** indicate to treatment effect being significant at $P \leq 0.01$, $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; and ^{ns} indicate to treatment effect not significant

4 Conclusions

Rate of S oxidation in Canadian prairie soils under incubation is enhanced with increasing temperature with a maximum close to 40°C and moisture until lack of aeration above field capacity inhibited S oxidation. Oxidation of elemental S to sulfate-S is positively related to pH, organic matter content, nutrient-supplying power, and microbial activity, while it is inversely related to clay content of soil. Techniques that increase the oxidation rate of elemental S in soil include reducing particle size of the fertilizer product, using tillage to incorporate elemental S fertilizer into the soil to increase contact area between elemental S particles and soil microorganisms, and application in advance of crop demand to allow oxidation to occur before plants require this element. Elemental S fertilizers were not effective in increasing seed yield and S uptake of canola in the first year of application, particularly when applied in spring. With multiyear annual applications, elemental S fertilizers increased seed yield and S uptake significantly over the zero-S control, but usually not at the same level as with sulfate-S-containing fertilizers. Autumn-applied elemental S usually had greater seed yield and S uptake than the spring-applied elemental S, and the opposite was true for ammonium sulfate in 3 of 6 years. Oil concentration in canola seed showed trends similar to seed yield, though the effects were smaller and less frequent. The need for greater dispersion of elemental S particles from granular elemental S fertilizers, to enhance microbial oxidation to sulfate-S in soil, was considered to be the main requirement for increasing the short-term availability of S in elemental S fertilizers. Canola seed yield and N and S uptake with surface application of suspension and powder formulations of elemental S fertilizers were similar to sulfate-S fertilizer. The residual benefit of many successive annual elemental S fertilizer applications on soil S fertility was not cumulative. Residual nitrate-N in soil was much higher in the zero-S control than with applied S, and it also tended to be higher in some elemental S treatments than in spring-applied ammonium sulfate. In summary, the amount of elemental S fertilizer needed to adequately meet crop S requirements should be adjusted based on environmental conditions, soil properties, microbial activity, dispersion of elemental S particles from fertilizer granules, and balance between oxidation and immobilization, leaching, or other S losses in the Parkland region of Canadian Prairies.

Acknowledgements The authors thank Western Co-operative Fertilizers Limited, Agrium and Fernz SulFer Works for financial assistance; D. Leach, K. Fidyk and K. Hemstad-Falk for technical help and for the internal review of the manuscript.

References

- Association of Official Analytical Chemists (AOAC) (1990) Fat (crude) or ether extract in animal feed (920.39). Official methods of analysis, 15th ed. AOAC Washington DC Association of Official Analytical Chemists (AOAC) (1995) Protein (crude) in animal feed. Combustion method (990.03). Official methods of analysis, 16th ed. AOAC Washington DC

- Bertrand RA (1973) Reclaiming of soils made barren by sulfur from gas processing plants. M.Sc. Thesis, University of Alberta, Edmonton, Alberta, Canada
- Bettany JR, Janzen HH (1984) Transformations of sulphur fertilizers in prairie soils. In: Terry JW (ed) Proc. international sulphur '84 conference, Sulphur Development Institute of Canada Calgary, Alberta, Canada, pp. 817-22
- Bettany JR, Janzen HH, Stewart JWB (1983) Sulphur deficiency in the prairie provinces of Canada. Proc. Int. Sulphur '82 Conf., vol. 1 November 1982, London, UK, pp. 787-800
- Combs SM., Denning JL, Frank KD (1998) Sulphate-sulfur. In: Recommended chemical soil test procedures for the north central region. Missouri Agric. Expt. Sta. Publication No. 221 (revised). Extension and Agricultural Information, I-98 Agricultural Building, University of Missouri, Columbia, MO 65211, USA., pp. 35-39
- Doyle PJ, Cowell LE (1993) Sulphur. In: Rennie DA, Campbell CA, Roberts TL (eds) Impact of micronutrients on crop responses and environmental sustainability on the Canadian prairies. pp. 202-50
- Freney JR, Spencer K (1960) Soil sulphate changes in the presence and absence of growing plants. Aust J Agric Res 11:339-45
- Grant CA, Bailey LD (1993) Fertility management in canola production. Can J Plant Sci 73:651-70
- Grant CA, Johnston AM, Clayton GW (2001) Sulphur fertilizer forms and placements for canola. Proc. Manitoba Agronomists Conference 2000, 12-13 December 2000, Winnipeg, Manitoba, Canada. pp. 51-59
- Grant CA, Johnston AM, Clayton GW (2003a) Sulphur fertilizer and tillage effects on canola seed quality in the Black soil zone of western Canada. Can J Plant Sci 83:745-58
- Grant CA, Johnston AM, Clayton GW (2003b) Sulphur fertilizer and tillage effects on early season sulphur availability and N:S ratio in canola in western Canada. Can J Soil Sci 83:451-63
- Heaney DJ, Nyborg M, Solberg ED, Malhi SS, Ashworth J (1992) Overwinter nitrate loss and denitrification potential of cultivated soils in Alberta. Soil Biol Biochem 24:877-84
- Huang CL, Schulte EE (1985) Digestion of plant tissue for analysis by ICP-AES. Commun. Soil Sci Plant Anal 16:943-58
- Janzen HH (1984) Sulphur nutrition of rapeseed. Ph.D. Thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada
- Janzen HH (1990) Elemental sulphur oxidation as influenced by plant growth and degree of dispersion within soil. Can J Soil Sci 70:499-502
- Janzen HH, Bettany JR (1984a) Sulfur nutrition of rapeseed. I. Influence of fertilizer nitrogen and sulfur rates. Soil Sci Soc Am J 48:100-7
- Janzen HH, Bettany JR (1984b) Sulfur nutrition of rapeseed. II. Effect of time of sulfur application. Soil Sci Soc Am J 48:107-12
- Janzen HH, Bettany JR (1986) Release of available sulfur from fertilizers. Can J Soil Sci 66:91-103
- Janzen HH, Bettany JR (1987a) Oxidation of elemental sulphur under field conditions in Central Saskatchewan. Can J Soil Sci 67:609-18
- Janzen HH, Bettany JR (1987b) The effect of temperature and water potential on sulfur oxidation in soils. Soil Sci 144:81-9
- Janzen HH, Bettany JR (1987c) Measurement of sulphur oxidation in soils. Soil Sci 143:444-52
- Janzen HH, Karamanos RE (1991) Short-term and residual contribution of selected elemental S fertilizers to the S fertility of two Luvisolic soils. Can J Soil Sci 71:203-11
- Karamanos RE, Janzen HH (1991) Crop response to elemental sulfur fertilizers in Alberta. Can J Soil Sci 71:213-25
- Karamanos RE, Poisson DP (2004) Short and long term effectiveness of various S products in prairie soils. Commun Soil Sci Plant Anal 35:2049-66
- Malhi SS (2005) Influence of four successive annual applications of elemental S fertilizers on yield, S uptake and seed quality of canola. Can J Plant Sci 85:777-92
- Malhi SS, Gill KS (2002) Effectiveness of sulphate-S fertilization at different growth stages for yield, seed quality and S uptake of canola. Can J Plant Sci 82:665-74

- Malhi SS, Solberg ED, 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
- Noellemeyer EJ, Bettany JR, Henry JL (1981) Sources of sulphur for rapeseed. *Can J Soil Sci* 61:465-7
- Nuttall WF, Boswell CC, Sinclair AG, Moulin AP, Townley-Smith LJ, Galloway GL (1993) The effect of time of application and placement of sulphur fertilizer sources on yield of wheat, canola, and barley. *Commun Soil Sci Plant Anal* 24:2193-2202
- Nyborg M, Malhi SS, Solberg ED (1990) Effect of date of application on the fate of ^{15}N -labelled urea and potassium nitrate. *Can J Soil Sci* 70:21-31
- Ridley AO (1972) Effect of nitrogen and sulfur fertilizers on yield and quality of rapeseed. *Proc. 17th Annual Manitoba Soil Science Meeting*, January 1972, University of Manitoba, Winnipeg, Manitoba, Canada. pp. 182-7
- SAS Institute Inc (1993) SAS/STAT user's guide. ver 6, 4th ed, vol. 2. Cary, NC, USA
- Schoenau JJ, Germida JJ (1992) Sulphur cycling in upland agricultural systems. In: Howarth RW, Stewart JWB, Ivanov MV (eds.), *Sulphur cycling on the continents*, John Wiley and Sons, New York, pp. 261-77
- Solberg ED (1986) Oxidation of elemental S fertilizers in agricultural soils of northern Alberta and Saskatchewan. MSc. thesis. University of Alberta, Edmonton, Alberta, Canada
- Solberg ED, Laverty DH, Nyborg M (1987) Effect of rainfall, wet-dry, and freeze-thaw cycles on the oxidation of elemental sulfur fertilizers. *Proc Alberta Soil Science Workshop*, February 1987, Edmonton, Alberta, Canada. pp. 120-6
- Solberg ED, Malhi SS, Nyborg M, Gill KS (2003) Fertilizer type, tillage, and application time effects on recovery of sulfate-S from elemental sulfur fertilizers in fallow field soils. *Commun Soil Sci Plant Anal* 34:815-30
- Solberg ED, Malhi SS, Nyborg M, Gill KS (2005a) Source, application method, and cultivation effects on recovery of elemental sulfur as $\text{SO}_4\text{-S}$ in incubated soils. *Commun Soil Sci Plant Anal* 36:847-62
- Solberg ED, Malhi SS, Nyborg M, Gill KS (2005b) Temperature, soil moisture, and antecedent S application effects on recovery of elemental sulfur as $\text{SO}_4\text{-S}$ in incubated soils. *Commun Soil Sci Plant Anal* 36:863-74
- Solberg ED, Malhi SS, Nyborg M, Henriquez B, Gill KS (2007) Crop response to elemental S and sulfate-S sources on S-deficient soils in the Parkland region of Alberta and Saskatchewan. *J Plant Nutr* 30:321-333
- Statistics Canada (2002) Agriculture 2001 Census – Data Tables: <http://www.statcan.ca/english/freepub/95F0301XIE/tables.htm>.
- Swan M, Soper RJ, Morden G (1986) The effect of elemental sulphur, gypsum and ammonium thiosulphate as sulphur sources on yield of rapeseed. *Commun Soil Sci Plant Anal* 17:1383-90
- Wen G, Schoenau JJ, Yamamoto T, Inoue M (2001) A model of oxidation of an elemental sulfur fertilizer in soils. *Soil Sci* 166:607-13
- Wen G, Schoenau JJ, Mooleki SP, Inanaga S, Yamamoto T, Hamamura K, Inoue M, An P (2003) Effectiveness of an elemental sulfur fertilizer in an oilseed-cereal-legume rotation on the Canadian prairies. *J Plant Nutr Soil Sci* 166:54-60
- Ukrainetz H (1982) Oxidation of elemental sulphur fertilizers and response of rapeseed to sulphur on Gray Wooded soils. *Proc. 19th Annual Alberta Soil Science Workshop*, 23-24 February, 1982. Edmonton, Alberta, Canada. pp. 278-307



<http://www.springer.com/978-3-540-76326-0>

Sulfur Assimilation and Abiotic Stress in Plants

Khan, N.A.; Singh, S.; Umar, S. (Eds.)

2008, XIV, 372 p.,

ISBN: 978-3-540-76326-0