

CHAPTER 6

Sulphur

P.J. Doyle and L.E. Cowell¹

ABSTRACT

Sulphur (S) deficient soils were first identified on Luvisols on the Canadian prairies in 1927 when dramatic responses by legumes to soluble sulphate fertilizers were obtained.

Sulphur deficient soils are rare in the Chernozemic soil regions because these soils contain relatively large amounts of ester bonded sulphates in the soil organic matter. Generally, soils with low organic matter content, or cold wet soils, are usually deficient in S (and also N). Slope position directly affects the form, amount and profile distribution of S, with lower slope positions containing larger amounts of soluble sulphate. Mineralization and immobilization processes also affect the content of soluble sulphates present within the rooting zone.

Of the 36 M ha of cultivated soils across the prairie provinces, approximately 4.0 M are deficient and 6.7 M are potentially deficient in S. Thus, production is potentially limited by shortage of S in about 30% of soils. Sulphur is the third most limiting nutrient to crop production on the prairies after N and P.

Sulphur fertilizers can conveniently be grouped into two categories: (i) those containing $\text{SO}_4\text{-S}$ which is generally highly available, and (ii) elemental S forms which require oxidation prior to becoming plant available. The former are used extensively while the latter (high analysis) have slow release properties which contribute to long-term availability. Elemental S oxidation rates are, however, unpredictable as they are dependent on soil temperature, water content, and the population of S-oxidizing bacteria.

The increase in area of S-deficient cultivated soils noted in the last decade, is partly related to the increase in extended cropping, partly to the significantly higher crop yields being obtained, and partly to the increased production of high S-requiring crops, such as canola.

Strong interactions between N and S have been recorded with canola. Where the N/S ratio is wide (such as a S-deficient soil), N fertilization can result in a sharp decrease in grain yields of this oilseed crop and vice versa. A desirable N/S ratio for canola is approximately 7.

Subsoil S reserves are an important and effective source of available S.

Extensive S fertilization tests have been conducted in Alberta, Saskatchewan, and Manitoba. Generally, crop response to S fertilization has been less frequent in Manitoba than in Saskatchewan and Alberta.

¹ Ciba-Geigy Canada Ltd., Plant Protection Division, 484 Henderson Dr., Regina, SK, S4N 6E3, and Dept. of Soil Science, Univ. of Saskatchewan, Saskatoon, SK, S7N 0W0.

Sulphur fertilization can have a large influence on oilseed quality. Both the protein concentration and total yield of oil may be enhanced by addition of S; however, increases in oil concentration are less frequently encountered than increases in protein. In general, the extensive field testing that has taken place has illustrated that responses to S on S-deficient soils can vary widely from year to year. However, a wise manager will rely on a reliable soil test for guidance.

CONTENTS

	<u>Page</u>
6 ABSTRACT.....	202
INTRODUCTION.....	205
FACTORS AFFECTING S DEFICIENCY.....	205
SULPHUR DEFICIENT AREAS.....	207
SULPHUR FERTILIZERS	209
Sulphate Sources.....	210
Elemental S	210
Other S Sources	212
CROP RESPONSE TO S ADDITIONS	212
Cereals and Grain Legumes.....	213
Alberta.....	213
Manitoba.....	219
Saskatchewan.....	221
Grain Quality	224
Oilseeds	225
Nitrogen/S balance	225
Yield responses.....	226
Oilseed quality	240
CONCLUSIONS	241
REFERENCES	243

INTRODUCTION

Sulphur deficiencies in Western Canada were first identified in 1927 on Luvisolic (Grey Wooded) soils of Alberta. Experiments conducted as early as 1935 showed yield responses of clover crops to applications of ammonium sulphate and gypsum (Newton, 1936). During the next decade, dramatic responses to S fertilization were reported for legume crops grown on the University of Alberta Breton Experimental Station (Cormack et al., 1951; Agriculture Canada, 1957). Similarly, beneficial effects of S fertilization were reported for alfalfa grown on the Luvisolic soils, particularly the lighter-textured soils in northeastern Saskatchewan (Rowles, 1938). By 1947, the need for S fertilization on most sandy Luvisolic soils had been clearly established (Schalin, 1947).

The earliest recorded investigations of the S status of Manitoba soils were conducted in the 1960s (Soper, 1963), but it was not until the early 1970s that it was established that soils likely to be S-deficient were the Luvisolic and the well-drained coarse-textured soils (Bailey, 1978; Hamm, 1967).

Until the late 1960s, cereal grains and grasses were generally considered insensitive to S deficiencies, apparently because early S field experiments included little or no N. Nyborg (1968) eventually showed that cereal grains were as sensitive as most crops to a S deficiency when other nutrients were in good supply. Large yield responses of barley and oats were reported at seven Alberta sites, when combinations of N and S were used (Nyborg and Bentley, 1971), at four of these sites the application of N alone or S alone had little effect.

An excellent general review of research on the S requirements of cereals, fruits, vegetables, and other crops is provided by Beaton (1966).

FACTORS AFFECTING SULPHUR DEFICIENCY

Generally, reports of S-deficient soils are common on Gray Luvisolic soils and rare for Brown and Dark Brown Chernozems. Three factors may be responsible for this

occurrence (Janzen, 1984a, b): 1) the potential for S mineralization decreases from the Brown to Gray soil zones because of widening C:S ratios and declining proportions of ester-bonded SO_4^{2-} in soil organic matter; 2) in more humid Gray Luvisolic soils, the generally higher crop yields, the selection of crops which have a large S requirement (e.g., canola and alfalfa), and the increased frequency of stubble cropping, accelerates S removal from soil; and 3) there is greater leaching of soil gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) from the rooting zone in more humid soil zones.

Uncultivated Gray Luvisolic soils have relatively large amounts of organically bound S; however, most of this S is associated with the surface L-H horizon which upon cultivation is rapidly lost through organic matter decomposition (Lowe, 1965; Roberts and Bettany, 1985). The organic S fractions in Chernozemic soils are generally not subject to such rapid degradation and they provide a more stable reserve of available soil S.

Generally, soils with low organic matter levels, or cold wet soils with slow organic matter decomposition rates, are usually deficient in both available N and S. Sulphur-deficient soils typically have low amounts of inorganic S (e.g., CaSO_4) within the rooting zone and tend to release small amounts of S through the mineralization of soil organic matter (Cairns and Richer, 1960; Nyborg et al., 1986).

Field topography has been shown to influence the forms, amounts, and distribution of soil S. In Saskatchewan, lower slope positions of a catena sequence were found to have larger amounts of soluble $\text{SO}_4\text{-S}$ (in surface and in sub-soil horizons), relative to soils at higher slope positions (Roberts and Bettany, 1985). In some fields, acute S deficiencies in soil may only occur on the knolls and not in the depressional areas of the field (Nuttall and Ukrainetz, 1991).

Plant availability of S in prairie soils is also dependent on the dynamics of the soil microbial population. Microbial turnover of S has a great effect on the short-term supply of S in soils, especially where most of the S is in organic fractions and inorganic $\text{SO}_4\text{-S}$ concentrations are low (Saggar et al., 1981). Mineralization and immobilization processes,

governed by soil microbes, have a large influence on available levels of grassland and parkland soils (Maynard et al., 1984).

For detailed information regarding the nature and transformations of S within the soil S cycle (Fig. 1), the reader is referred to reviews by Biederbeck (1978), Kowalenko (1978), Stewart and Bettany (1982), and Germida et al. (1992).

SULPHUR DEFICIENT AREAS

The distribution pattern of S deficiencies among prairie soils may be related to factors governing soil formation. Differences in climate and vegetation across the soil zones have had a notable influence on the nature and distribution of soil S (Bettany et al., 1973).

Beaton et al. (1974) estimated that there are approximately 1.6 million ha of agricultural land in the prairie provinces which may be considered borderline S-deficient. Eight years later, Bettany et al. (1982) concluded that of the 36 million ha of cultivated soil in the prairie provinces, approximately 4.0 million were S-deficient, and another 6.7 million ha were potentially S-deficient. The move from potentially deficient to deficient can be expected to occur on well-drained soils where farming practices lead to declining soil organic matter (Bettany et al., 1973).

Prior to the mid 1960s, most S responses in Alberta were confined to Gray Luvisolic soils; however, more recent research has shown that S-deficient soils are also present in the Black, and Dark Brown Chernozemic soils (Bentley, 1974; Walker, 1969a). Fifteen percent of the improved cropland in central and northern Alberta (approximately 1.2 million ha) is rated low in S for cereal grains and grasses. For canola and legume crops, as much as 46% (2.5 million ha) of the improved land in these areas may be deficient (McGill, 1987).

Manitoba soils that are suspected of being S-deficient are the coarse-textured, well-drained Black and Dark Gray soils. Measurement of water soluble $\text{SO}_4\text{-S}$ in Manitoba

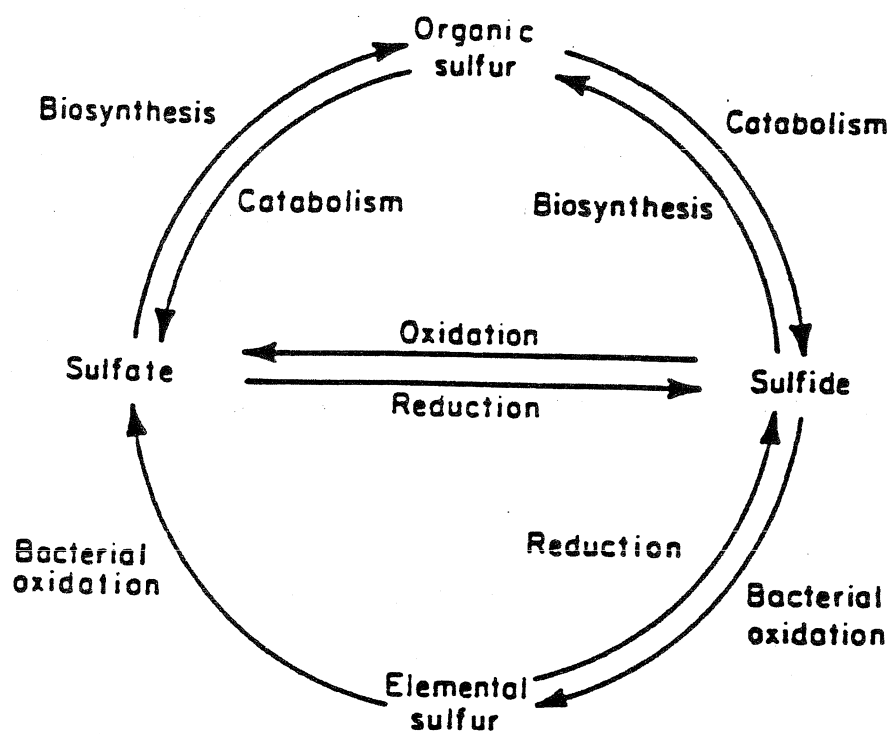


Figure 1. The sulfur cycle (Biederbeck, 1978).

soils in the mid 1960s indicated that most soils contained adequate levels of plant available S. The lowest $\text{SO}_4\text{-S}$ contents were found in soils from the Stockton Association (Anderson, 1966). More recently, 200 000 ha (4%) of the cultivated land in Manitoba has been estimated as S-deficient for the production of cereals. A total of 500 000 ha (11%) of Manitoba's cultivated land requires S fertilization for optimal canola and alfalfa production (McGill, 1987). During the period 1979 to 1991, an average of 14% (range = 6 to 22%) of field samples submitted to the soil testing laboratory in Manitoba for analysis received a recommendation for S fertilizer (McGill, 1991).

In Saskatchewan, approximately 2.5 million ha of S-deficient soils occur in the northern agricultural areas. Most of these soils are in the Dark Gray and Gray Luvisolic soil zones. About 20% of the S-deficient Gray Luvisolic soils in Saskatchewan are located in the northwestern part of the province. Sulphur deficiencies have also been identified in the Dark Brown soil zone of Saskatchewan (Janzen and Bettany, 1981). In an earlier report, Hamm et al. (1973) estimated that 4, 10, and 19% of the soils in the Black, Gray-Black, and Gray soil zones, respectively, were low in plant-available S.

SULPHUR FERTILIZERS

There are a number of S fertilizers available for use in correcting S deficiencies in crops. The majority of these materials may be split into two groups: sulphate (SO_4) forms, which are readily available for plant assimilation, and non-sulphate forms which require oxidation to $\text{SO}_4\text{-S}$ to become plant available (e.g., elemental S). In general, S sources cannot be ranked in order of effectiveness because each form fulfills a different role in crop nutrition (Janzen and Bettany, 1986). Soluble forms (e.g., $(\text{NH}_4)_2\text{SO}_4$) may be used to correct acute S deficiencies, while slow release products (e.g., elemental S, or S bentonite products) may be used to gradually maintain soil S fertility (Janzen and Karamanos, 1991). Beaton et al. (1971) provide a comprehensive review of the nature and properties of S fertilizers used throughout North America.

Sulphate Sources

Under adequate moisture conditions, spring broadcast or broadcast-incorporated applications of water soluble $\text{SO}_4\text{-S}$ will be readily available for crop use. When soil conditions are dry, side- or deep-banding of $\text{SO}_4\text{-S}$ may be more effective. Seed-placed $\text{SO}_4\text{-S}$ is also readily available; however, crops such as canola may be sensitive to high rates of seed-placed S fertilizer. Poor germination and reduced canola yield may result from over-application of S in the seed placed form (Grant and Bailey, 1991).

Although $\text{SO}_4\text{-S}$ fertilizers should be applied prior to, or at seeding, post-seeding applications have been shown to increase crop yields (Ukrainetz, 1982). In the growth chamber, applications of $\text{SO}_4\text{-S}$ up to the rosette stage may correct S deficiencies in canola without sacrificing yield or maturity (Janzen and Bettany, 1984b). However, under field conditions, $\text{SO}_4\text{-S}$ application after seeding has resulted in significant yield reductions of some canola cultivars (e.g., *napus* species) (Nuttall and Ukrainetz, 1991).

In a growth chamber experiment, Janzen and Bettany (1986) examined S release from various fertilizers and found that soluble S sources (sulphate and thiosulphate) were plant available shortly after application. Because of their high solubility, $\text{SO}_4\text{-S}$ fertilizers are subject to leaching losses which may limit their effectiveness in the following growing season.

In the year of application, $\text{SO}_4\text{-S}$ fertilizers are much more likely to produce a crop response than elemental S (S^0) sources.

Elemental S

A common problem with S^0 fertilizer in prairie soil conditions is slow or incomplete conversion to the SO_4 form (Harapiak, 1980; Nyborg et al., 1980; Ukrainetz, 1982). As a result, S^0 sources should be applied as far in advance of seeding as possible and should be well-mixed with soil to encourage S oxidation (Hagstrom, 1986; Swan et al., 1986). Adjustments in S^0 particle size and rate of application may also have to be made to

compensate for the delay in obtaining plant available S from this source (Janzen and Bettany, 1987b).

The efficiency with which S^0 can be used to meet plant needs is dependent on its oxidation to SO_4 -S. Some soil factors which affect S^0 oxidation include: temperature, moisture, aeration, and the population density of S oxidizing microbes (e.g., *Thiobacillus* bacteria) (Nyborg et al., 1980; Solberg et al., 1987; Nuttall et al., 1990). Sulphur oxidation is especially responsive to changes in soil temperature. This sensitivity may account for the limited effectiveness of some S^0 applications on prairie soils where soil temperatures remain below 15°C for most of the year (Janzen and Bettany, 1987a).

Elemental S oxidation rates in soils are also influenced by the degree of dispersion within the soil, which determines the extent of contact between soil and S^0 particles (Solberg et al., 1987; Janzen, 1990). Fertilizer materials with relatively large diameters generally oxidize slowly in prairie soils (Janzen, 1986; Ukrainetz, 1982; Solberg and Nyborg, 1982). Application methods may also reduce contact area and slow the oxidation process. Banding or nesting the S, places large numbers of small particles in close proximity to one another, and reduces the exposed surface area which slows the oxidation process (Nyborg et al., 1980; Solberg et al., 1986). Cultivation practices during or after application also affect S^0 oxidation rates because cultivation can greatly increase contact between fertilizer and soil (Nyborg et al., 1980; Solberg and Nyborg, 1982; Solberg et al., 1982).

Spring-applied S^0 is not recommended for annual crops on S-deficient soils because S oxidation rates are typically less than the SO_4 -S demand by crops (Noellemeyer et al., 1981). However, residual effects of S^0 fertilizers in subsequent years tends to produce similar crop responses as SO_4 sources applied in the current year (Solberg et al., 1986; Nuttall et al., 1990; Grant, 1991). Elemental S fertilizers blended with bentonite clay are not expected to provide much plant available SO_4 -S in the year of application, but may

lead to residual effects in the second and third year after application (Janzen et al., 1987; Janzen and Karamanos, 1991).

Research has shown that the annual applications of S^0 can significantly alter the microbial activities within a S-deficient soil (Gupta et al., 1988). Heavy or repeated applications of S^0 may eventually increase the S^0 oxidation potential of a soil to several tonnes per hectare per year by increasing soil *Thiobacillus* populations (Bertrand, 1973; Nyborg, 1974). In other words, the initial oxidation of S^0 fertilizer in a soil may enhance the effectiveness of subsequently applied S^0 for crop use and enhance the 'residual effect' of this S source (Noellemeyer et al., 1981; Janzen and Bettany, 1987b).

Other S Sources

During the 1960s, the presence of increased S in the atmosphere, resulting from oil and gas production and S extraction plants in west central Alberta, may have been a partial reason for a slight reduction in the number of fertilizer tests responding positively to S fertilizer on Gray soils of this region (Walker, 1969b). Beaton and Soper (1986) provide a thorough review of the agricultural implications of S emissions from industrial sources in western Canada.

CROP RESPONSES TO S ADDITIONS

The increase in the need for S research and the increased need to apply S throughout the late 1970s were related to: i) increased annual cropping; ii) use of higher yielding crops; iii) less incidental application of S in higher analysis fertilizers/pesticides; iv) use of heavier rates of N and other fertilizer sources; and v) increased production of oilseed crops (Beaton and Soper, 1986).

Sulphur research increased with oilseed production because of the high S requirements of oilseed crops. For example, to produce adequate seed yields, canola requires between 3 and 10 times as much S as a cereal such as barley (Bole and Pittman,

1984; Hamm, 1967). For this reason, yield response to S application is often obtained for canola on sites where no S response occurs for cereals (Hamm, 1967; Nyborg et al., 1974). Oilseed crops have a relatively high S requirement because the oil storage organs of these plants are usually rich in S-containing proteins (Stanford and Jordan, 1966).

Cereals and Grain Legumes

Although wheat, barley, and oats are generally considered to have a low metabolic demand for S (Bettany et al., 1982), yield increases to applied S fertilizers have often been quite dramatic (Beaton and Soper, 1986). The majority of the data reported was obtained from field experiments conducted on previously selected 'S-deficient' soils in the more humid regions of the prairies.

Alberta: Bentley et al. (1955) reported sizeable yield increases for wheat, oats and barley grown on Gray Luvisols when fertilized with Na_2SO_4 at 25 kg ha^{-1} (Table 1). Yield increases from S addition were also reported for wheat, oats, and barley on soils which had received $(\text{NH}_4)_2\text{SO}_4$ continually for 20 years (Bentley et al., 1955). While yield increases were highly variable for each crop, wheat generally showed the greatest mean response to S fertilization. On the Breton plots (Gray Luvisolic), three out of four wheat trials showed a significant yield response to S, barley and oats only produced one significant yield increase. No significant yield increases from S addition were obtained in any of the University of Alberta experiments (Table 2). No mention of a residual response to S was reported for these experiments. However, yield increases obtained from SO_4 -S fertilization on soils which had already received long-term application of S fertilizer suggest a minimal residual benefit from previous S additions.

Limited studies of the S needs of crops grown elsewhere in Alberta were determined in the 1950s. At Chedderville, Alberta, the application of 22 kg ha^{-1} of S^0 to a S-deficient Grey Luvisolic soil increased wheat yields by 10.4% relative to the control (Agriculture Canada, 1958). Sulphur fertilization is most effective when applied with

Table 1. Average yield responses of small grains to S application on soils which had never received fertilizer S. (Sulphur broadcast annually as Na_2SO_4 at 25.3 kg ha^{-1}) (from Bentley et al., 1955).

Crop	Average yield		Yield inc.	No. of trials
	Control	Fertilized		
		(kg ha ⁻¹)	(%)	
Gray Wooded soils [†]				
Wheat	1422	1619	14	12
Oats	2192	2520	15	24
Barley	1773	1971	11	18
Barley ^{††}	1642	1690	3	6
Breton [*]				
Wheat	949	1830	93	20
Oats	667	1131	70	10
Barley	316	565	79	10
U of A [§]				
Wheat	2482	2731	10	8
Barley	2041	1910	-6	8

[†] S-deficient Gray Wooded soils (Ave. total S = 123 $\mu\text{g g}^{-1}$, pH = 6.5)

^{††} Lacustrine soil in the Black soil zone (Ave. total S = 400 $\mu\text{g g}^{-1}$, pH = 6.1)

[‡] Breton loam soil (Grey Wooded soil, Ave. total S = 100 $\mu\text{g g}^{-1}$, pH = 6.5)

[§] University of Alberta plots (Grey Wooded soil, Ave. total S = 670 $\mu\text{g g}^{-1}$, pH = 5.9)

Table 2. Yield responses of small grains to S application on soils which had received fertilizer S continually for 20 years. (Sulphur broadcast as Na_2SO_4 at 25.3 kg ha^{-1}) (from Bentley et al., 1955).

Crop	S rate [†]	Yield		Yield inc.	Statistical significance	No. trials
		Control	Fertilized			
	(kg ha^{-1})	(kg ha^{-1})		(%)		
Breton [‡]						
Wheat	14.7	774	1178	52.3	($P \leq 0.05$)	5
Wheat	14.7	2059	2225	8.1		5
Wheat	14.7	1690	2737	62.0	($P \leq 0.01$)	5
Wheat	14.7	2523	3641	44.3	($P \leq 0.05$)	5
Oats	14.7	1416	1285	-9.2		5
Oats	7.1	797	1345	68.7	($P \leq 0.05$)	5
Barley	14.7	536	595	11.1		5
Barley	7.1	928	1297	39.7	($P \leq 0.05$)	5
U of A [§]						
Wheat	12.7	3379	2011	8.3		4
Wheat	12.7	1999	2023	1.2		4
Barley	12.7	3142	2884	-9.5		4
Barley	12.7	1571	1714	9.1		4

[†] Sulphur applied as $(\text{NH}_4)_2\text{SO}_4$ on plots every year since 1930

[‡] Breton loam soil (Grey wooded soil zone, Ave. total S = $100 \mu\text{g g}^{-1}$, pH = 6.5)

[§] University of Alberta, Soils Dept. plots (Grey Wooded soil total S = $670 \mu\text{g g}^{-1}$, pH = 5.9)

adequate amounts of other nutrients. Thus, the application of N and P_2O_5 alone only increased wheat yields by 7.4% relative to the control, but sulphur, when applied with N and P_2O_5 , resulted in the highest wheat yields (Table 3). Sulphur applied without adequate N, P, and K fertility, will often produce disappointing yield results. Nyborg (1968) conducted a series of experiments to determine the response of oats to Na_2SO_4 fertilization on four Gray Luvisolic soils in northern Alberta. In six field tests, S did not increase the yield of oats when applied by itself. However, when S application was combined with NPK, it increased oat yields in five of the tests. The average yield for the NPKS treatment was 1010 kg ha^{-1} higher than the yield of the NPK treatment. The most dramatic yield difference was on the Beryl soil where NPKS gave a grain yield of 2580 kg ha^{-1} and NPK only 960 kg ha^{-1} . Similar results were obtained for barley from S fertilization in a series of experiments conducted on three S-deficient Gray Luvisolic soils (Nyborg and Bentley, 1971; Nyborg et al., 1974). In this study no yield benefit was observed from adding the S alone at 22 kg ha^{-1} .

On a Gray Luvisolic soil in Alberta, Solberg et al. (1982) reported that barley yields were highest when N and S were applied together. The application of N or S fertilizer alone gave significantly lower barley yields than N plus S and, in terms of fertilizer recovery, fine S^0 and urea-S fertilizers were approximately half as effective as the soluble Na_2SO_4 source (Table 5). The limited effectiveness of the S^0 sources was likely due to incomplete oxidation of S^0 to the SO_4 form. Other experiments on Gray Luvisolic soils (Beaverlodge) have shown yield responses of 9 and 70 % for oats fertilized with broadcast Na_2SO_4 (Nyborg, 1965; Nyborg and Hoyt, 1965).

Several other field trials involving response of various cereals to S fertilizer have been conducted in Alberta (Table 6). Yield responses of barley ranged from 12 to 142%, with an average barley yield increase of 714 kg ha^{-1} from S fertilization. Yield increases were also noted for oats and wheat crops fertilized with S.

Table 3. Effect of fertilizers on 10-year average wheat yields on a Caroline loam soil at Chedderville, Alberta (1946-1955) (from Agriculture Canada, 1958).

Treatment	N	Fertilizer P ₂ O ₅	S	Wheat yield [†]
	———— (kg ha ⁻¹) ————			
1	0	0	0	2310
2	0	0	22	2550
3	18	22	0	2480
4	18	22	22	3020

[†] Wheat seeded after one fallow year on soil previously cropped to legume hay

Table 4. Yields of oats in field tests with different N,P,K, and S fertilizers on four Gray Luvisolic Alberta soils (from Nyborg, 1968).

Fertilizer	Oat grain yield					
	Beryl	Braeburn	Demmitt		Hazelmere	
	1966	1966	1965	1966	1965	1966
	———— (kg ha ⁻¹) ————					
None	570 <i>a</i> [§]	1300 <i>a</i>	810 <i>a</i>	1400 <i>a</i>	1150 <i>a</i>	1340 <i>a</i>
S [†]	690 <i>a</i>	1350 <i>a</i>	820 <i>a</i>	1290 <i>a</i>	1270 <i>a</i>	1600 <i>a</i>
NPK [‡]	960 <i>a</i>	1410 <i>a</i>	2320 <i>b</i>	2990 <i>b</i>	1880 <i>b</i>	1950 <i>b</i>
NPKS	2580 <i>b</i>	2700 <i>b</i>	2510 <i>b</i>	3560 <i>c</i>	3030 <i>c</i>	3180 <i>c</i>

[†] S applied at 22 kg ha⁻¹ as Na₂SO₄

[‡] NPK applied at 67, 15, and 34 kg ha⁻¹ (1965) and 67, 22, and 28 kg ha⁻¹ (1966)

[§] In each column, values with different letters are significantly different at the 95% probability level

Table 5. Yield and S uptake response of barley grain fertilized with 11.2 or 70.0 kg ha⁻¹ of S fertilizer—Glendon site, 1981 (from Solberg et al., 1982).

Treatment	Nutrient rate		Yield	Recovery of S fertilizer in grain
	N	S		
	(kg ha ⁻¹)			(%)
Check	0	0	1820 <i>d</i> [‡]	--
Urea [†]	112	0	2280 <i>cd</i>	--
Urea [§]	112	0	2480 <i>bc</i>	--
Urea [†] + Na ₂ SO ₄	112	11.2	3150 <i>a</i>	20.1
Urea [§] + Na ₂ SO ₄	112	11.2	2950 <i>ab</i>	20.1
Urea [†] + Urea-S	112	11.2	2750 <i>abc</i>	10.8
Urea [§] + Urea-S	112	11.2	2680 <i>abc</i>	3.6
Urea-S [†]	112	70.0	2960 <i>ab</i>	3.0
Urea-S [§]	112	70.0	2960 <i>ab</i>	1.3

[†] Early application: May 1, [§] Late application: May 23. Urea-S = urea coated S

[‡] In each column, values with different letters are significantly different at the 95% probability level

Table 6. Summary of cereal yield response to S application for Alberta soils (from Beaton and Soper, 1986).

Crop	Number of tests	Yield		Yield increase	Reference
		Control	Fertilized		
		(kg ha ⁻¹)		(%)	
Barley	1	1021	2473	142	Walker, 1968
Barley	1	1720	2204	28	Walker, 1968
Barley	1	2009	2512	25	Beaton and Soper, 1986
Barley	1	2160	2830	31	Ratanalert, 1973
Barley	1	2480	3270	32	Dick, 1974
Barley	1	5280	5941	12	Bole and Pittman, 1979
Barley	3	3542	3979	12	Berg, 1982
Oats	2	2050	2710	32	Dick, 1974
Oats	1	1831	2279	24	Berg, 1982
Wheat	1	1245	1596	28	Beaton and Soper, 1986
Wheat	2	1873	2268	21	Dick, 1974

Bole and Pittman (1984) conducted experiments in southern Alberta to determine the effect of subsoil S on S nutrition of barley. Barley was found to be adequately supplied with $\text{SO}_4\text{-S}$ at a depth of 54-72 cm. The crop obtained 55% of its S nutrition from a high $\text{SO}_4\text{-S}$ ($25 \mu\text{g g}^{-1}$) layer of soil at that depth, although 40 days of growth were required before the S was effectively utilized.

McKenzie et al. (1987) reported that S fertilization (30 kg ha^{-1}) had no effect on the yield of wheat or barley in a series of experiments conducted from 1982 to 1986 on irrigated soils of southern Alberta. They attributed the lack of yield response to relatively high $\text{SO}_4\text{-S}$ levels in the irrigation water (approximately 33 kg SO_4 was applied with every 30 cm of irrigation water). A second possible explanation was related to the $\text{SO}_4\text{-S}$ in the subsoil of the research plots.

In experiments conducted in central Alberta, response to (i) broadcast S application, (ii) a S/bentonite blend (90% S^0), and (iii) a finely divided S^0 'flowable' suspension (95% S^0), were compared to ammonium sulphate over a two year period (Karamanos and Janzen, 1989, 1991). In the year of application, the $\text{SO}_4\text{-S}$ forms and flowable S^0 products (thoroughly mixed with soil upon application) corrected S deficiencies in 'Bonanza' barley (Fig. 2) whereas application of the S^0 /bentonite blend had no effect. No residual benefit was observed from any of the fertilizers after three years of application despite large differences in short-term availability of the fertilizer products.

Manitoba: One of the first field experiments conducted to document cereal response to S in Manitoba was carried out at Roland where a 15% yield increase was obtained for oats fertilized with 40 kg ha^{-1} of $(\text{NH}_4)_2\text{SO}_4$ (Beaton et al., 1966). In contrast, barley, which in three field experiments responded strongly to N and P, did not respond to S (Hamm, 1967).

The yields of fababeans (not shown) and soybeans (Fig. 3) were directly proportional to rates of S^0 broadcast before seeding on three S-deficient light-textured soils in Western Manitoba (Bailey, 1976, 1977). However, a series of field trials with grain

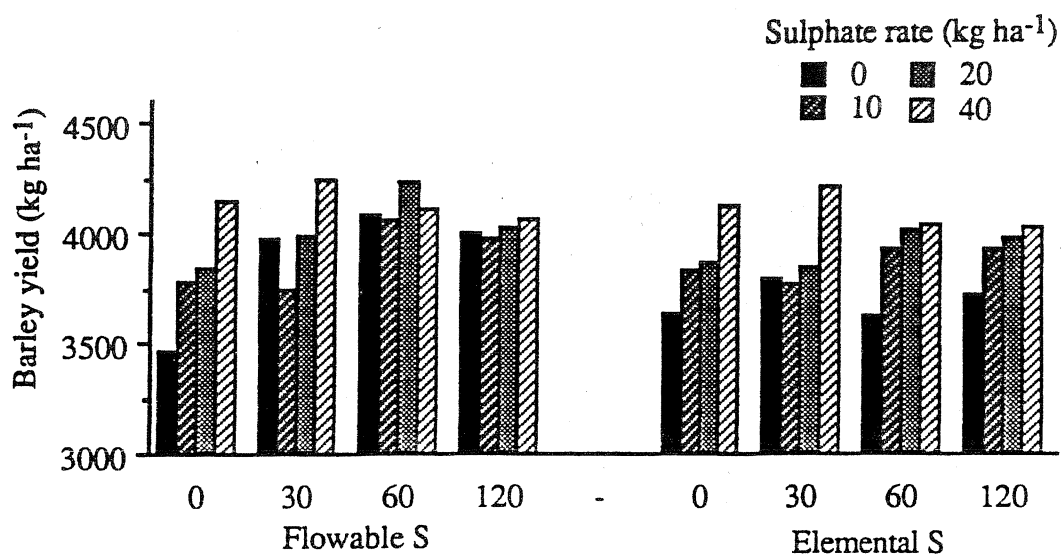


Figure 2. Yield response of Bonanza barley (kg ha⁻¹) in 1987 to four rates of sulphate S applied in 1987 and four rates of flowable S and S⁰ applied in 1986 (from Karamanos and Janzen, 1989, 1991).

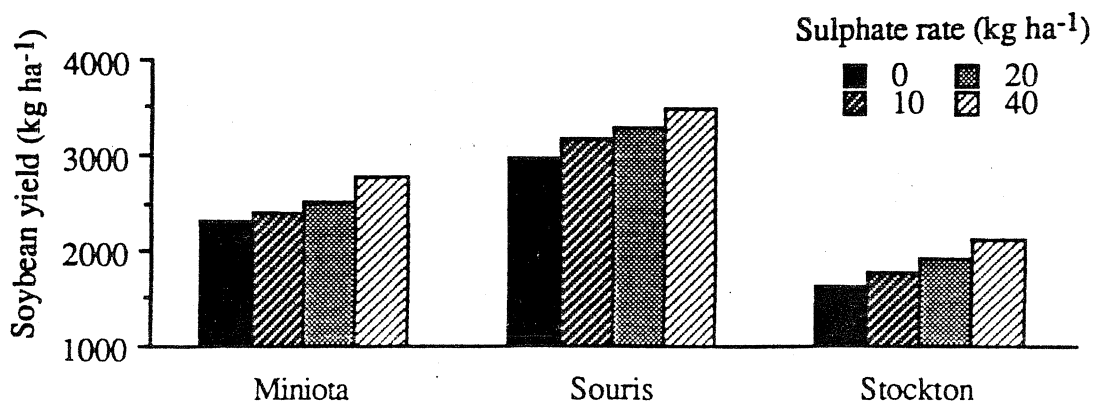


Figure 3. Effect of elemental S broadcast prior to seeding on soybean yields (kg ha⁻¹) on three soils in Western Manitoba, 1974-1977 (from Bailey, 1977).

lentil, on three soils in Manitoba, failed to show a substantial yield increase from S fertilization at 34 kg ha^{-1} . A slight yield increase of 8% was noted on an Altona clay loam soil which had moderate soil $\text{SO}_4\text{-S}$ levels (44 kg ha^{-1} in 0-60 cm) (Hnatowich et al., 1982).

Saskatchewan: Early S research in Saskatchewan was focused in the northern areas of the province and was initiated to address crop production concerns in S-deficient areas. There were reports that long-term S^0 fertilization at 22 kg ha^{-1} increased the yield of wheat by 20% and oats by 14% at Loon Lake in 1955 (Agriculture Canada, 1958). Gypsum (CaSO_4) was also reported to be an effective S source because it is soluble enough to correct acute crop deficiencies of S and can lead to residual effects on future crops. For example, in the Black soil zone, Nuttall (1979) reported up to 12% yield increase for oats grown one year after the application of 21 kg S ha^{-1} as gypsum. No information regarding the nutrient status or location of the soil was presented and relatively low levels of N and K were used in the experiment.

Research on soils of western and northwestern Saskatchewan showed a negligible response of barley to S fertilization (Ukrainetz, 1992), while S applied as $(\text{NH}_4)_2\text{SO}_4$, for two years (1973-74) slightly increased barley yields on five S-deficient soils in northwestern Saskatchewan. In contrast, S application at a site in the Brown soil zone (Kindersley) resulted in a negative yield response in barley yield (Fig. 4). The results of this study were similar to the results in Alberta and Manitoba showing S responses restricted to cooler, more humid northern soils.

The results of 26 trials in which crop response to S fertilization ($(\text{NH}_4)_2\text{SO}_4$) at various locations in the Brown and Dark Brown soil zones showed no consistent or significant response to S (Figs. 5 and 6) (Tomasiewicz et al., 1989). In the Brown soil zone, wheat fertilized with S at rates ranging from 27 to 45 kg ha^{-1} produced no significant yield response. Even crops sensitive to S fertilization did not respond to S. Soil moisture, rather than S fertility, was likely the limiting yield factor for these experiments. Sulphur

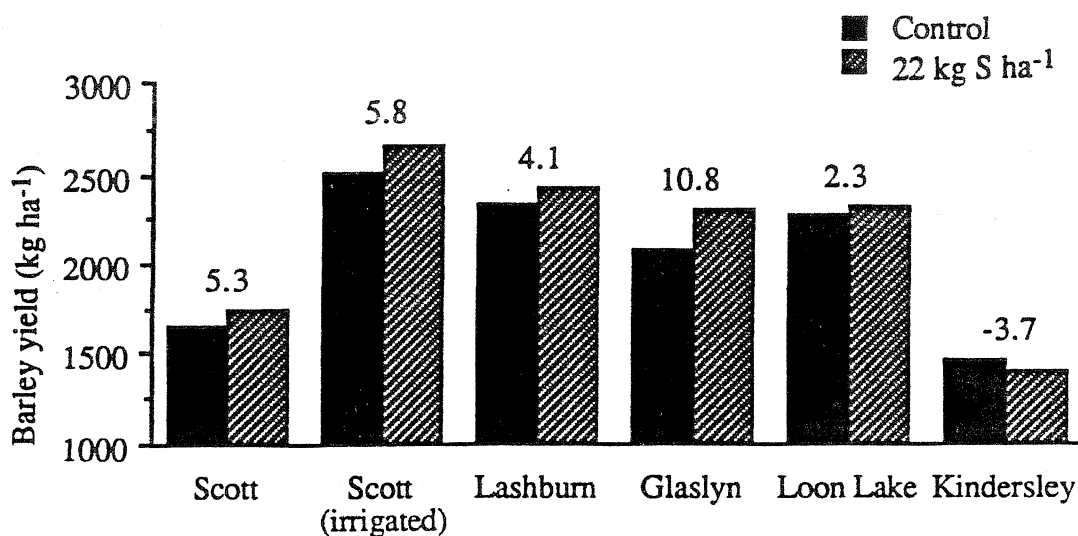


Figure 4. Average barley response (kg ha^{-1}) to S application (1972-1974) at five sites in northwestern Saskatchewan, and one site in west-central Saskatchewan (S broadcast as $(\text{NH}_4)_2\text{SO}_4$) (from Ukrainetz, 1992). (Percent yield increase noted above the columns at each site)

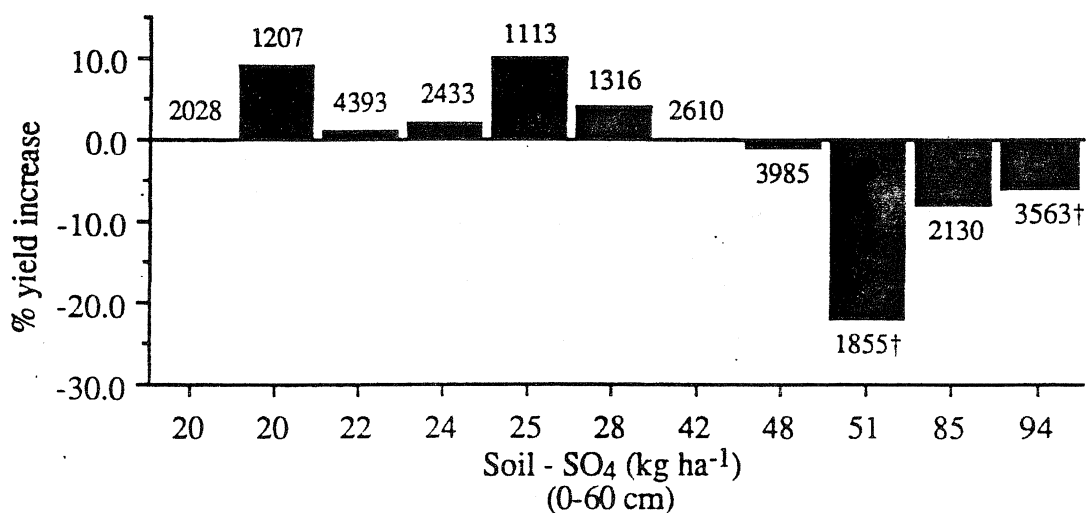


Figure 5. Response of wheat in the Brown soil zone to S fertilization as $(\text{NH}_4)_2\text{SO}_4$. [Control (No S) yields (kg ha^{-1}) shown above the % yield increase values.] Fertilizer rate 40-45 kg S ha^{-1} unless otherwise noted. † Sulphur rate = 27 kg ha^{-1} (from Tomasiewicz et al., 1989).

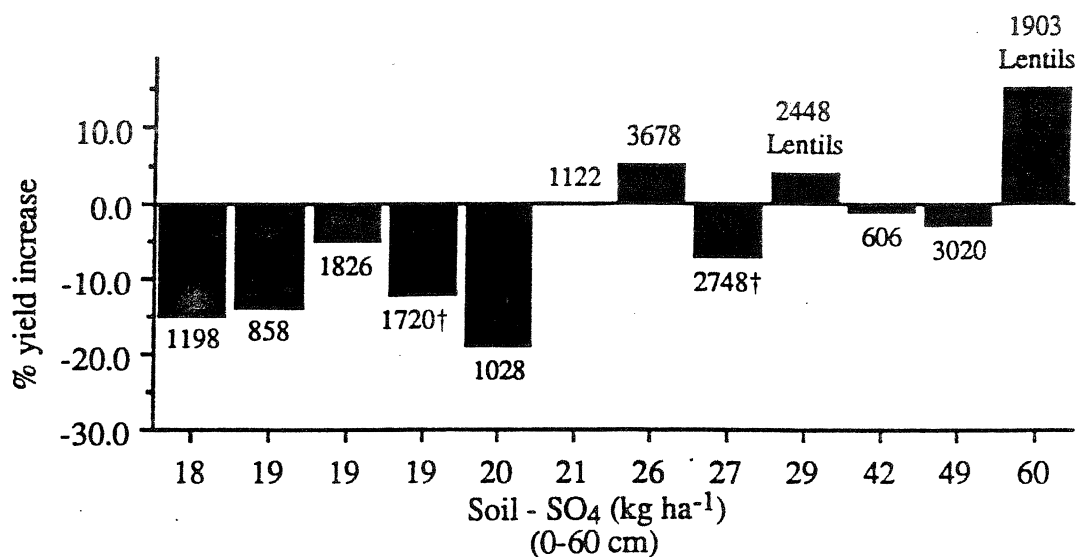


Figure 6. Response of crops in the Dark Brown soil zone to S fertilization as $(\text{NH}_4)_2\text{SO}_4$. Control (No S) yields (kg ha⁻¹) shown above the % yield increase values. Fertilizer rate was 40-45 kg S ha⁻¹ unless otherwise noted. † Sulphur rate = 27 kg ha⁻¹ (from Tomasiewicz et al., 1989).

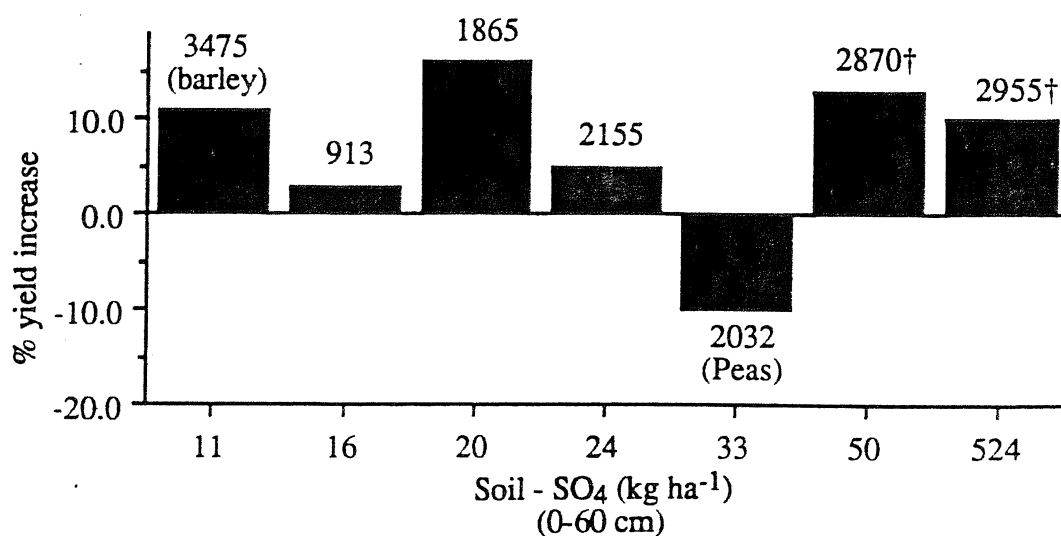


Figure 7. Response of crops in the northern Saskatchewan to S fertilization $(\text{NH}_4)_2\text{SO}_4$. Control (No S) yields (kg ha⁻¹) shown above the % yield increase values. Fertilizer rate was 40-45 kg S ha⁻¹ on Dark Gray soils, unless otherwise noted. † Locations in the Thin Black soil zone (from Tomasiewicz et al., 1989).

fertilizer tended to depress yields at higher soil SO_4 levels (Fig. 5). The responses in the Brown soils tended to be opposite to those from the Dark Brown soil zone (Fig. 6). Large yield responses to S fertilization were unlikely for these experiments, because these soils were not S-deficient. Extractable SO_4^{2-} levels (0 - 60 cm) were relatively high for both the Brown and Dark Brown soils (Figs. 5 and 6).

Cereal response to S on 7 soils in the Black and Dark Gray soil zones was generally positive (Fig. 7), though none were significant. The largest yield increase was for barley at a site testing only 11 kg extractable $\text{SO}_4\text{-S ha}^{-1}$. Barley at this location had a yield response of 11% (380 kg ha^{-1} increase). Field peas had a yield response of -10% to S addition, even though the $\text{SO}_4\text{-S}$ level suggested a slight deficiency for this soil (Tomasiewicz et al., 1989). An explanation for the limited yield response of the crops to S fertilization may be due to moisture limitations, rather than S deficiency.

Various fertilizer companies have conducted research in S response on the prairies. In a series of field trials conducted by Cominco (1983) in Alberta and Saskatchewan during 1980-82, the yields of barley, oats, rye, and wheat were raised by an average of 14-17% through additions of S fertilizer. These results are typical of the majority of cereal yield responses to S addition on S-deficient Saskatchewan soils.

A series of 11 field trials over three years in northern Saskatchewan suggested that the S requirements of dry peas (*Pisum sativum*) was much less than that of canola and more like that of cereal crops (Ferrie and Slinkard, 1992). In these experiments, the rate, timing, and method of placement of S fertilizer had no consistent effect on grain or total dry matter yield.

Grain Quality

The beneficial effects of S on grain crops is not restricted to yields. Sulphur application to deficient soils also affects the quality of grains. Sulphur is an important component of several amino acids and plant proteins. In Alberta, wheat grown after S

fertilized legumes contained more cystine and methionine than wheat grown in an unfertilized cropping system (Kastings, 1948). This effect was attributed to the larger amounts of N and S available to the wheat following the legumes because cysteine levels were correlated with S levels, and methionine content was correlated to both N and S. The application of S fertilizers in this study produced variable results: in some cases S content of wheat increased and, in later studies at the same location, S additions had no effect on N and S content of wheat (Bentley et al., 1955).

Protein concentration in cereal crops, and the general nutritive value of wheat was increased by the presence of S fertilized legumes in crop rotations (Bentley et al., 1960; Toogood et al., 1962).

The proportions of gluten N, and of cysteine and methionine in gluten protein in wheat, have been shown to increase with S fertilization (Toogood et al., 1962). In a series of baking tests, the largest loaves of the best quality bread were obtained from wheat grown after legumes receiving S fertilizer (Beaton et al., 1971).

Oilseeds

Nitrogen/S balance: Sulphur and N are closely linked in the nutrition of oilseed crops. The efficiency of the assimilation of one nutrient is directly related to the availability of the other in the soil medium (Janzen and Bettany, 1981). Consequently, optimal canola yields are often achieved when N and S nutrition is properly balanced (Grant, 1991). If N/S ratios are wide (e.g., fertilizer N applied to a S-deficient soil without the addition of fertilizer S), protein synthesis within the plant may become restricted and this may lead to N accumulation within the plant in non-protein forms (e.g., as nitrate, ammonium, or amides) (Finlayson et al. 1970; Nyborg et al., 1986). The buildup of N in canola plants when N/S ratios are wide can result in decreased canola yields (Nyborg et al., 1974; Janzen and Bettany, 1984a). A detailed review of the use of plant N/S ratios in relationship to canola fertility is provided by Maynard and Stewart (1980).

The optimal plant N/S ratio varies among soils because of inherent differences in available N and S in the various soils. A desirable N/S ratio for soils in which canola is being grown, calculated as $[(\text{soil NO}_3\text{-N} + \text{fertilizer N}) / (\text{soil SO}_4\text{-S} + \text{fertilizer S})]$, has been estimated to be approximately 7 for prairie soils (Janzen and Bettany, 1984a). Ratios < 7 result in inefficient utilization of the assimilated S, while ratios > 7 result in reduced seed yields. Bailey (1987) suggested that the use of such a ratio may not be effective for predicting a response to S in the field, because it is difficult to accurately predict the quantities of these nutrients that will be available to the crop throughout the growing season. For further discussion of canola fertility considerations for western Canada see Ukrainetz et al. (1975) and Grant and Bailey (1990).

Yield responses: A series of trials conducted by Western Cooperative Fertilizers Ltd. measured the response of rapeseed to S fertilization on a variety of soils across the prairies (Harapiak, 1980). Generally, large rapeseed yield responses were observed from gypsum application on low S soils. When applied in the same year, the average yield response of rapeseed to Agri-sul™ (90% elemental S and 10% bentonite) was only one-third of the response obtained from gypsum. Even on soils with low soil SO₄-S levels, Agri-sul™ (elemental S) appeared to be of little value in the year of application (Table 7). The residual effects of these fertilizers were not reported, however one could expect eventual yield responses from the S⁰ treatments.

Alberta: One of the earliest reports involving oilseed response to S fertility was carried out in 1962-63 in the Peace River region of Alberta. The application of S⁰ at 22 kg ha⁻¹ on three northern soils produced no significant yield increases in the year of application. However, the authors did not mention any residual effect of the S⁰ fertilizer; very low rates of N, P, and K fertilizer were used in these field trials (Beaton et al., 1974). As stated earlier, on soils very low in N and S, adequate amounts of the two nutrients must be applied to obtain satisfactory yields, especially for sensitive crops such as canola. Studies have shown that when N was applied without S on a soil deficient in both

Table 7. Rapeseed yield response to gypsum and Agri-sul™ application on 27 trials across the prairie provinces (from Harapiak, 1980).

Treatment	Yield			
	Average soil SO ₄ -S †			
	< 17	18 - 22	23 - 34	> 35
	(kg ha ⁻¹)			
Check	674	1057	776	1045
N + P ‡	1135	1315	1057	1259
N + P + S (Agri-sul)¥	1113	1394	1158	1191
N + P + S (gypsum)§	1293	1472	1158	1214

† 0.001 M CaCl₂ ext. soil SO₄-S. ¥ S as Agri-sul™, § S as gypsum

‡ N and P₂O₅ broadcast at 76 kg ha⁻¹ (low rate) or 152 kg ha⁻¹ (high rate), K₂O broadcast at 67 kg ha⁻¹

Table 8. Yield response of rapeseed (*Brassica campestris* L.) on three S-deficient Gray Wooded soils from additions of N, P, K, and S fertilizers in 1970 (from Nyborg et al., 1974). Sulphur broadcast as Na₂SO₄ for each trial.

Fertilizer	Yield					
	Site 1 †	Site 2 †	Site 3 †	Site 4 ‡	Site 5 ‡	Site 6 ‡
	(kg ha ⁻¹)					
Check	nil	220 a	350 b	250 a	390 b	400 a
PKS (22)	--	--	--	370 a	580 b	650 bc
NPK¥	260 a	870 b	100 a	30 a	90 a	480 ab
NPKS (11)	1210 b	960 b	1230 c	--	--	--
NPKS (22)	1310 b	980 b	1400 c	1930 b	1790 c	830 c
NPKS (56)	1330 b	970 b	1410 c	1670 b	1940 c	800 c

¥ Figures in parenthesis show the rate of applied S (kg ha⁻¹)

† 1967: N, P, and S applied at 11, 22, and 28 kg ha⁻¹. ‡ 1970: 112, 34, and 43 kg ha⁻¹, respectively
In each column, values with different letters are significantly different at the 95% probability level.

nutrients, canola yields was markedly reduced, with the plants producing largely empty pods. For example, on sites 3, 4 and 5 (Table 8), the application of a NPK fertilizer blend sharply depressed canola yields relative to treatments receiving no fertilizer (Nyborg et al., 1974). The application of N and S to the S-deficient soils produced dramatic rapeseed yield increases. Rapeseed grown at sites 1 and 3 scarcely produced any seed unless fertilized with S. Increasing the S rate from 11 to 22 to 45 kg ha⁻¹ did not increase rapeseed yields further. Generally, S additions of up to 30 kg ha⁻¹ are considered to be sufficient for annual rapeseed production on S-deficient soils. Data from this experiment give a good example of yield increases which can be achieved from the combined application of N and S. The yield reduction from the application of N without S is the result of the accumulation of toxic N levels of metabolites in the rapeseed plant tissue (Janzen and Bettany, 1984a).

Oilseed response to S fertilization varies widely (Fig. 8). Some studies have shown very large yield increases to S while others have shown negative effects. The variability can be attributed to five factors: (i) soil moisture; (ii) soil N and P availability; (iii) type and amount of S product applied; (iv) fertilizer application methods; and (v) cultivar of rapeseed/canola used in the experiment. For example, Harapiak (1980) reported a very large rapeseed yield increase from the application of gypsum to a S-deficient soil (SO₄-S = 12.4 kg ha⁻¹) near Vermillion, Alberta. On the same site, Agri-sul™ essentially had no effect on rapeseed yields in the year of application (Table 7).

Experiments conducted in southern Alberta suggest that S fertilizer recommendations should be based on soil analysis to a depth of at least 60 cm. Canola has been observed to utilize added SO₄-S from soil depths ranging from 54 to 72 cm (Bole and Pittman, 1984). In a series of irrigated trials conducted in southern Alberta, McKenzie et al. (1987) showed that soil SO₄-S measurements made from 0-15 cm depth had little value for predicting S fertilizer requirements for canola and flax. On soils which contained

less than 6 kg ha^{-1} of $\text{SO}_4\text{-S}$ to a 15 cm depth, fertilizer S did not produce a yield response because there was adequate levels of SO_4 at depth.

In a series of experiments conducted in central Alberta, the application of sulphate and flowable S fertilizers (together and separately) produced dramatic yield increases in Westar canola (Karamanos and Janzen, 1989, 1991). Flowable S (95 % S^0) produced maximum yield at a rate of 30 kg ha^{-1} . The S^0 sources proved to be less effective than the 95% S^0 source. The application of S^0 alone (i.e., without SO_4), had only a marginal effect on canola yield in the year of application and showed a minimal residual effect on subsequent crops.

Manitoba: Sulphur experiments were established in the late 1960s in Manitoba to measure the response of oilseed crops to N and S fertilizer on soils suspected to be S-deficient. In the 1960s and early 1970s, researchers established the relationship between soil $\text{SO}_4\text{-S}$ levels and crop yield. Field experiments established in 1964 on two S-deficient soils failed to show a yield response of rapeseed to S fertilizer (Soper, 1964). However, Bell (1970) reported large increases in rapeseed yield to S on soils with soil $\text{SO}_4\text{-S}$ levels (0-60 cm) below 30 kg ha^{-1} (Table 9). The data reported for flax suggests that the crop is not as responsive to S additions as rapeseed. A limited amount of additional field testing was conducted in the 1970s and 1980s to assess the S requirement of flax. Hamm (1973) found that flax will respond to S addition when the $\text{SO}_4\text{-S}$ content of the soil to 60 cm was less than 35 kg ha^{-1} ; however, expected flax yield increases at $\text{SO}_4\text{-S}$ levels above 22 kg ha^{-1} would be small.

In 1965, Soper and Anderson (1965) established that rapeseed was sensitive to both S and B deficiencies on certain Manitoba soils. Sulphur applied at 22 kg ha^{-1} as CaSO_4 on a Stockton fine sandy loam increased the yield of 'Tanka' (*B. napus*) rapeseed and corrected S deficiency as effectively as S applied as CaSO_4 or $(\text{NH}_4)_2\text{SO}_4$ at 45 kg ha^{-1} . Seed placement of 11 kg S ha^{-1} or 1.1 kg B ha^{-1} were not effective fertilization methods (Soper, 1965).

Table 9. Summary of early rapeseed and flax S fertility research on various Manitoba soils.

Soil	Crop	S Rate	Yield		Reference
			Control	Fertilized	
————— (kg ha ⁻¹) —————					
Almasippi, LFS (16.9)	Rapeseed	45 [†]	1182	1206	Soper (1964)
Red River, C (37.1)	Rapeseed	45 [†]	707	707	Soper (1964)
Almasippi, FSL	Flax	34 [†]	1198	1096	Racz (1967)
Myrtle, C	Flax	34 [†]	1742	1723	Racz (1967)
Red River, C	Flax	34 [†]	1373	1276	Racz (1967)
Almasippi, FSL	Flax	34 [†]	512	529	Racz (1969)
Almasippi, FSL	Flax	34 [†]	1083	949	Racz (1969)
Duck Mountain, C (25)	Rapeseed	26 [‡]	511	1222	Bell (1970)
		30 [†]		978	
Gilbert, FSL (23)	Rapeseed	30 [†]	1014	1231	Bell (1970)
		61 [†]		1197	

[†] S source = CaSO₄, [‡] S source = (NH₄)₂SO₄

Values in brackets represent the soil SO₄-S content in kg ha⁻¹ from 0-60 cm

Ridley (1972) reported the results of experiments involving the response of rapeseed to S fertilization on various Manitoba soils. Fertilizer S was broadcast on each soil as K_2SO_4 (0-0-50) after seeding. With adequate N fertilization, the response of rapeseed to S was variable in 1971. Sulphur application consistently increased rapeseed yields on the Stockton and Newdale soils (Fig. 9). The addition of 11 kg S ha^{-1} to the Pine Ridge soil increased rapeseed yields from 315 to 2556 kg ha^{-1} (840% increase). The lack of response at the Granville site was not explained. In contrast, rapeseed yields were increased on only one of six sites in 1972 and were reduced on two of the six (Ridley, 1972) (Fig. 10). Results of four trials conducted in 1973 (Fig. 11) generally agree with the yield results from similar 1972 experiments. In most cases, no response to S was observed when soil $SO_4\text{-S}$ levels were over $20\text{-}30 \text{ kg ha}^{-1}$. These results suggest that S deficiency on coarse-textured soils can be expected when $SO_4\text{-S}$ is less than 22 kg ha^{-1} . One conclusion drawn from the three year study was that S deficiency in Manitoba was not as widespread as previously thought (Ridley, 1973).

In a series of field experiments established by Hnatowich et al. (1982), S fertilization of sunflowers and soybeans did not result in yield increases (Table 10). Sadler (1984) carried out a series of field trials with corn on three S-deficient soils in Manitoba. In two of three trials, the addition of S^0 at 22 or 45 kg ha^{-1} did not increase grain yield. However, a notable yield response was observed on the Pembina soil at the 45 kg ha^{-1} S rate (Table 10).

In a recent field trial Racz (1992) reported dramatic corn yield increases from additions of ammonium thiosulphate solution and ammonium sulphate-S (granular) fertilizers on a coarse-textured S-deficient Willowrest soil (Table 10). In addition, no difference was noted between broadcast and banded application methods.

Saskatchewan: Very little research has been reported in Saskatchewan regarding the S fertility of oilseed crops other than rapeseed/canola. Nonetheless, crops such as flax and mustard have relatively high S requirements and respond well to fertilizer S when S

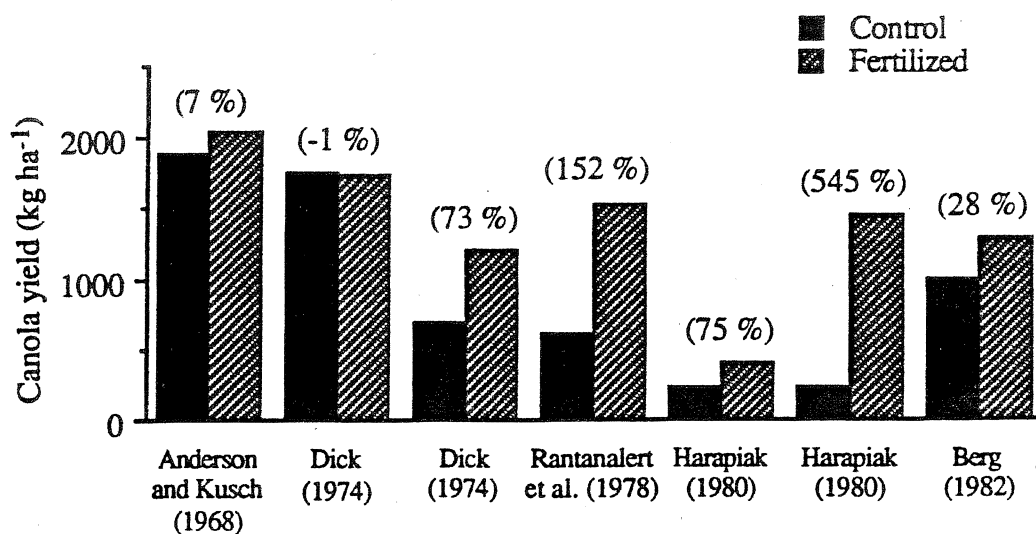


Figure 8. Canola yield responses to S application for various soil types and fertilizer products (from Beaton and Soper, 1986).

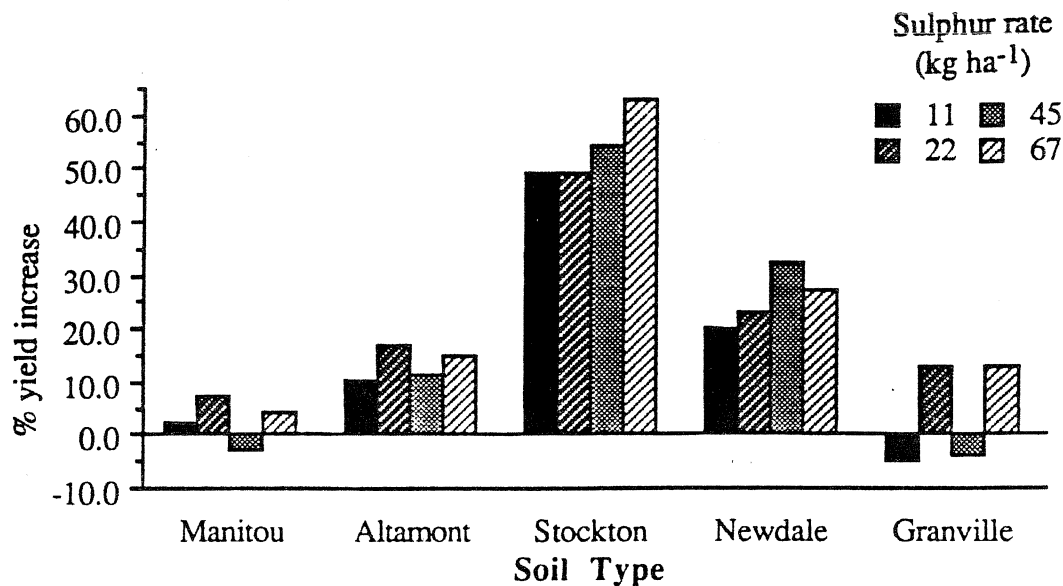


Figure 9. Yield response of rapeseed (var. Zephyr) to four rates of S fertilizer on five Manitoba soil types. Data from 1971. Fertilizer N at 202 kg ha⁻¹ for all treatments, and basal applications of P₂O₅ and K₂O for each experiment (from Ridley, 1972).

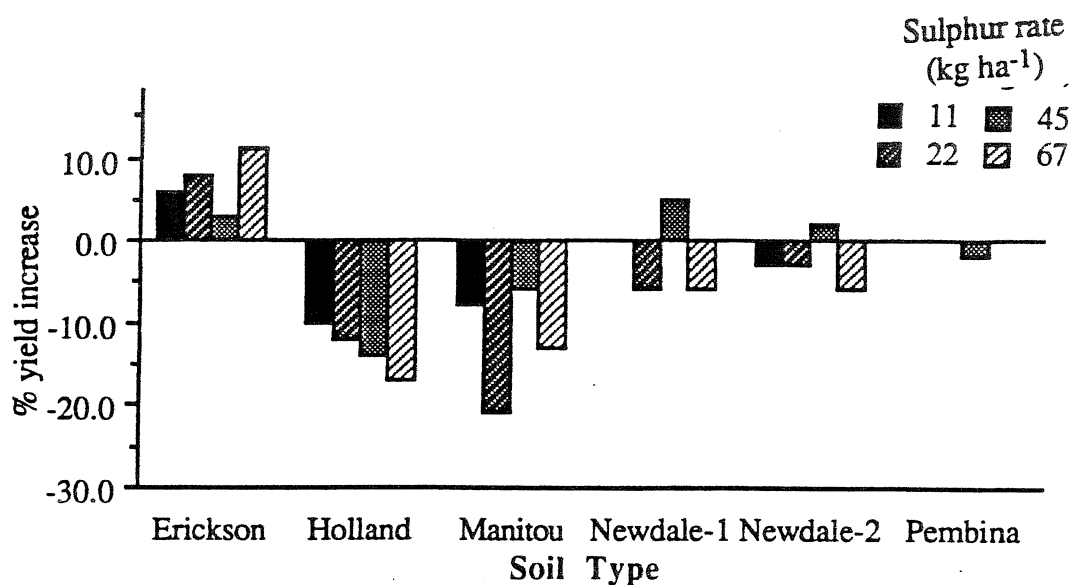


Figure 10. Yield response of rapeseed (var. Zepher) to four rates of S fertilizer on six Manitoba soil types. Data from 1972. Fertilizer N at 202 kg ha⁻¹ for all treatments, and basal applications of P₂O₅, and K₂O for each experiment (from Ridley, 1972).

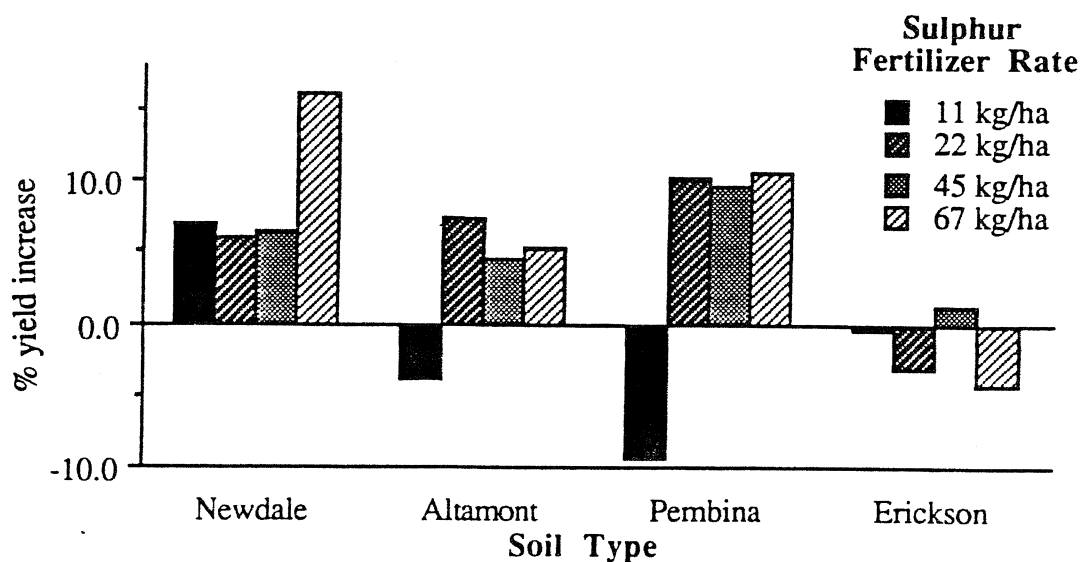


Figure 11. Yield response of rapeseed (var. Zepher) to four rates of S fertilizer on four Manitoba soil types. Data from 1972. Fertilizer N at 202 kg ha⁻¹ for all treatments, and basal applications of P₂O₅, and K₂O for each experiment (from Ridley, 1973).

Table 10. Yield response of sunflowers, soybeans, and corn to S fertilizer on various Manitoba soils.

Soil	Crop	S Rate	Yield		Reference
			Control	Fertilized	
————— (kg ha ⁻¹) —————					
Gnadenthal, L (495)	Sunflowers	34 [†]	2842	2541	Hnatowich et al. (1982)
	Lentils	34 [†]	984	890	
	Soybeans	34 [†]	3290	3098	
Altona, CL (44)	Sunflowers	34 [†]	2486	2557	Hnatowich et al. (1982)
	Lentils	34 [†]	1208	1306	
Pine Ridge, LS (36)	Sunflowers	34 [†]	2213	1749	Hnatowich et al. (1982)
	Lentils	34 [†]	934	754	
Souris, LFS (26)	Corn (grain)	30 [‡]	4890	4310	Sadler (1984)
		45 [‡]		4490	
Pembina, CL (12)	Corn (grain)	30 [‡]	2250	2270	Sadler (1984)
		45 [‡]		3480	
Waskada, C (13)	Corn (grain)	30 [‡]	4660	4660	Sadler (1984)
		45 [‡]		4740	
Willowcrest, VFSL (8)	Corn [§] (grain)	30 [‡]	3692	4577	Racz (1992)
		30 [¥]		4360	

[†] (NH₄)₂SO₄, [‡] elemental S, [¥] ammonium thiosulphate

[§] Average yield from broadcast/banded application methods

Values in brackets represent the soil SO₄-S content in kg ha⁻¹ from 0-60 cm

deficiencies exist. For example, Halstead (1972) reported a yield increase of 43% for flax fertilized with urea ammonium sulphate at 27 kg S ha⁻¹. Similarly, Ukrainetz (1979) noted a yield increase of 45% for mustard fertilized with gypsum at 22 kg S ha⁻¹ on a S-deficient Loon River soil.

One of the earliest reported S fertility experiments involving oilseeds was carried out in northeastern Saskatchewan in 1957 (Agriculture Canada, 1958). Improved canola yields were observed with the addition of gypsum on a Waitville Gray Wooded soil. This experiment established the need for maintenance of S fertility on S-deficient northern soils. However, it wasn't until the late 1970s that S fertility was recognized as a widespread problem for canola production throughout the Luvisolic soils of northeastern Saskatchewan (Button, 1979). Most of the S-deficient canola fields were found to have been previously seeded to legume crops such as alfalfa, sweet clover, or red clover which are heavy S consumers (Ukrainetz, 1979). An example of the magnitude and variability of the response to SO₄-S in northwestern Saskatchewan is shown in Figure 12.

From a series of trials in northeastern Saskatchewan, Nuttall (1979) reported that increased rapeseed yields were only observed when S was applied with a high rate of N (67 kg ha⁻¹) (Fig. 13). The lack of response to S at the lower rates of N, reflects the inefficient use of fertilizer S when N is insufficient (i.e., 'optimal' soil N/S ratio < 7.0).

Timing of S fertilizer application was also investigated (Ukrainetz, 1982). The experiments were established to determine if S could be applied later in the growing season, to a S-deficient canola crop, without yield reduction. Broadcast Na₂SO₄ fertilizer, applied from 14 to 42 days after seeding, did not deleteriously affect the yields of Regent (*napus* species) canola at the three sites and produced substantial yield increases at two of the sites (Fig. 14). In contrast, Nuttall and Ukrainetz (1991) report that SO₄-S fertilizer applied at 14, 28, and 42 days after seeding, significantly reduced the grain yields of canola in six of eight trials in northern Saskatchewan. The cultivar 'Regent' was found to be more sensitive to timing of SO₄ application than the 'Candle' (*campestris* species) variety of

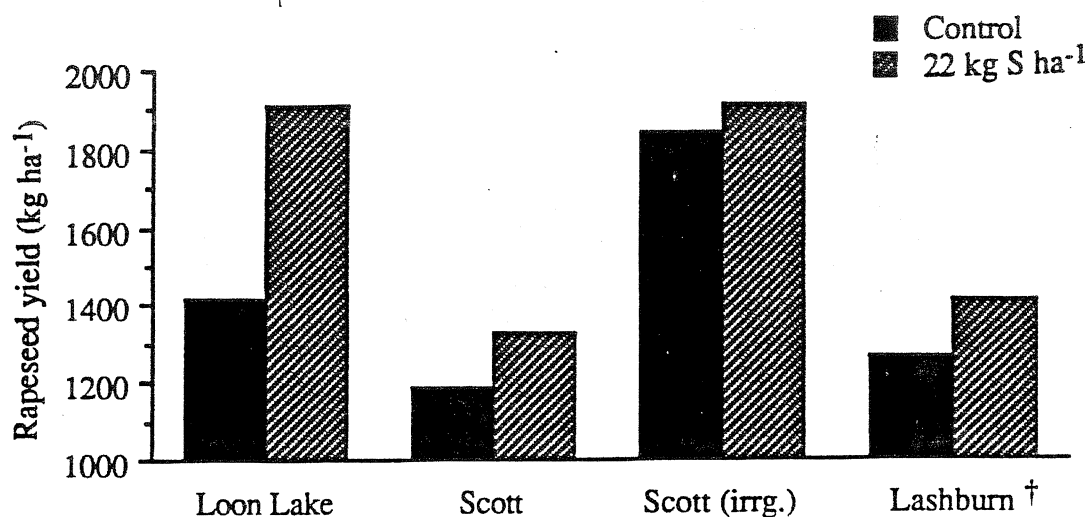


Figure 12. Canola response to S application at four sites in northwestern Saskatchewan from 1972 to 1974. Sulphur applied as broadcast $(\text{NH}_4)_2\text{SO}_4$, except at Lashburn where it was gypsum (from Ukrainetz, 1979; 1992).

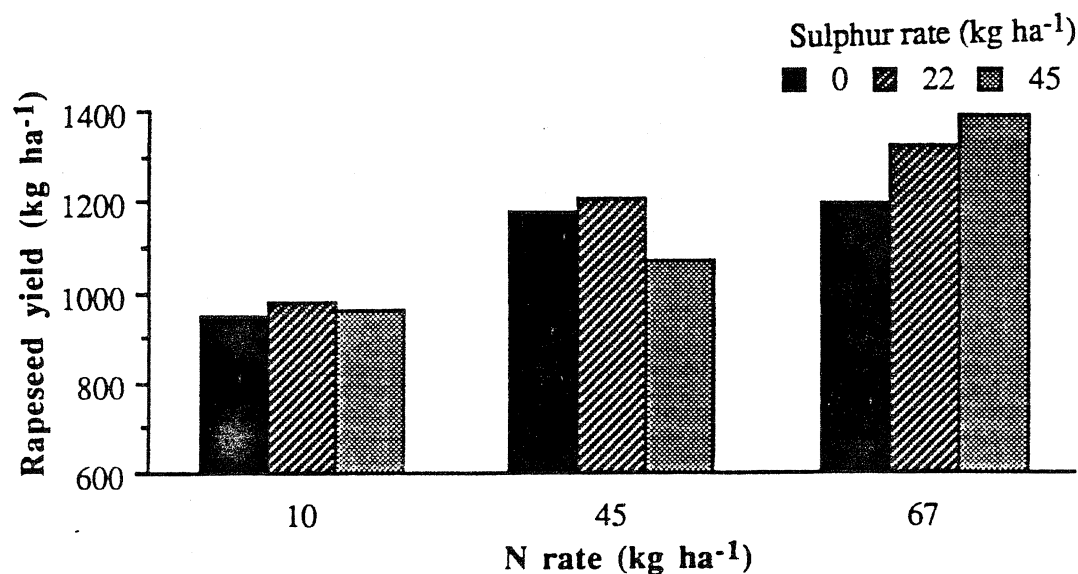


Figure 13. Response of Torch rapeseed to N and S fertilizer on a S-deficient Waitville loam stubble soil (average of 1975-77) (from Nuttall, 1979).

rapeseed. They suggested that S applied at later stages may not be used as efficiently in seed production because other parts of the plant have a high S requirement ('sink effect').

Research was also conducted to compare the relative efficiency of various S sources to correct S deficiencies. In an experiment on a S-deficient Gray Luvisolic soil, the most effective sources in the year of application were the $\text{SO}_4\text{-S}$ fertilizers (Fig. 15). Flowable S^0 increased yields but not as much as the more soluble SO_4 forms. As expected, the prilled S^0 fertilizers (Agri-sulTM, granular S, and urea-S) had relatively little effect on rapeseed yields, presumably because the rate of oxidation to $\text{SO}_4\text{-S}$ was not rapid enough to meet current year crop demands (Ukrainetz, 1982). The results of this study are similar to conclusions reached in Alberta and Manitoba.

In addition to an NxS interaction, crop response to fertilizers may also be influenced by a boron (B) deficiency. Extensive research has been conducted to examine the response of different canola cultivars to S and B fertilization. Yields for two canola varieties tested for 3 years on three soils (one Sylvania FL and two Loon River L) showed that a modest B deficiency does not mask a response to S, and that varietal differences can be expected to change yield responses to S (Table 11) (Ukrainetz, 1982; Nuttall and Ukrainetz, 1983). The high sensitivity of Regent canola to B deficiency is further confirmed in the data given in Table 11. Little benefit in canola yield was obtained from N and B additions above 100 and 1.4 kg ha⁻¹, respectively. These studies indicate that consideration should be given to proper N - S - B levels to achieve top yields of canola. However, in terms of relative importance, B fertilization in canola is generally not critical.

As part of a survey of S-fertility, field experiments on oilseeds were recently conducted across the major soil zones of Saskatchewan (Tomasiewicz et al., 1982). Sulphur addition resulted in yield decreases in the Brown and Dark Brown soil zones, irrespective of soil $\text{SO}_4\text{-S}$ test values (Fig. 16). Yield increases, while not large at any site, were generally positive for Gray Luvisolic soils. Soil test values which ranged from very low to very high, did not appear to have influenced the response pattern. Two mustard

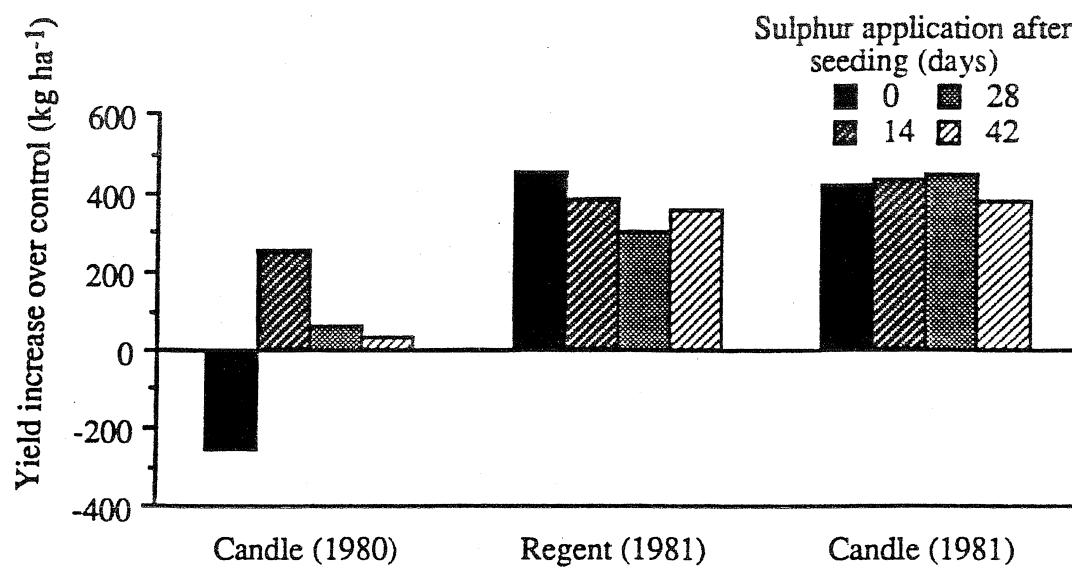


Figure 14. Yield response of Candle and Regent rapeseed to post-seeding broadcast application of Na_2SO_4 fertilizer on a S-deficient Gray Wooded soil (from Ukrainetz, 1982).

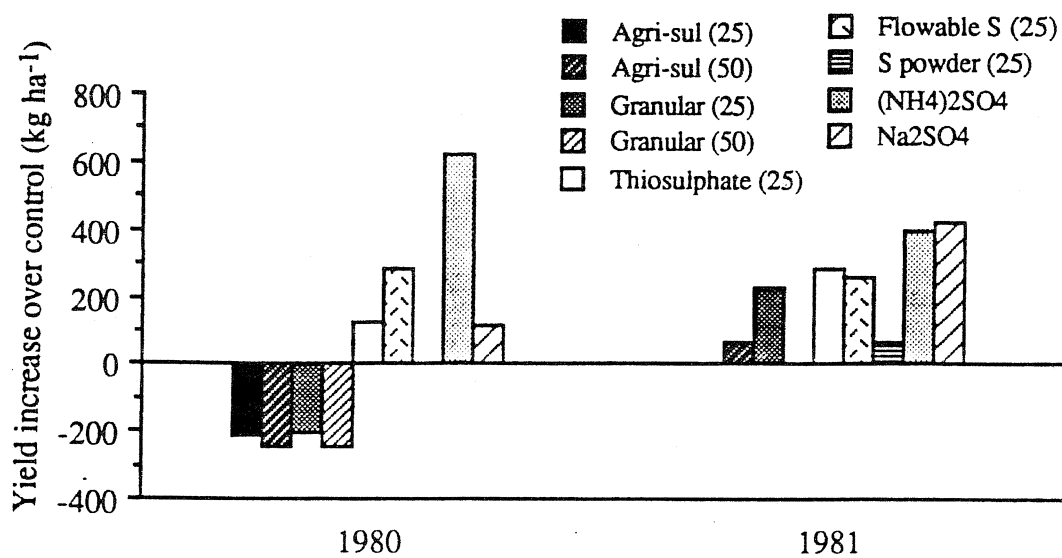


Figure 15. Yield response of Regent rapeseed to various S fertilizers on a S-deficient Gray Wooded soil in 1980 and 1981 (from Ukrainetz, 1982).

Table 11. Response of Candle and Regent canola to S and B at two sites in northern Saskatchewan (from Nuttall and Ukrainetz, 1983).

Nutrient [†] S	B	Yield					
		1980		1981		1982	
		Sylvania (FSL)		Loon River (L)		Loon River (L)	
		Candle	Regent	Candle	Regent [‡]	Candle	Regent
(kg ha ⁻¹)							
0	0	1093	1592	1482	521	492	1266
25	0	996	1705	1741	812	937	1841
0	1.4	1147	1782	1415	794	670	747
25	1.4	1136	2103	1716	978	868	1764

[†] All treatments except 'control' received N, P₂O₅, and K₂O at: 100, 46, and 60 kg ha⁻¹

[‡] Frost damage

Table 12. Response of Regent and Candle canola to N, S, and B fertilizers on a Loon River loam soil (from Nuttall and Ukrainetz, 1983).

Nutrient [†]			Yield	
N	S	B	Regent, 1981	Candle, 1982
(kg ha ⁻¹)				
0	25	1.4	--	1742
100	25	1.4	1898	2042
200	25	1.4	1991	1876
100	0	1.4	--	1248
100	25	0	1625	2046
100	25	2.8	1864	--

[†] All treatments except 'control' received P₂O₅ and K₂O at 46 and 60 kg ha⁻¹

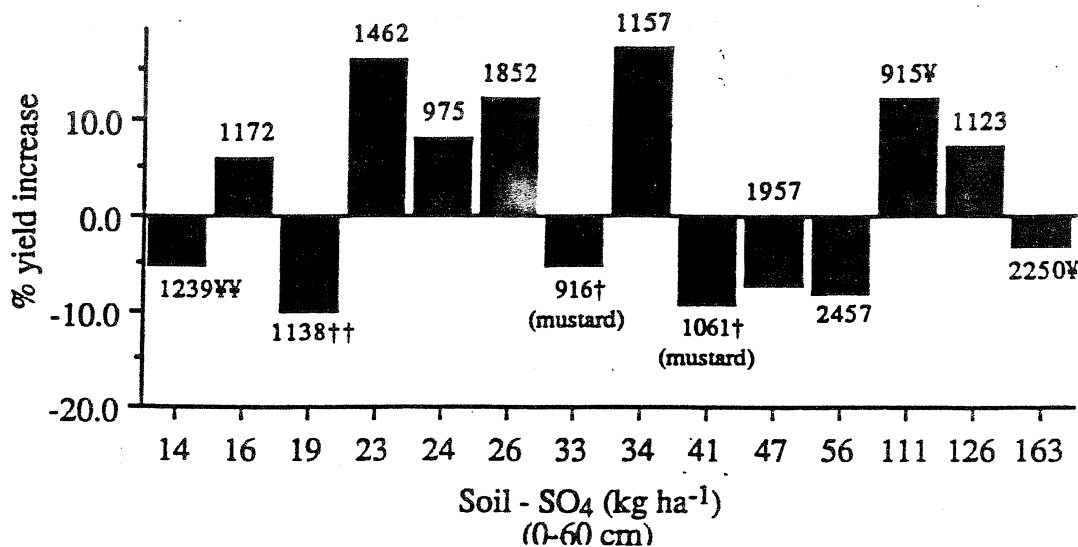


Figure 16. Response of oilseeds to S fertilization on Saskatchewan soils. Control (No S) yields shown above the % yield increase values. All experiments involve canola response to 40-45 kg S ha⁻¹ on Dark Gray soils, unless otherwise noted. Other soil zones: [†] Brown, ^{††} Dark Brown, [¥] Thin Black, and ^{¥¥} Gray (from Tomasiewicz et al., 1989).

trials on Brown soils and one canola experiment in the Dark Brown soil zone produced negative responses to S additions.

Oilseed quality: As stated earlier, S fertilization can have a large influence on oilseed quality. As with oilseed production, quality is dependent on adequate soil S levels and a balance between available N and S levels. Several parameters are available as indices of oilseed quality; however, the most important ones are: the concentration of protein, gluconsinolate, and oil, and the level of cysteine and methionine.

Applications of S to S-deficient canola will increase protein concentration (Table 13) (Nuttall et al., 1987). Finlayson et al. (1970) observed that the addition of N fertilizer in the absence of sufficient S led to the production of free amino acids. When S was applied, S-containing amino acids (i.e., cysteine and methionine) were produced within plant tissue which combined with the free amino acids resulting in a higher plant protein concentration.

Oil quantity and quality are also affected by S additions (Ukrainetz, 1982; Grant, 1991). Sulphur fertilization may decrease (Wetter et al., 1970; Nuttall and Ukrainetz, 1983), increase (Ridley, 1972; Nyborg et al., 1974) or not affect (Ridley, 1973) oil concentrations in S-deficient canola plants. To date, no satisfactory explanation has been given for these contrasting observations.

Increase in glucosinolate content of canola has been observed at high rates of S fertilization (Table 13). Such increases are typically of little concern because, even at high S rates (e.g., 50 kg ha⁻¹), glucosinolate concentrations are usually well below the standard 30 µmol g⁻¹ limit (Grant, 1991).

CONCLUSIONS

Sulphur-deficient soils, which are rare in the Brown and Dark Brown soil zone, have been widely identified in the more humid cool regions of the prairies. Approximately 10 and 18% of the 36 million hectares of cultivated soils have been classified as deficient and potentially deficient, respectively.

Where N is deficient, the application of S fertilizers may lead to dramatic decline in yield where canola is grown. Cereal grains, legumes and flax may respond well to added S where the available S content in the soil is in the deficient category (i.e., 25 to 35 kg ha⁻¹).

Fertilizer management practices for S have been well researched. The use of S⁰ can lead to very disappointing results where sufficient time is not given for its transformation to water-soluble form. Like N, available soil S is subject to biological immobilization when abundant crop residues are present.

Oilseed crops generally have higher S requirements than cereal grains because the oil storage organs within the plants are usually rich in S-containing proteins. This does not mean, however, that dramatic yield increases to applied S cannot be expected where cereal grains are grown on S-deficient soils. Canola seed quality, in particular protein concentration, is usually enhanced by optimum rates of S fertilization.

Table 13. The effect of N and S on protein, oil, and glucosinolate concentration of Regent canola, grown on Sylvania fine sandy loam, Saskatchewan, 1980-83 (from Nuttall et al., 1987).

Treatment		Protein [†]	Oil [†]	Glucosinolates
N	S	(Oil and moisture-free)		
(kg ha ⁻¹)		—————(%)—————		(μmol g ⁻¹)
0	25	48.4	46.1	9.5
40	10	47.2	46.7	7.9
40	40	48.1	46.5	10.1
100	0	48.9	43.9	7.3
100	25	49.9	45.0	9.2
100	50	49.7	45.5	9.1
160	10	50.7	43.7	6.7
160	40	51.9	44.3	10.1
200	25	51.6	43.3	9.3

[†] Protein increased by N ($P<0.01$) and by S ($P<0.05$). Oil decreased by N ($P<0.01$) and increased by S ($P<0.05$). Glucosinolates increased by S ($P<0.01$).

Yield responses to S fertilization can be expected to vary widely from year to year. Factors that may in part be responsible for this variation include: available S present below the depths of normal soil test sampling, soil temperature which affects all biological reactions, in particular, S-immobilization. While many of these factors cannot be measured, the least a wise manager must do is to base S fertilizer rates on a reliable soil test. Care must be taken, at least in the drier regions not to apply S fertilizers without a soil test; S additions may result in oilseed yield decreases in the Brown and Dark Brown soil zones.

At the present time, S is the third most frequently encountered nutrient that limits crop production, in the prairies.

REFERENCES

- Anderson, D.W. 1966. Available sulfur in some Manitoba soils as estimated by plant growth and chemical analysis. M.Sc. Thesis, Department of Soil Science, University of Manitoba, Winnipeg, Man.
- Agriculture Canada. 1957. Fertility and management studies on grey wooded soils. Progress Report: 1927-1956.
- Agriculture Canada. 1958. Experimental Farm, Melfort, Saskatchewan. Progress Report: 1954-1958.
- Bailey, L.D. 1976. Nutrient requirements of fababeans. pp. 140-143. In: 20th Ann. Manitoba Soil Science Meetings. University of Manitoba, Winnipeg, Man.
- Bailey, L.D. 1977. Nutrient requirements of soybeans. pp. 196-200. In: 21st Ann. Manitoba Soil Science Meetings, University of Manitoba, Winnipeg, Man.
- Bailey, L.D. 1978. Sulphur status of some western Manitoba soils. pp. 101 - 109. In: 22nd Ann. Manitoba Soil Science Meeting, University of Manitoba, Winnipeg, Man.
- Bailey, L.D. 1979. Fertilizing Flax - A Review. pp. 92 - 95. In: 23rd Ann. Manitoba Soil Science Meeting, University of Manitoba, Winnipeg, Man.
- Bailey, L.D. 1987. Sulphur status of Eastern Canadian prairie soils. Sulphur in Agriculture. 11: 20-24.
- Beaton, J.D. 1966. Sulfur requirements of cereals, tree fruits, vegetables, and other crops. Soil Sci. 101: 267-282.

- Beaton, J.D., Harapiak, J.T. and Tisdale, S.L. 1966. Crop responses to sulphur in western Canada. *Sulphur Inst. J.* 2(3): 9-16.
- Beaton, J.D., Tisdale, S.L. and Platou, J. 1971. Crop responses to sulphur in North America. *Tech. Bull.* 18. The Sulphur Institute, Washington, DC.
- Beaton, J.D., Leich, R.H., McAllister, R.E., and Nyborg, M. 1974. The projected need for sulphur fertilizers in western Canada and their integration in soil fertility programs. *Can. Sulphur Symp. Pap.*
- Beaton, J.D. and Soper, R.J. 1986. Plant response to sulphur in western Canada. pp. 375-403. In: *Sulphur in Agriculture*. Soil Science Society of America Monograph no. 27. Madison, WI.
- Bell, N.J. 1970. Fertilizer experiments with special crops. pp. 128-135. In: 14th Ann. *Man. Soil Sci. Soc. Proc.*, Winnipeg, Man.
- Bentley, C.F. 1974. Comment-new areas with some sulphur. *Agric. Bull.* 23:1. University of Alberta, Edmonton, Alta.
- Bentley, C.F., Hoff, D.J., and Scott, D.B. 1955. Studies with radioactive sulphur: II. *Can. J. Agric. Sci.* 35: 264-281.
- Bentley, C.F., Carson, J.A., and Rowland, J.P. 1960. Fertilizers and the nutritive value of wheat grown on sulphur-deficient grey wooded soil. *Can. J. Soil Sci.* 40: 146-155.
- Berg, E.R. 1982. Urea sulphur. No. 50. Cominco Ltd., Calgary, AB.
- Bertrand, R.A. 1973. Reclaiming of soils made barren by sulfur. M.Sc. Thesis, University of Alberta, Edmonton, Alta.
- Bettany, J.R., Stewart, J.W.B., and Halstead, E.H. 1973. Sulphur fractions and carbon, nitrogen, and sulphur relationship in grassland, forest and associated transitional soils. *Soil Sci. Soc. Am. J.* 37: 915-918.
- Bettany, J.R., Janzen, H.H., and Stewart, J.W.B. 1982. Sulphur deficiency in the prairie provinces of Canada. pp. 573. *Proc. of Sulphur 1982. An International Symposium on Sulphur*, Nov. 1982, London, England.
- Biederbeck, V.O. 1978. Soil organic sulfur and fertility. pp. 273 - 310. In: *Soil Organic Matter*. M. Schnitzer and S.U. Khan (eds.), Elsevier Scientific Publ. Co., New York, NY.
- Bole, J.B. and Pittman, U.J. 1979. Crop response of to applied sulphur in southern Alberta and the uptake of subsoil sulphates. pp. 335-338. In: *Proc. Alberta Soil Science Workshop*, Alberta Agriculture, Feb. 26-27.
- Bole, J.B. and Pittman, U.J. 1984. Availability of subsoil sulphates to barley and rapeseed. *Can. J. Soil Sci.* 64: 301-312.
- Button, R.S. 1979. Sulphur deficiencies in Northeast Saskatchewan. *Farm and Home Week*, Univ. of Saskatchewan, Saskatoon, Sask.

- Cairns, R.R. and Richer, A.C. 1960. A comparative study of a sulphur responsive and a non-responsive Grey Wooded soil. *Can. J. Soil Sci.* 40: 246-254.
- Cominco Ltd. 1983. Urea sulphur review. No. 54. Cominco Ltd., Calgary, Alta.
- Cormack, D.V., Bentley, C.F., and Scott, D.B. 1951. Fertilizer studies with radioactive sulphur. I. *Sci. Agric.* 31: 41-51.
- Dick, A.C. 1974. Effects of fertilizers on nitrogen-sulphur relationships. M.S. thesis, University of Alberta, Edmonton, Alta.
- Ferrie, J. and Slinkard, A. 1992. The effect of sulphur fertilizer on the agronomic traits of dry pea in Saskatchewan. pp. 415-428. In: *Proc. of Soils and Crops Workshop*, Univ. of Saskatchewan, Saskatoon, Sask.
- Finlayson, A.J., Christ, C.M., and Downey, R.K. 1970. Changes in the nitrogenous components of rapeseed (*Brassica napus*) grown on a nitrogen and sulfur deficient soil. *Can. J. Plant Sci.* 50: 705-709.
- Germida, J.J., Wainwright, M., and Gupta, V.V.S.R. 1992. Biogeochemistry of sulfur cycling in soil. pp. 1-53. In: *Soil Biochemistry*, Volume 7. G. Stotzky and J.M. Bollag (eds.). Marcel Dekker, Inc., New York.
- Grant, C.A. 1991. Sulphur requirements of canola. *Sulphur Inst. J.* 15: 3-6.
- Grant, C.A. and Bailey, L.D. 1990. Fertility management in canola production. pp. 122-159. In: *Proc. International Canola Conference*, April 2-6, 1990, Atlanta, Georgia.
- Grant, C.A. and Bailey, L.D. 1991. Evaluation of the effects of method, rate, and composition of fluid fertilizer application for barley and canola grown on the soils of the Canadian prairies. In: *Proc. Fluid Fertilizer Foundation. 1991. Research Symposium*. March 4-6, 1990, Scottsdale, AZ. U.S.A. (In Press).
- Gupta, V.V.S.R., Lawrence, J.R., and Germida, J.J. 1988. Impact of elemental sulfur fertilization on agricultural soils. I. Effects on microbial biomass and enzyme activities. *Can. J. Soil Sci.* 68: 463-473.
- Hagstrom, G.R. 1986. Fertilizer sources of sulphur and their uses. pp. 567-581. In: *Sulphur in Agriculture*. Soil Science Society of America Monograph no. 27. Madison, WI.
- Halstead, E.H. 1972. Nitrogen and sulphur requirements of annual crops. pp. 133-140. In: *1972 Soil plant nutrient research report*. Sask. Inst. Pedol. Rep. M23, Univ. of Saskatchewan, Saskatoon, Sask.
- Hamm, J.W. 1967. Sulphur on rapeseed and cereals. pp. 91-108. In *10th Ann. Manitoba Soil Science Meeting*, University of Manitoba, Winnipeg, Man.
- Hamm, J.W. 1973. The sulphur test-background and interpretive criteria for Saskatchewan. pp. 109-116. In: *Proc. 1973 Soil Fertility Workshop*, Univ. of Saskatchewan, Saskatoon, Sask.

- Hamm, J.W., Bettany, J.R., and Halstead, E.H. 1973. A soil test for sulfur and interpretation criteria for Saskatchewan. *Comm. Soil Sci. Plant Anal.* 4: 219-231.
- Harapiak, J.T. 1980. Rapeseed response to sulphur, boron, and fertilizer placement. pp. 145-154. In: *Proc. 1980 Soils and Crops Workshop*, University of Saskatchewan, Saskatoon, Sask.
- Hnatowich, G.L., Loewen-Rudgers, L., and Soper, R.J. 1982. Fertility studies of special crops. pp. 145-153. In: *25th Ann. Man. Soil Sci. Soc. Proc.*, Winnipeg, Man.
- Janzen, H.H. 1984. Sulphur nutrition of rapeseed. Ph.D. Thesis, Department of Soil Science, University of Saskatchewan, Saskatoon, Sask.
- Janzen, H.H. and Bettany, J.R. 1981. Sulphur nutrition of canola. pp. 212-221. In: *Proc. 1981 Soils and Crops Workshop*, University of Saskatchewan, Saskatoon, Sask.
- Janzen, H.H. and Bettany, J.R. 1983. Release of available sulphur from fertilizers. *Can. J. Soil Sci.* 66: 91-103.
- Janzen, H.H. and Bettany, J.R. 1984a. Sulfur nutrition of rapeseed: I. Influence of fertilizer nitrogen and sulfur rates. *Soil Sci. Soc. Am. J.* 48: 100-107.
- Janzen, H.H. and Bettany, J.R. 1984b. Sulfur nutrition of rapeseed: II. Effect of time of sulfur application. *Soil Sci. Soc. Am. J.* 48: 107-112.
- Janzen, H.H. and Bettany, J.R. 1986. Release of available sulfur from fertilizers. *Can. J. Soil Sci.* 66: 91-103.
- Janzen, H.H. and Bettany, J.R. 1987a. The effect of temperature and water potential on sulfur oxidation in soils. *Soil Sci.* 144: 81-89.
- Janzen, H.H. and Bettany, J.R. 1987b. Oxidation of elemental sulfur under field conditions in central Saskatchewan. *Can. J. Soil Sci.* 67: 609-618.
- Janzen, H.H., Karamanos, R.E., and Ramsay, P. 1987. Short-term oxidation of several elemental sulfur fertilizers in central Alberta. pp. 240-254. In: *Proc. Alberta Soil Science Meetings*.
- Janzen, H.H. and Karamanos, R.E. 1991. Short-term residual contribution of selected elemental S fertilizers to the S fertility of two Luvisolic soils. *Can. J. Soil Sci.* 71: 203-212.
- Karamanos, R.E. and Janzen, H.H. 1989. Yield response to elemental sulphur over a three year period. pp. 42-50. In: *Proc. Alberta Soil Science Meetings*.
- Karamanos, R.E. and Janzen, H.H. 1991. Crop response to elemental sulfur fertilizers in central Alberta. *Can. J. Soil Sci.* 71: 213-225.
- Kastings, R. 1948. The sulphur-containing amino acids of wheat proteins. M.Sc. thesis, University of Alberta, Edmonton, Alta.

- Kowalenko, C.G. 1978. Organic nitrogen, phosphorus and sulphur. pp. 95-136. In: Soil Organic Matter. M. Schnitzer and S.U. Khan (eds.), Elsevier Scientific Publ. Co., New York, NY.
- Lowe, L.E. 1965. Sulphur fractions of selected Alberta soil profiles of the Chernozemic and Podzolic orders. Can. J. Soil Sci. 45: 297-303.
- Maynard, D.G. and Stewart, J.W.B. 1980. Sulphur deficiency in rapeseed—Diagnostic plant analysis. pp. 155-176. In: Proc. 1980 Soils and Crops Workshop, University of Saskatchewan, Saskatoon, Sask.
- Maynard, D.G., Stewart, J.W.B., and Bettany, J.R. 1984. Sulfur cycling in grassland and parkland soils. Biogeochemistry 1: 97-111.
- McGill, K.S. 1987. Determining the need for sulphur. In: Western Canada Sulphur Handbook. Western Canadian Fertilizer Association, Calgary, Alta.
- McGill, K.S. 1991. Trends in nutrient levels in Manitoba soils. pp. 115-136. In: 34th Ann. Man. Soil Sci. Soc. Proc., Winnipeg, Man.
- McKenzie, R.H., Kryzanowski, L., and Carefoot, J.M. 1987. Fertilizer requirements of irrigated grains and oilseed crops in southern Alberta. pp. 97-115. In: Alberta Soil Sci. Soc. Proc., Calgary, Alta.
- Newton, J.D. 1936. The fertilizing value of sulphate in natural "alkali" for Gray Wooded soils. Sci. Agric. 16: 241-243
- Noellemeyer, E.J., Bettany, J.R., and Henry, J.L. 1981. Sources of sulfur for rapeseed. Can. J. Soil Sci. 61: 465-467.
- Nuttall, W.F. 1979. Response of crops to sulphur in northeastern Saskatchewan. pp. 146-151. In: Proc. Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.
- Nuttall, W.F. and Ukrainetz, H. 1983. Effect of sulphur and boron on canola yield. pp. 96-102. In: Proc. 1983 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.
- Nuttall, W.F., Ukrainetz, H., Stewart, J.W.B., and Spurr, D.T. 1987. The effect of nitrogen, sulphur, and boron on yield and quality of rapeseed (*Brassica napus* L. and *B. campestris* L.). Can. J. Soil Sci. 67: 545-559.
- Nuttall, W.F., Boswell, C.C., and Swanney, B. 1990. Influence of sulphur fertilizer placement, soil moisture, and temperature on yield response of rape to sulphur-bentonite. Fertilizer Res. 25: 107-114.
- Nuttall, W.F. and Ukrainetz, H. 1991. The effect of time of S application on yield and sulphur uptake of canola. Comm. Soil Sci. Plant Anal. 22: 269-281.
- Nyborg, M. 1965. Report on soil fertility research - Beaverlodge. Third British Columbia Soil Sci. Workshop Report, Oct. 14-15, 1965, Vancouver, B.C.
- Nyborg, M. 1968. Sulphur deficiency in cereal grains. Can. J. Soil Sci. 48: 37-41.

- Nyborg, M. 1974. Reclamation of soils and waters made acid by windblown sulphur dust. pp. 55-70 In: Proc. Workshop on Reclamation of Disturbed Land in Alberta. Research Secretariat, Alberta Environment, Edmonton, Alta.
- Nyborg, M. and Hoyt, P.B. 1965. Sulphur deficiency in grey wooded soils of the Peace River region. *Soil Horizons* 6 (3) 9.
- Nyborg, M. and Bentley, C.F. 1971. Sulphur deficiency in rapeseed and cereal grains. *Sulphur Inst. J.* 7(3): 16-17.
- Nyborg, M., Bentley, C.F., and Hoyt, P.B. 1974. Effect of sulphur deficiency on seed yield of turnip rape. *Sulphur Inst. J.* 10(1): 14-15.
- Nyborg, M., Ayala, M., Yeung, P., Malhi, S.S., and Shier, M. 1980. The rate of oxidation of elemental sulphur fertilizers. pp. 216-223. In: Proc. 1983 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.
- Nyborg, M., Penney, D.C., and Lavery, D.H. 1986. Sulphur fertilizer application in crop production. Agdex 542-10, Alberta Agriculture, May, 1986.
- Racz, G.J. 1967. Effect of fertilizer on flax. pp. 233-234. In: 11th Ann. Man. Soil Sci. Soc. Proc., Winnipeg, Man.
- Racz, G.J. 1969. Effect of fertilizer on flax. pp. 177-179. In: 13th Ann. Man. Soil Sci. Soc. Proc., Winnipeg, Man.
- Racz, G.J. 1992. A comparison of the agronomic effectiveness of liquid and granular sulphur fertilizers. pp. 254-260. In: 35th Ann. Man. Soil Sci. Soc. Proc., Winnipeg, Man.
- Ratanalert, P. 1973. Sulphur studies with some Chernozemic soils. M.S. thesis, University of Alberta, Edmonton, Alta.
- Ridley, A.O. 1972. Effect of nitrogen and sulphur fertilizers on yield and quality of rapeseed. pp. 149-155. In 16th Ann. Manitoba Soil Sci. Meeting, Univ. of Manitoba, Winnipeg, Man.
- Ridley, A.O. 1973. Effect of nitrogen and sulphur fertilizers on yield and quality of rapeseed. pp. 182-187. In 17th Ann. Manitoba Soil Sci. Meeting, Univ. of Manitoba, Winnipeg, Man.
- Roberts, T.L. and Bettany, J.R. 1985. The influence of topography on the nature and distribution of soil sulfur across a narrow environmental gradient. *Can. J. Soil Sci.* 65: 419-434.
- Rowles, C.A. 1938. Effects of fertilizers on alfalfa yields on wooded soils of Saskatchewan and related investigations on black, degraded black and gray soils. M.S. thesis, Univ. of Saskatchewan, Saskatoon, Sask.
- Sadler, J.M. 1984. Sulphur nutrition of corn. pp. 113-121. In: 27th Ann. Man. Soil Sci. Soc. Proc., Winnipeg, Man.
- Saggar, S., Bettany, J.R., and Stewart, J.W.B. 1981. Sulfur transformations in relation to carbon and nitrogen in incubated soils. *Soil Biol. Biochem.* 13: 499-511.

- Schalin, E. 1947. The effect of fertilizers on yield and composition of alfalfa on podzolic soils of northeastern Saskatchewan. M.S. thesis, Univ. of Saskatchewan, Saskatoon, Sask.
- Solberg, E.D. and Nyborg, M. 1982. Comparison of sulphate and elemental sulphur fertilizers. pp. 843-852. In: Proc. Int. Sulphur '82 Conference, London, England (November).
- Solberg, E.D. and Nyborg, M. 1986. Banding versus incorporation of elemental sulphur fertilizer. pp. 81-86. In: 30th Ann. Manitoba Soil Sci. Meeting, Univ. of Manitoba, Winnipeg, Man.
- Solberg, E.D., Lavery, D.H., and Nyborg, M. 1987. Effects of rainfall, wet-dry, and freeze-thaw cycles on the oxidation of elemental sulphur fertilizers. pp. 120-126. In: Alberta Soil Science Workshop, Alberta Agriculture, Calgary, Alta.
- Solberg, E.D., Nyborg, M., Lavery, D.H., and Malhi, S.S. 1982. Oxidation of elemental sulphur used as a fertilizer. pp. 207-252. In: Proc. Alberta Soil Science Workshop, Alberta Agriculture, Edmonton, Alta.
- Soper, R.J. 1963. Sulphur status of some Manitoba soils. pp. 75-77. In: 7th Ann. Manitoba Soil Sci. Meeting, Univ. of Manitoba, Winnipeg, Man.
- Soper, R.J. 1965. Effect of fertilizers on rape grown on stubble land. pp. 140-144. In: 9th Ann. Manitoba Soil Sci. Meeting, Univ. of Manitoba, Winnipeg, Man.
- Stanford, G. and H.V. Jordan. 1966. Sulfur requirements of sugar, fiber, and oil crops. *Soil Sci.* 101: 258-266.
- Stewart, J.W.B. and Bettany, J.R. 1982. Dynamics of organic sulphur. pp. 184-206. In: Proc. Alberta Soil Science Workshop, Alberta Agriculture, Edmonton, Alta.
- Swan, M., Soper, R.J., and Morden, G. 1986. The effect of elemental sulfur, gypsum, and ammonium thiosulfate as sulfur sources on yield of rapeseed. *Comm. Soil Sci. Plant Anal.* 17: 1383-1390.
- Tomasiewicz, D.J., Thomas, A., and Kruger, G.A. 1989. Responses to sulphur and micronutrient fertilization in Saskatchewan 1986-1988. Proc. 1989 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.
- Toogood, J.A., Bentley, C.F., Webster, G.R., and Moore, A.W. 1962. Grey wooded soils and their management. *Bull.* 21, Univ. of Alberta, Edmonton, Alta.
- Ukrainetz, H. 1979. Sulphur Deficiencies. Proc. 1979 Soils and Crops Workshop, Univ. of Saskatchewan, Saskatoon, Sask.
- Ukrainetz, H. 1982. Oxidation of elemental sulphur fertilizers and response of rapeseed to sulphur on a Gray Wooded soil. pp. 241-252. In: Proc. Alberta Soil Science Workshop, Alberta Agriculture, Edmonton, Alta.
- Ukrainetz, H. 1992. Unpublished work conducted at Agriculture Canada Research Station, Saskatoon, Sask. Summarized by P.J. Doyle and L.E. Cowell 1991.

- Ukrainetz, H., R.J. Soper, M. Nyborg. 1975. Plant nutrient requirements of oilseed and pulse crops. pp. 325-374. In: Oilseed and Pulse Crops in Western Canada - A Symposium, Winnipeg, Man.
- Walker, D.R. 1968. Sulphur deficiencies. pp. 29-30. In: Inf. Div. S-145. Canada Department of Agriculture, Ottawa, Ont.
- Walker, D.R. 1969a. Sulphur deficiency not confined to grey wooded soils. pp. 22-23. In: 1968 Research hi-lites. Lacombe Res. Stn., Agriculture Canada, Lacombe, Alta.
- Walker, D.R. 1969b. Sulphur precipitation in central Alberta. Can. J. Soil Sci. 49: 409-410.
- Wetter, L.R., Ukrainetz, H., and Downey, R.K. 1970. The effect of chemical fertilizers on the content of oil, protein and glucosinolates in *Brassica* including rapeseed. pp. 92-112. In: Proc. Int. Conf. Science, Technology, and Marketing of Rapeseed and Rapeseed Products, Ste. Adele, Que., Sept. 20 - 23.