Sulphur Deficiencies

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Introduction

Plants, like animals, must have good nutrition in order to achieve high production. Varieties with high potential for yield cannot fully express themselves when grown on soils that are deficient in essential, readily available nutrients. Soils differ in inherent fertility and ability to provide nutrients to crops. Our soils are gradually becoming depleted and progressively less fertile. Those soils that were originally low to medium in fertility status are unable to supply nutrients in sufficient quantity and at an adequate rate to provide for satisfactory crop production.

The Extent of Sulphur Deficiency in Western Canada

Substantial areas of soils having severe deficiencies of sulphur for certain crops were observed and identified in the 1940's. These early cases of sulphur deficiency occurred almost entirely on certain light to medium textured gray wooded soils in the northern areas of Alberta, Manitoba and Saskatchewan. One of the first crops on which sulphur deficiency was observed, and which has received the greatest amount of attention in subsequent sulphur fertilizer studies, is alfalfa.

Field studies, since the early 1950's, and soil testing during the past decade have identified and delineated large additional areas of soils deficient in sulphur for various crops. The largest areas of sulphur deficient soils occur in the Dark Gray and Gray wooded soil zones of western Canada. However, there is a substantial area of well-drained, coarse textured, soils in the Black soil zone that are low in available sulphur. Soil testing in recent years has shown that there may be a significant number of heavier textured luvisolic soils and Black chernozemic soils that have available sulphur levels below that required for adequate crop nutrition.

Sulphur Requirements of Field Crops

Many studies with crops such as alfalfa and clovers have shown that such legume forage crops require relatively large amounts of sulphur for high production. These crops are generally high in protein, and where large yields of forage are removed in several harvests during a growing season, large amounts of sulphur are removed from the soil annually. The grasses generally require less sulphur than legume forages, and may grow relatively well on soils which produce poor yields of crops such as alfalfa or clover. The cereal grains also are not as sensitive to sulphur deficiency as legume forage crops, but on severely sulphur-deficient soils, yields of cereal grains, particularly coarse grains, can be substantially reduced. Oil crops have a relatively high sulphur requirement because the oil storage organs are usually rich in protein (38).

Responses of Crops to Sulphur Fertilizers

Results from some of the early trials with sulphur fertilizers on sulphur-deficient gray wooded soils in western Canada show large responses to application of sulphur, both as direct and residual effects.

Table 1. Effect of sulphur fertilizers and legume hay crops on wheat yields and residual effect of fertilizers on legume hay - Caroline loam, Chedderville, Alta. 1946-55 (1).

Fertilizer lb/ac				Wheat after fallow and legume hay	Legume hay after wheat
N	P_2O_5	K_2O	S	bu/ac 10-yr av.	tons/ac 8-yr av.
0	0	0	0	34.3	1.18
16	0	0	0	38.8	1.24
0	0	0	20	37.9	2.52
16	0	0	20	43.7	2.55
16	20	0	0	36.9	1.41
16	20	0	20	44.9	3.06

Data from field studies at Chedderville, Alberta on a Caroline loam (Table 1) show a 27% increase in yield of wheat grain where sulphur was applied with nitrogen for wheat on fallow and after legume hay. When nitrogen or sulphur were applied alone, less than half of this increase was obtained. Residual sulphur more than doubled yields of legume hay following the wheat. The nitrogen applied was not beneficial to the hay crop. On a gray wooded Loon River loam in north-western Saskatchewan both wheat on fallow and established alfalfa

Table 2. Effect of direct and residual fertilizer applications on wheat, coarse grains and alfalfa hay on Loon River loam (1).

Fertilizer treatment	Wheat on fallow bu/ac (1951-54)	Alfalfa tons/ac 1953	Coarse grains after wheat bu/ac 1953-54 residual	Alfalfa tons/ac 1954 residual
Check	25.0	1.39	29.8	2.43
N	24.7	.87	23.4	2.08
S	30.0	2.44	34.0	3.30
NS	34.6	3.34	34.0	3.66
NPS	34.5	3.42	33.4	3.20

responded strongly to application of sulphur and nitrogen plus sulphur as a direct effect, and yields of coarse grains following wheat and second crop alfalfa were substantially increased by the residual fertilizer sulphur from these same treatments (Table 2). It is interesting to note that where only nitrogen was applied, both the cereals and alfalfa yielded less than on unfertilized plots, and the combination of nitrogen and sulphur produced highest yields of both wheat and alfalfa as direct and residual effects.

A comparison of different sulphur fertilizer materials for alfalfa on a Loon River loam soil showed that the smallest direct response was obtained from elemental sulphur and the largest response from soluble sulphate sources such as ammonium sulphate. For subsequent residual effects, however, the differences between sulphur sources

Table 3. Yields of alfalfa on sulphur-deficient Loon River loam as influenced by sulphur treatments (43).

Fertilizer		Hay (D.M.) yield - lb/ac	
Form	lb/ac S	Direct effect 3-yr av. (1953-55)	Residual effect* 4-yr av. (1954-59)
Sulphur	20 + NPK**	2774	2181
Gypsum	20 "	3508	2088
Na_2SO_4	20 "	3485	1794
$(NH_4)_2SO_4$	20 "	3995	2463
K_2SO_4	20 "	3790	2346
	0 "	956	1261
	Check	348	821

* Second year crop after fertilizer application.
** Applied at 23, 28 and 56 lb/ac of N, P_2O_5 and K_2O respectively.

were much smaller (Table 3). Apparently the rate of oxidation of elemental sulphur was not sufficiently rapid to adequately supply the crop with available sulphate in the year of application. Added sulphur in elemental form varies in effectiveness depending on how favorable soil conditions are for oxidation of the sulphur material. High soil pH and low temperatures are generally unfavorable for sulphur oxidation. The Loon River soils have a surface pH of about 7.0.

In fertilizer studies carried out during the 1950's on a gray wooded soil at Breton, Alberta, an application of 20 lb S/ac as sodium sulphate produced substantial increases in yields of wheat, oats and barley (8).

In 1960, field trials with sulphur fertilizers were carried out on established alfalfa at four locations on different textures of the Loon River soils in north-western Saskatchewan to determine the extent of sulphur deficiencies. Responses to sulphur were obtained at all four trial locations on soils varying from light loam to

Table 4. The response of alfalfa to fertilizers on different textures of a gray wooded Loon River loam at several locations - 1960.

Sulphur		Hay (D.M.) yields - lb/ac			
Source	lb/ac	LnLL Pierceland	LnL Loon Lake	LnL Golden Ridge	LnCL Bigbush
$(NH_4)_2SO_4$	20	1836	3053	2100	2859
	40	1596	2671	2192	3016
	80	2367	2915	2448	3029
K_2SO_4	40	2111	2124	1655	2557
$MgSO_4$	40	2837	2438	1805	2879
Gypsum	20	2376	2013	1630	2405
	40	2558	2264	1934	2680
Check		493	797	1387	1808
LSD 5%		787	740		664

clay loam in texture (Table 4), indicating that this association was extensively S-deficient for certain crops.

Rapeseed requires considerably larger amounts of sulphur for high yields than the cereal grains (21), and good yields of rapeseed and mustard cannot be obtained without fertilizer on soils deficient in sulphur. On the sulphur deficient Loon River loam soil in north-western Saskatchewan, an application of 20 lb S/acre as gypsum increased the yields of yellow mustard and rapeseed by more than 400 lb/acre (Table 5). On soils very low in both nitrogen and

Table 5. Response of rapeseed and mustard to sulphur fertilizer on a gray luvisol Loon River loam in N. W. Saskatchewan

	Seed yield - lb/ac	
S lb/ac	Yellow mustard	Nugget rapeseed
0	910	1268
20	1321	1708

sulphur, adequate amounts of the two nutrients must be applied to obtain satisfactory yields, particularly for crops such as rapeseed. Studies on gray wooded soils in northern Alberta showed that when nitrogen was applied without sulphur on a soil deficient in both nutrients, the yields of rapeseed were markedly reduced, with plants producing largely empty pods. The application of both deficient nutrients produced spectacular increases in yields of rapeseed and

Table 6. Effect of nitrogen and sulphur fertilizers on yields of Turnip rape and barley on two gray luvisol soils in northern Alberta - 1970 (30).

Fertilizer applied	Seed yield - cwt/ac			
	Soil 1		Soil 2	
	Rape	Barley	Rape	Barley
0	2.2	13.1	3.5	15.5
NPK	0.3	13.0	0.8	12.2
PKS_1	3.3	14.4	5.2	20.4
$NPKS_1$	17.2	39.5	16.0	35.6
$NPKS_2$	14.9	36.9	17.3	30.4

S_1 - 20 lb/ac; S_2 - 50 lb/ac

barley (Table 6). Similar results were obtained on a sandy soil in Manitoba (Table 7).

Table 7. The effect of nitrogen and sulphur fertilizers on yields of rapeseed on several Manitoba soils (35).

Fertilizer treatment	Seed yield - lb/ac		
	Pine Ridge LFS Steinbach	Altamont CL Manitou	Newdale CL Clanwilliam
Check	900	530	1090
NP	250	1990	2430
NPS_1	2350	2180	2920
NPS_2	1810	2330	3000

N - Broadcast after seeding as 34-0-0 @ 60 lb N/ac; S - broadcast after seeding as K_2SO_4 @ 10 (S1) and 20 (S2) lb S/ac; P - drilled with seed as 11-55-0 @ 20 lb P_2O_5/ac.

The yields of faba beans and soybeans were increased by broadcast applications before seeding of elemental sulphur and Agri-sul on several sulphur-deficient light-textured soils in western Manitoba (5, 6). The effect of sulphur fertilizers on soybean yields is shown in Table 8. Well nourished plants are better able to resist and recover from the ravages of diseases often associated with winter killing of legume forage crops. Studies in north-western Saskatchewan showed that sulphur fertilizers applied on a deficient gray wooded soil markedly improved the ability of the crop to recover from a devastating attack of crown bud rot which "winter-killed" large acreages of alfalfa in the area.

Table 8. Effect of sulphur broadcast prior to seeding on soybean yields on several soils in western Manitoba, 1974-1977 (6).

	Dried beans - lb/ac		
S lb/ac	Miniota FSL	Souris FSL	Stockton FSL
0	2066	2656	1463
9	2151	2824	1572
18	2245	2924	1713
36	2484	3117	1891
SO_4-S lb/ac	6-9	4-6	6-7

18 lb P_2O_5/ac drilled with seed; 107 lb K_2O/ac broadcast prior to seeding.

Sulphur deficiencies affect not only the yield of crops, but also the chemical composition and the levels of the various important constituents. The application of sulphur fertilizers has been shown to increase the nitrogen and sulphur content in alfalfa and clover (9, 3, 42). Adequate sulphur in alfalfa has been shown to increase protein synthesis by accelerating protein metabolism. With increasing rates of applied sulphur, the concentrations of total N, protein N, total S, protein S and total soluble S in plants increase, while the non-protein fractions decrease (4). Sulphur fertilization increased the protein-nitrogen in S-deficient timothy plants by 26% (13). When sulphur is deficient, plants cannot completely utilize nitrogen fertilizer, and as a result protein production is limited or decreases and non-protein forms of nitrogen tend to increase in plant tissues (33, 39). In rapeseed, the addition of nitrogen fertilizer without sulphur produced amino acids which were not incorporated into protein because of lack of sulphur. Addition of sulphur allowed plants to synthesize larger amounts of sulphur-containing amino acids and produced a greater amount of protein (14). Where available sulphur is insufficient, yields are low and the quality of the plant protein deteriorates. In pot experiments it was found that methionine content in barley grain fell by 9% and cysteine by 38% when sulphur was deficient (36).

Sulphur has a very important function in the nitrate reductase enzyme system (7, 22). Sulphur-containing amino acids are part of the enzyme structure and sulfhydryl groups are involved in enzyme activity (7). In the presence of adequate sulphur, uptake of nitrogen triggers the synthesis of NRA to process the nitrogen and incorporate it into proteins (19). Friedrich and Schrader (17, 18), in a growth chamber study observed a 50% decline in nitrate reductase activity in 12-day old maize seedlings, a 25% decrease in soluble leaf protein

Also, studies have shown that soils and crops downwind from natural gas and oil processing plants and other industrial plants absorb significant amounts of sulphur from sulphur gases and particulate matter emitted into the atmosphere (32, 45). During the past decade there have been various indications to suggest that sulphur deficiencies and responses to sulphur on certain soils have been increasing. The extensive growing of rapeseed, a sulphur-sensitive crop, during this period throughout northern Saskatchewan has brought about a greater awareness of sulphur deficiencies. Continued cropping has reduced the levels of organic matter, available nitrogen and sulphur on many soils to the extent that they cannot supply adequate amounts of nitrogen and sulphur for high crop yields. In order to maintain yields the rates of nitrogen fertilizers have been increasing in recent years. Where attention is not given to the status of soil sulphur, the added nitrogen may intensify sulphur deficiencies by creating acute imbalances between nitrogen and sulphur in plant metabolism (29). The addition of nitrogen fertilizers to some soils can also result in a decreased net sulphur mineralization (24).

Diagnosis of Sulphur Deficiencies

In the search for methods of accurately assessing the sulphur status of soils for various crops, a number of different soil and plant analyses have been tried and related to crop response to fertilizer application.

Soil Analyses - Numerous soil extraction procedures and availability determinations have been investigated by researchers. Sulphate sulphur has been determined by extracting with water, neutral salt solutions, phosphate solutions, and acidic solutions. Measures of sulphate-sulphur plus a fraction of organic sulphur have been obtained by heating soil samples, or extracting with neutral N ammonium acetate or 0.5 M sodium bicarbonate. Other procedures have been used to measure organic and total sulphur, and availability of soil sulphur has also been determined by use of microorganisms, incubation and "A" value techniques. Fox, et al (15), and Ensminger and Freney (12) have compared and discussed the various extraction procedures and availability determinations and their relative efficiencies in assessing soil available sulphur status for different crops. The ultimate value of a soil test method depends on how well the S values obtained correlate with plant growth or response of the plant to sulphur fertilizers. Phosphate extraction procedures appear to offer considerable promise for determining the available S status of soils (12, 15). However, for soils containing appreciable amounts of organic matter, the organic S fractions should be considered (12).

Soil analyses for soluble sulphate are used as a basis for determining sulphur fertilizer requirements in western Canadian soil testing laboratories. In general, the methods relate quite well to response of crops to sulphur fertilizers, but there are some problems that must be resolved to make the test more reliable.

The importance of sulphate-sulphur located at different depths in the profile, within the 60 cm depth sampled for sulphur tests in Saskatchewan, and below this depth, has not been adequately assessed for different crops in relation to soil characteristics. Under conditions of abundant rainfall or other moisture moving down through the soil, sulphate, like nitrate, can be readily leached from surface soil. The effect on crop growth would depend on the rate of mineralization of sulphur from organic sources in topsoil and the rate of growth and depth of proliferation of roots and their ability to tap available sulphur at depth.

More research information is required to determine the contribution to plant nutrition of organic sulphur mineralized during the growing season in different soil types and under different climatic conditions. The mineralization of organic sulphur and the oxidation of other reduced forms in the soil are influenced by such factors as organic matter content, soil temperature and pH. Further clarification of the nature of available sulphur in soils would help to improve soil test methods and their interpretation.

Plant Analyses - Plant analyses have been widely used to assess the sulphur status of various crops. Of the various methods used and plant constituents measured, the determinations of sulphate-sulphur, total sulphur and N:S ratio appear to have the greatest promise as relatively quick and fairly reliable tests when properly applied and interpreted, and their limitations taken into account.

Sulphate content in plants is generally considered to be an indication of luxury consumption. When sulphur is present in the plant in excess of that required for formulation of protein and other organic sulphur compounds, the excess accumulates in the plant as sulphate (12, 28). Cairns (9) found that soluble SO_4-S content of alfalfa herbage appeared to be the best index of sulphur-supplying status of a gray wooded soil in northern Saskatchewan, and this correlated well with yield. Dijkshoorn, et al (10) found that sulphur and nitrogen are utilized in the building up of protein in an atomic ratio $(S/N)_p = 0.027$ (or on a percentage basis $(S/N)_p = 0.062$), which is approximately equal to the ratio of organic sulphur to organic nitrogen. When sulphur is present in excess of this requirement, this excess occurs as inorganic sulphate in the herbage, and indicates adequate sulphur uptake by the plant. When total sulphur levels in the plant are less than 0.027 x Kjeldahl N, sulphate-sulphur is generally absent or at very low levels, indicating inadequate sulphur uptake. Sulphate-sulphur levels in plant tissue have been used as a diagnostic measurement by many other workers (12, 25, 28). Recently Freney, et al (16) suggested that sulphate as a percentage of total sulphur is a more reliable index than sulphate-sulphur or total sulphur.

Total sulphur in plant tissue is also widely used as a diagnostic indicator of sulphur nutrition of plants. Total sulphur in plants tends to change less than sulphate-sulphur in response to available sulphur supply in the soil, and has been considered to be a less sensitive index of sulphur deficiency than sulphate sulphur (12).

When using sulphate-sulphur or total sulphur values as indicators of sulphur nutrition status of crops, the influence of a number of factors must be considered. Sulphate-sulphur and total sulphur contents in plant tissue are affected by supply of other nutrients, particularly N, in the soil or from fertilizer (12, 27, 28), plant part sampled (12, 37, 40), and stage of growth or age of plant (12, 16, 34, 37). Also, McKell and Wilson (26) showed that temperature had a marked effect on uptake of S by clovers, and Herath (23) observed that temperature influenced S uptake in barley, rapeseed and peas. The three plant types differed in their response to increase in temperature. Under conditions of sulphur deficiency, at high temperatures the uptake of sulphur in rapeseed and peas decreased, but was relatively unaffected in barley. With added sulphur, rape plants had a greater uptake at higher temperatures, but barley and peas showed lower uptake.

Any major change in the nutrient supply of nitrogen or sulphur which leads to the accumulation of non-protein N (sulphur deficiency) or non-protein sulphur (sulphur excess or nitrogen deficiency) will be reflected in a corresponding change in the ratio total N/total S $(N/S)_t$ (28). A high $(N/S)_t$ should indicate sulphur deficiency, and a low ratio a sufficiency of sulphur or a deficiency of nitrogen (33). Pumphrey and Moore (34) showed that N/S ratios remained relatively constant at different growth stages. Dijkshoorn and Van Wijk (11) proposed organic nitrogen/organic sulphur ratios, given in percentages, of approximately 17.5 for legumes and 13.6 for gramineous plants. In sulphur deficient plants, the N/S ratio tends to increase because of an increase in non-protein organic compounds low in sulphur. Under certain conditions a decrease in protein nitrogen/protein sulphur ratio may occur under extreme sulphur deficiency (28) or N/S ratios may be high even when plant sulphur contents are high (27).

Although the N/S ratio in plant tissue appears to be a relatively good index of sulphur status, it also must be viewed critically. Recent investigations have shown that N/S ratios in plants are influenced by growing temperatures (23), and growth stage or age of crop (23). Generally N/S ratios are lower at early growth stages and higher with approaching maturity. Critical N/S ratio also varies with the plant part sampled (20), in part related to the amount of sulphur translocated from vegetative to seed or storage organs (40). Herath (23) found that the protein nitrogen/protein sulphur ratio tended to vary less with temperature and plant stage, and considered this to be a more suitable indicator than total nitrogen/total sulphur. Andrew (2) considered the use of N/S ratios unsuitable for diagnosing sulphur deficiency in legumes, because the nitrogen content is influenced by the efficiency of N-fixation.

It is obvious that when using plant sulphur content or N/S ratios to diagnose sulphur nutrition status of crops, sampling procedures must be clearly specified and standardized and critical values established for specific crops, plant parts and crop stages. More research is required to more adequately assess these and other diagnostic methods for specific crops. Plant analysis can be most effective when used as a complementary check to soil analysis. Often plant analysis used alone does not reveal a deficiency until it is too late to apply corrective fertilizer treatment.

Recent Occurrences of Sulphur Deficiencies in Northern Saskatchewan

Suspected sulphur deficiencies have occurred in numerous rapeseed fields in northern Saskatchewan in 1977 and 1978. Deficiency symptoms have occurred throughout entire fields, resulting in complete crop loss. These fields were located mainly on light-textured Dark Gray and Gray Soils. In other fields, scattered patches of poor crops occupying from 10 to 70% of the area occurred on upland areas and knolls on light-textured or highly degraded soils. About 80% of the problem fields were previously planted to legume crops such as alfalfa, red clover or sweet clover. Legumes are heavy users of sulphur.

Sulphur deficiency was the most likely cause of poor growth and yields of rapeseed. Generally the fields were fertilized with adequate levels of nitrogen and phosphorus and potassium where required. Soil analyses on samples taken from twelve of the problem fields showed that the soils were sulphur-deficient for rapeseed. The symptoms observed in rapeseed were 1) cupping of the leaves and a reddish tinge to the underside of leaves of young plants 2) a reddish-purplish coloring of leaves, stems and pods of mature plants and 3) poor pod and seed development, shrunken and shrivelled seeds and severely reduced yields.

Sulphur deficiencies occur mainly in the Black, Gray-Black and Gray soil zones. Examination of 1977-78 soil test data shows 7-12% of the Black soils tested fall into the deficient category for rapeseed. In the gray-black soils, 27% show deficient levels of sulphur and 34% of the gray soils tested deficient. Low levels of available sulphur were found mainly in the coarse to medium textured soils in each zone. A review of the soil test data shows that sulphur deficiencies are as likely to occur in summerfallow as in stubble crops.

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