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Importance of sulphur in crop production*

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Abstract. Sulphur in agricultural soils occurs in organic and inorganic forms, with organic S accounting for $> 95\%$ of the total S. Analysis of a wide range of soils shows that from 25 to 75% of the organic S in soils is HI-reducible, from 7 to 30% is C-bonded, and from 11 to 22% is unidentified S. Nitrogen is associated with S in soil organic matter in a ratio of about 8 : 1, although the extreme ratios may vary from 5 : 1 to 13 : 1. Laboratory studies showed that humus S is depleted faster than humus N. Mineralization of S in crop residues varied with type of crop residue and soil studied. The amounts of S fertilizers (gypsum, elemental S, and sulfuric acid) used in the United States in 1981 and 1982 were 1.9×10^6 and 1.5×10^6 tons, respectively. Of the total amount used in 1982, 3, 5, 20, and 71% were used in the West North Central, Mountain, South Atlantic, and Pacific regions, respecitively. A survey of S deposition at about 100 sites in the United States and many other sites in Canada in 1980 showed that annual addition by precipitation in North America ranged from 0.5 to slightly above 10 kg/ha. The usual ranges of values in concentrations and spatial rates of N, P, and S in precipitation is well within the ranges of these elements in natural waters. Atmospheric sources are important components in meeting crops S requirements and should be considered in benefit-cost analyses relating to S emissions.

Introduction

Sulfur has been recognized as an essential element for plant growth and development for more than 100 years, and Liebig (1859) was aware of the close relationship between N and S in many plants. According to Hall (1909) and Juhalin-Dannfelt (1911), the beneficial effect of gypsum as a fertilizer was already known by the ancient Romans and Greeks. Alway (1940) has presented an interesting review of the history of S as a plant nutrient element. The history of the use of S fertilizers may be divided into three periods. The first period was the Reign of Gypsum (1760–1845). During this period gypsum was used widely and its beneficial effect generally overestimated. The second period was the Reign of Superphosphate (1845–1905) during which the need for any S additions to soils was ignored and

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the use of gypsum was discouraged by agricultural scientists. The third period is the Renaissance, or Modern Period. This last period dawned when a Russian chemist, Bogdanov, in 1899 questioned the assumption that the natural supply of S is everywhere sufficient for crops and three English agronomists (Dymond, Hughes, and Jupe) stationed at an Essex County laboratory, put the question to practical test on local fields from 1896 to 1901 with red clover, peas, cabbage, rutabagas, oats, barley, and permanent pasture, and published their work in the first volume of the Journal of Agrucultural Science in 1905 (Alway, 1940).

The use of gypsum as a fertilizer in modern times can be traced back to the middle of the eighteenth century. A field trial with gypsum applied to a clover field was reported in Switzerland in 1768 (Johansson, 1959). Application of gypsum increased the yield of clover by more than 2-fold. This resulted in a rapid increase of use of gypsum as a fertilizer. In the U.S. the introduction of gypsum was greatly encouraged by a classical experiment by B. Franklin, who applied gypsum to part of an alfalfa field situated beside a main road near Washington, D.C. Passing travelers on the road saw the effect of S in the gypsum in dark green letters against a light green background which read, 'This has been plastered'. The history of the use of S as fertilizer since the beginning of this century is reported by Johansson (1959), Evans (1975), and Alway (1940).

Interest in fertility-related aspects of the S cycle is increasing because S deficiencies on agronomic crops are observed with increasing frequency. Sulfur is considered the fourth important nutrient element after N, P, and K. Sulfur fertilization is now required in many areas in the United States to ensure satisfactory crop production. Other areas that have shown responses to S fertilization are in Australia, Africa, Asia, Canada, New Zealand, and South and Central America (Anonymous, 1982a). The factors responsible for the increased need for S fertilization has been discussed by Coleman (1966). They include increased use of high-analysis fertilizers that contain little or no S, increased crop yields, decreased use of S as a pesticide, more intensive cropping, and decreased gain of atmospheric S by soils and plants as a result of decreased combustion of coal and other S-containing fuels. This paper will deal primarily with the parts of the S cycle as they relate to crop production.

Sulfur requirements of crops

The importance of S in agriculture is obvious because plants require S for synthesis of an essential amino acid and proteins, certain vitamins and coenzymes, glucocide oils, structurally and physiologically important disulfide linkages and sulfhydryl groups, and activation of certain enzymes (Coleman, 1966). Generally, agronomic crops require about the same amount of S as they do of P. Although the S content of plants varies depending on the

Table 1. Sulfur content of crops.

Crop	Yield tons/ha	Total S content kg/ha	Crop	Yield tons/ha	Total S content kg/ha
Grain and oil crops			Cotton and tobacco		
Barley	5.4	22	Cotton (lint + seed)	4.3	34
Corn	11.2	34			
Grain sorghum	9.0	43	Tobacco		
Oats	3.6	22	Burley	4.5	21
Rice	7.8	13	Flue cured	3.4	50
Wheat	5.4	22			
Peanuts	4.5	24			
Soybeans	4.0	28			
Hay crops			Fruit, sugar and vegetable crops		
Alfalfa	17.9	45			
Clover-grass	13.4	34	Beets		
Bermudagrass			Sugar	67	50
Common	9.0	17	Table	56	46
Coastal	22.4	50	Cabbage	78	72
Bromegrass	11.2	22	Irish potatoes	56	27
Orchardgrass	13.4	39	Onions	67	41
Pangolagrass	26.4	52	Oranges	52	31
Timothy	9.0	18	Pineapple	40	16
			Sugarcane	224	96

Estimates by Potash/Phosphate Institute of North America (Terman, 1978).

supply available, some crops have greater S requirements than others (Table 1). An average yield of forage crops removes 17 to 50 kg of S per ha and the cereal grains generally remove < 30 kg/ha. Other crops such as cabbage, turnip, and alfalfa have a particularly high requirement for S. Such crops commonly need from 45 to 70 kg of S per ha. One of the crops that require a very high amount of S is sugarcane. A yield of 224 tons per ha removes about 100 kg of S (Table 1).

Another factor that affects the S requirement of plants is the available N. Sulfur and N are closely associated in protein synthesis, thus S requirements vary with the supply of N to crops. Therefore, when S becomes limiting, additions of N do not increase the yield or protein level of plants (Dijkshoorn and Van Wijk, 1967).

The N:S ratio of many crops at maximum yields have been determined. Alfalfa requires one part of S with every 11 to 12 parts of N to ensure maximum production (Aulakh et al., 1976); with wheat, corn, beans, and sugar beet leaf blades, one part of S is required for every 12 to 17 parts of N (Stewart, 1966; Steart and Porter, 1969). During early growth, cereals are also very sensitive to S deficiency; the N:S ratios of grains such as oats and barley are 13:1 and 9:1, respectively (Saalbach, 1970). It has been suggested that many soils known to be deficient in S for alfalfa may also provide insufficient S for optimum cereal growth (Nyborg, 1968).

Crop plants obtain their S requirements from a number of sources. These are (1) soils, crop residues, and manures, (2) irrigation waters, (3) rainfall and the atmosphere, and (4) fertilizers and soil amendments. The order of importance of each of these sources varies with the type of crop, location, and management practices.

Sulfur in soils

Total S in mineral soils may range from < 20 ppm in sandy soils to > 600 ppm in heavy textured soils. Organic soils may contain as much as 0.5% S. Most soils in the United States, however, contain between 100 and 500 ppm of S.

Sulfur occurs in soils in organic and inorganic forms, with the organic S accounting for more than 95% of the total S in most soils from the temperate, humid, and semi-humid regions. The proportion of organic and inorganic S in soils, however, varies widely according to soil type and depth of sampling. While much of the organic S in soils remains unidentified, three broad fractions have been identified. The analytical methods currently in use permit differentiation between three broad fractions of organic S in soils: (1) HI-reducible S, (2) C-bonded S, and (3) unidentified S (residual or inert). The first fraction contains S compounds that are not directly bonded to C and it is believed to consist primarily of sulfate esters such as phenol sulfate, sulfated polysaccharides, choline sulfate, and sulfated lipids (Freney, 1967; Tabatabai and Bremner, 1972a; Chae and Tabatabai, 1981). Because the S in this fraction can be readily hydrolyzed to inorganic sulfate by acid and alkali, HI-reducible S is considered to be the most labile fraction of organic S (Spencer and Freney, 1960; Lowe, 1965; Freney et al., 1971; Cooper, 1972). Analyses of a wide range of soils have shown that, on the average, about 50% of the total organic S in soils of humid and temperate regions is present in the HI-reducible form, although the percentage may range from 25 to 75% (Table 2).

The second fraction, the C-bonded fraction, is determined by reduction to H_2S with Raney nickel (Tabatabai, 1982). Table 2 shows results obtained for the C-bonded S and the unidentified fractions in soils from different regions. Expressed as percentage of total S in soils, the means of the C-bonded S fraction range from 7 to 30; and the unidentified S fraction from 11 to 22.

The presence of large amounts of organic S in surface soils is indicated by the close relationship found between organic N and S. In many of the soils studied in North America and other parts of the world, these elements are associated approximately in the ratio of 8:1 for N and S, respectively, although this ratio may vary from 5:1 to 13:1 (Table 3). The N:S ratio appears to be the same for virgin soils as for their cultivated counterparts (Table 4), suggesting that organic N and S are mineralized in about the same ratio as they occur in soil organic matter. However, recent laboratory studies (will be discussed below) show that organic S is depleted faster than organic N.

As is true with N, when land is first cultivated the S content of the soil declines rapidly and an equilibrium level is reached which is characteristic of climate, cultural practices and soil type. At the equilibrium level, soil humus essentially ceases to act as a source of S for plant growth. Before reaching this equilibrium, the rate of mineralization of S will be so slow that it cannot cope with the plant's requirements. This results in the appearance of S deficiency symptoms on the plants. Recent studies show that most of the soils in the Midwest may be at or near the marginal levels of supplying S to plants. This is suggested from laboratory tests and greenhouse experiments showing that soils do not contain sufficient plant-available S and most respond to S fertilization when cropped under greenhouse conditions (Tabatabai and Bremner, 1972b; Widdowson and Hanway, 1974).

Studies on transformation of N and S under field conditions show mineralization patterns for N differ from those for S, with sulfate levels in uncropped soil undergoing much greater seasonal variation than levels of mineral N (Simon-Sylvestre, 1965). Recent laboratory work at Iowa State University to simulate field conditions showed that humus S is depleted faster than humus N. The data in Table 5 show that the rates of S mineralization from 12 Iowa surface soils are much lower than those of N mineralization. This observation is expected because soil humus contains more N

Table 2. Fractionation of sulfur in surface soils.

Location[b]	Percentage of total S in form specified						Ref.
	HI-reducible		C-bonded[a]		Unidentified		
	Range	Mean	Range	Mean	Range	Mean	
Alberta, Canada (15)	25–74	49	12–32	21	7–45	30	Lowe (1965)
Australia (15)	32–63	47	22–54	30	3–31	23	Freney et al. (1970)
Brazil (6)	36–70	51	5–12	7	24–59	42	Neptune et al. (1975)
Iowa, USA (24)	36–66	52	5–20	11	21–53	37	Tabatabai and Bremner (1972a)
Iowa, USA (10)	42–58	51	7–14	11	33–44	38	Chae and Tabatabai (1981)
Quebec, Canada (3)	44–78	65	12–32	24	0–44	11	Lowe (1964)

[a] Determined by reduction with Raney Ni.

[b] Figures in paretheses indicate number of samples.

Table 3. Mean ratios of nitrogen to sulfur in surface horizons of soils.

Location	Description[a]	N:S ratio	Ref.
	Virgin soils		
Alberta, Canada	Brown Chernozems (4)	7.1	Lowe (1965)
	Black Brown Chernozems (4)	7.7	
	Grey Wooded (7)	12.5	
	Gleysols (6)	5.0	Lowe (1969)
U.S.A. (several states)	Not specified (10)	8.7	Stewart and Whitefield (1965)
	Cultivated soils		
N.S.W., Australia	Pasture soils (5)	8.5	Barrow (1961)
	Clover pasture, podzolic (44)	7.1	Williams and Donald (1957
Eastern Australia	Acid soils (128)	8.3	Williams and Steinbergs (1958)
	Alkaline soils (27)	6.6	
Sao Paulo and Parana, Brazil	Agricultural, varied (6)	7.7	Neptune et al. (1975)
Canterbury, New Zealand	Grassland, unfertilized	7.7	Walker and Adams (1958)
North Scotland	Agricultural, non-calcareous (40)	7.1	Williams, Williams, and Scott (1960)
U.S.A.			
Iowa	Agricultural, varied (37)	6.5	Tabatabai and Bremner (1972a)
Iowa	Agricultural, varied (6)	7.7	Neptune et al. (1975)
Minnesota	Brown Chernozems (6)	6.4	Evans and Rost (1945)
	Black prairie soils (9)	6.1	
	Podzols (24)	8.5	
Mississippi	Podzols (4)	13.1	Nelson (1964)
Oregon	Agricultural, varied (16)	9.9	Harward et al. (1962)
Several states	Agricultural, varied (10)	8.0	Stewart and Whitefield (1965)

[a] Figures in parentheses are number of soils examined.

Table 4. Organic nitrogen and sulfur ratios in virgin soils (V) and their cultivated (C) counterparts[a].

Location		N:S ratio
Big Springs, TX	V	12.0
	C	11.1
Colby, KS	V	6.5
	C	6.8
Mays, KS	V	8.0
	C	6.8
Moccasin, MT	V	7.6
	C	6.0
Dalhart, TX	V	9.6
	C	11.7
Mandan, ND	V	9.0
	C	9.6
North Platte, NE	V	9.9
	C	9.0
Lawton, OK	V	10.3
	C	10.4
Archer, WY	V	8.5
	C	8.0
Havre, MT	V	9.1
	C	8.2
Average		8.7
		8.0

[a] Stewart and Whitefield (1965).

Table 5. Comparison of rates of nitrogen and sulfur mineralization in Iowa surface soils.

	Rate of mineralization					
	at 20 °C			at 35 °C		
Soil	N	S	N:S	N	S	N:S
		kg per ha per week				
Lester	6.7	1.6	4.2	22.6	4.9	4.9
Ackmore	4.9	1.6	3.1	27.6	4.9	5.6
Fayette	5.6	1.8	3.1	23.5	5.2	4.5
Downs	8.1	2.7	3.0	35.9	7.0	5.1
Clarion	6.7	1.8	3.7	26.7	7.8	3.4
Muscatine	7.4	1.8	4.1	33.2	6.7	5.0
Nicollet	3.8	1.3	2.9	17.3	4.0	4.3
Tama	9.0	2.2	4.1	34.3	7.2	4.8
Webster	9.4	2.2	4.3	38.1	6.5	5.9
Canisteo	4.9	1.3	3.8	20.9	4.0	5.2
Harps	4.3	1.2	3.6	21.7	3.6	6.0
Okoboji	6.3	1.8	3.5	34.3	6.1	5.6
Avg.	6.4	1.8	3.6	28.0	5.7	5.0

Soil-glass beads columns were incubated at 20 or 30 °C and the mineral N and S produced were determined after leaching every 2 weeks with 0.01*N* KCl for a total of 26 weeks.

than S. The weakly amounts of N, in the form of nitrate, produced in soils will not be completely available to plants because some of it is lost by leaching to ground water and another portion is lost to the atmosphere by denitrification. Similarly, not all the sulfate produced from the soil organic matter is available to plants because of its loss to ground water. No significant amount of S gases, however, are evolved from soil humus (Banwart and Bremner, 1976). As is the case with the amount of N mineralization, the sulfate produced from soil organic matter is not enough to cope with the crop requirements. Therefore, S fertilization is needed in some soils, especially in areas where the levels of atmospheric S are very low.

Although the N:S ratio of the 12 soils studied ranged from 5.8 to 7.4 (avg. 6.8) (Tabatabai and Al-Khafaji, 1980), the ratios of mineral N to mineral S produced during incubation ranged from 2.9 to 4.8 (avg. 3.6) and from 3.4 to 6.0 (avg. 5.0) at 20 and 35 °C, respectively (Table 5). Similar results recently were reported by Maynard et al. (1983) for three Canadian Prairie soils. These results clearly show that the pattern of N mineralization in soils differs from that of S mineralization and that the two elements are not mineralized at the same proportion as they occur in soil organic matter.

The data reported in Table 6 show the percentage of depletion of N and S in Iowa surface soils during the 26 weeks of incubation at 20 and 35 °C. Generally, the rates of depletion of S are about 1.5 times those of N. The generally greater rates of depletion of organic S relative to that of organic N in soils supports the conclusion made by Fitzgerald (1978) that the belief held by some ecologists that S is nonlimiting in the environment requires reevaluation. This is especially true if the proposed transfer and use of N-fixing genes to improve plant growth becomes a reality. Because of the continued use of fertilizers that are free of or low in S and the proposed restriction on SO_2 emission into the atmosphere, a greater demand will be made by plants on the release of inorganic S from soil organic matter than in the past. Atmospheric sources are an important component in meeting crops S requirements and should be considered in benefit-cost analyses relating to S emissions.

Effect of soil management on sulfur mineralization

Soil management practices have been changing in recent years and minimum or no-till systems are becoming common methods. It is of considerable agronomic significance to know the extent to which the S returned in crop residue becomes available to succeeding crops. The release of plant available S from decomposing crop residue depends primarily on the rate of decomposition and the type and S content of the residue. To assess the effect of the type of residue on S mineralization in surface soils, crop residues (cornstalks and cobs, soybean residues, alfalfa, and sawdust) were applied at the rate of 50 mt/ha to five Iowa surface soils and soil-glass beads-crop residue mixtures

Table 6. Comparison of depletion rates of organic nitrogen and sulfur in Iowa surface soils.

	Percentage depletion after 26 weeks			
	at 20 °C		at 35 °C	
Soil	N	S	N	S
Lester	6.0	12.5	22.6	32.7
Ackmore	4.2	9.3	25.1	27.3
Fayette	4.3	9.5	18.7	27.2
Downs	6.7	13.3	26.8	32.9
Clarion	4.7	9.5	18.3	34.9
Muscatine	3.6	7.0	16.3	24.1
Nicollet	2.0	5.6	8.3	14.7
Tama	4.6	8.4	18.0	25.7
Webster	4.3	8.1	17.8	22.6
Canisteo	1.9	4.2	9.1	10.9
Harps	2.0	3.5	9.1	8.9
Okoboji	1.8	4.0	9.3	11.4
Avg.	3.8	7.8	16.6	22.8

Soil-glass beads columns were incubated at 20 or 30 °C and the mineral N and S produced were determined after leaching every 2 weeks with 0.01*N* KCl for a total of 26 weeks.

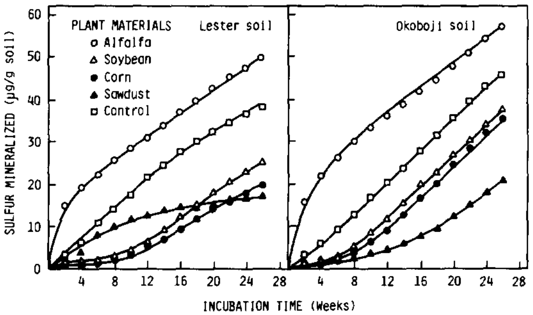

Figure 1. Effect of crop-residue treatment on sulfur mineralization in soils.

were incubated in columns as described by Tabatabai and Al-Khafaji (1980). The mineral S, present initially, was removed by leaching with 5 m*M* CaCl$_2$ and the columns were incubated at 30 °C. The soil columns were leached with the same solution every two weeks for a total of 26 weeks. The sulfate-S thus released was determined by ion chromatography (Dick and Tabatabai, 1979). The crop residues used contained 174, 719, 1285, and 460 ppm of organic S in corn, soybeans, alfalfa, and sawdust, respectively. The soil studied contained 168, 249, 377, 396, and 612 ppm of organic S in the Lester, Downs, Webster, Harps, and Okoboji soils, respectively.

Figure 1 shows the effect of the crop residues on S mineralization in Lester and Okoboji soils. Only alfalfa residue additions released more mineral

Table 7. Total amounts of S mineralized in crop residue treated soils.

Crop residue	Total amount of S mineralized in soil specified[a]				
	Lester	Downs	Webster	Harps	Okoboji
			μg S/g soil		
None	38	34	48	32	46
Corn	20	29	31	15	35
Soybean	25	26	40	17	37
Alfalfa	49	48	49	57	57
Sawdust	17	31	28	12	21

[a] Soil-glass beads columns were incubated at 30 °C and the mineral S produced was determined after leaching every 2 weeks with 5 m*M* $CaCl_2$ for a total of 26 weeks.

S than the control on incubation with the five soils. Addition of corn residue, soybeans, and sawdust to the five soils resulted in reduction in the amount of S mineralized. This is expected because of the high C:S ratios of such materials. The amount of sulfate-S produced after 26 weeks of incubation with and without crop residue treatment are shown in Table 7. The amounts of S mineralized in the soils ranged from 32 ppm with Harps soil to 48 ppm with Webster soil. The magnitude of the reduction of mineral S production from incorporation of crop residue varied with the type of crop residue and soil used.

With the increased use of N and P fertilizers containing little or no S, immobilization and S and yield reductions accompnaying decomposition of crop residues have become more prominent. In humid regions S immobolization due to crop residue application should aid the retention of fertilizer S in surface soils. According to Jones et al. (1971) heavy additions of straw to soils in California failed to reduce leaching losses of sulfate, but reduced leaching losses of nitrate.

In a field experiment where crop residues were added for 11 consecutive years to a silty clay loam in Iowa, cropped to corn and well fertilized with N, Larson et al. (1972) reported that soil organic S increased linearly in proportion to the amount of residues added. After 11 years, organic S had increased by 16% at 2 tons/ha/yr and by 49% at 16/tons/ha/yr with alfalfa, and by 9% and 40% at the corresponding application rate with cornstalks. The increases in the organic S content were similar to those for C but greater than the gains in organic N and P. These results indicate that S levels can be maintained or increased, even under intensive cropping, when adequate quantities of crop residues are regularly returned to the soil. Addition of crop residues to soils under the minimum or no-till system, however, may significantly reduce the plant-available S, and consequently may lead to increases in application of S fertilizers.

Significance of atmospheric sulfur

Rainfall and the atmosphere constitute a third important source of plant-nutrient S, and in any discussion about agricultural S balance, the contribution of S by the air and atmospheric deposition must be considered. Unfortunately, this subject is difficult to quantify. Data on the S content of rainfall indicate wide variations by geographical locations. Several reports on S in precipitation as it relates to agriculture have been published (Terman, 1978; Tabatabai et al., 1981; Tabatabai, 1983a, b). The annual rates of S deposition by precipitation in North America for 1980 ranged from 0.5 to slightly above 10 kg/ha (Cowling, 1983). Other reports show that individual sites may receive annual S deposition $\gg$ 10 kg/ha (Terman, 1978; Tabatabai, 1983a, b). As is true of N, the data available for S in precipitation in Iowa indicate that between 60 and 80% of the S is deposited during the crop growing season, the spring and summer (Tabatabai and Laflen, 1976). Therefore, the amounts of S added in precipitation in most rural areas of the United States are important for crop production. Laboratory and greenhouse experiments have shown that many soils of the United States do not contain sufficient plant-available S to meet crop requirements for this element, yet no S deficiency symptoms have been reported (Tabatabai and Bremner, 1972b). Since it is known that soils and plants absorb SO_2 directly from the atmosphere, it is believed that other S gases are also absorbed in this manner (Ulrich et al., 1967). Thomas and Hill (1935) showed that lucerne could take up a substantial portion of its S as SO_2 from the atmosphere without injury, and this finding has been subsequently confirmed for other crop plants such as cotton (Olsen, 1957) and rape (Bromfield, 1972). In certain areas, uptake of atmospheric SO_2 is able to compensate for soil S deficiency (Cowling et al., 1973). Indeed, SO_2 and H_2S can be used by sunflowers as their only source of S without affecting their normal growth (Faller, 1972). Studies in Wisconsin showed that under optimum yield 44% of the S in alfalfa is derived from atmospheric sources (Hoeft et al., 1972).

Water pollution by sulfate from nonpoint sources is usually not of concern; water pollution by nitrate and phosphate from leaching, runoff, and erosion, especially from managed land, can contribute to quality of lakes and streams, and therefore have received the most attention. Thus, numerous reports are available on the concentration of N, P, and S in waters and sediments. This makes comparison of these elements in waters derived from managed and unmanaged lands with those in precipitation possible. The usual ranges of values in concentrations and spatial rates are presented in Figures 2 and 3.

Losses of S by leaching vary widely, some drainage waters contain more S than the rain supplies even though little or none is added in fertilizer. The extra quantity may be deposited directly on plants and soils from the atmosphere or released from soil organic matter or minerals. Whitehead (1964) reported annual losses from unfertilized fallow soils in Illinois ranged from 1.5 to 65 kg S/ha. West German soils also lost an average of 33 kg S/ha. Freney et al. (1962) consider annual losses by leaching to average 15 kg S/ha in Europe and North America, 4.5 kg in South America, and $<$ 1 kg/ha in

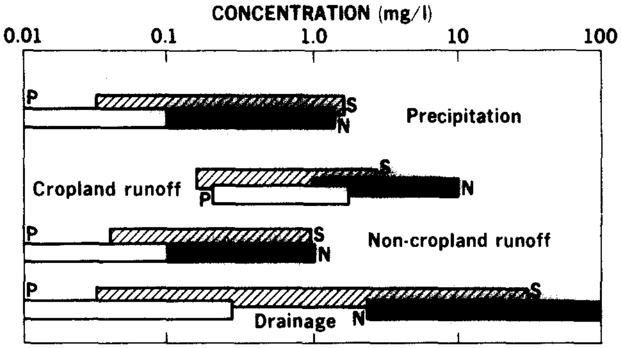

Figure 2. Range of inorganic nitrogen, sulfur and phosphorus concentrations in natural waters. Source: Tabatabai (1983b).

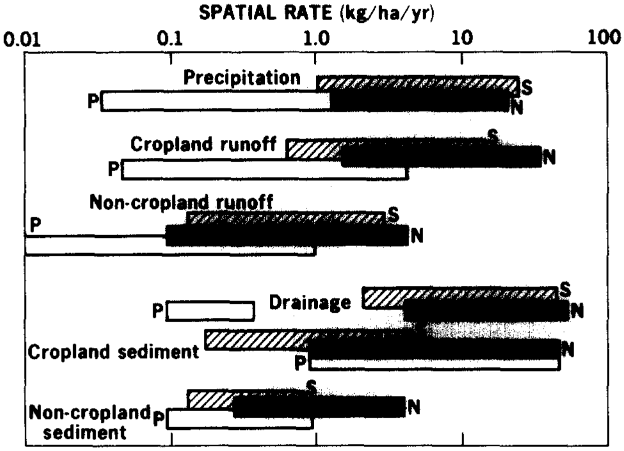

Figure 3. Range of spatial rates of inorganic nitrogen, sulfur and phosphorus (total for sediments) in natural waters and sediments. Source: Tabatabai (1983b).

some areas of Australia. It has been estimated that between 3 and 32 kg S/ha are lost by tile drainage in Iowa (Baker et al., 1975). In general, loss of S from soils by leaching varies from insignificant amounts to as much as 320 kg S/ha annually from soils treated with S fertilizers (Harward and Reisenauer, 1966).

Sulfur fertilizers

The sources of plant-nutrient S discussed in the other sections of this paper are generally beyond the control of the farmer. The last source of plant-nutrient S, which can be deliberately and easily controlled, is S added in fertilizers and soil amendments. Until about three decades ago, most fertilizers were formulated using large amounts of normal superphosphate and ammonium sulfate. Both of these materials contain appreciable amounts of S, 12 and 24%, respectively. With the introduction of high-analysis N and P fertilizer materials, the S included incidentally in fertilizers has been gradually decreasing. This trend, which began around 1950, is expected to continue until S is deliberately reintroduced into the fertilizer.

There are many fertilizer materials, both liquid and solid, which can be and are being used to supply S to growing crops. The one selected for any particular situation is determined by the crop to be grown, the S level of the soil, the cost of the material, and the ease with which its use can be fitted into a particular fertilizer program. As a general rule, all of the soluble sources (sulfates, thiosulfates, polysufides) are about equally effective and immediately available to growing plants. Elemental S must be converted by soil microorganisms to the sulfate form before being absorbed by plants. The rate of this conversion is generally quite rapid in warm, moist, well-aerated soil provided that the S is in a finely divided form or in granular forms which disintegrates quickly to finely divided particles.

Gypsum has been widely used for many years as an S- and Ca-bearing material for fertilization and soil reclamation. It is a constituent of normal superphosphate and therefore, S deficiencies seldom occur on land adequately fertilized with this material. In the manufacturing of concentrated superphosphate, however, the gypsum is largely removed and, thus, this material contains little or no S.

Another source of S is sulfuric acid. When added to soils, sulfuric acid is immediately available to neutralize alkalinity and to supply plant-nutrient S. Its use has largely been limited to metering into irrigation waters. However, more recent developments in equipment suggest that it may be directly applied to the soil by injection.

Table 8. Sulfur fertilizers consumed in regions of the U.S. in year ending June 39, 1982.

	Kind of sulfur fertilizer used (tons)			
Region	Gypsum	Elemental S	Sulfuric acid	Total[a]
New England	122	5	0	127
Middle Atlantic	589	757	6	758
South Atlantic	287 866	3 607	277	291 750 (20)
East North Central	6 357	839	0	7 196
West North Central	24 837	25 737	0	50 574 (3)
East South Central	2 624	30	128	2 682
West South Central	0	543	369	912
Mountain	54 428	11 900	637	66 965 (5)
Pacific	993 368	29 933	26 166	1 049 467 (71)
Alaska, Hawaii, Puerto Rico				
Total	1 370 191	72 757	27 583	1 470 531

[a]Figures in parentheses are S fertilizers used in the region expressed as percentage of the total amount used in the U.S.

The amounts of S fertilizers (gypsum, elemental S, and sulfuric acid) used in the United States in 1981 and 1982 were 1.9 x 10^6 and 1.5 x 10^6 tons, respectively. Of the total amounts used in 1982, 3, 5, 20, and 71% were used in the West North Central, Mountain, South Atlantic, and Pacific regions, respectively (Table 8). The amount of S fertilizer used in each region is an indication of the plant-available S status of the soils and cropping conditions. Another factor is the contribution of atmospheric S and S added by precipitation to the S requirements of the crops in the region.

Conclusions

Sulfur is required in large amounts by crops. Many crops contain as much S as P. Sulfur is ranked in importance with N and P in the formation of proteins. The increased use of more concentrated fertilizers which contain little or no S, combined with less S from rainfall in many areas, have decreased the supply of S to the crops. At the same time, higher crop yields have increased the uptake of S from soils. Soil which originally contained sufficient S often becomes deficient as agriculture is intensified, unless S-containing fertilizers are used.

Although the analytical methods available allow fractionation of soil organic S into three broad groups, little information is available about the specific S compounds present in each fraction. Among the various aspects of the S cycle, the factors affecting the mineralization and immobilization of S in agricultural soils deserves further investigation.

Despite the concern about atmospheric S deposition, significant amounts of S are added to agricultural soils as fertilizers. Of the total amount (1.5 x 10^6 tons) used in 1982, 3, 5, 20, and 71% were used in the West North Central, Mountain, South Atlantic, and Pacific regions, respectively. The current rates of S additions by wet deposition should be beneficial to crop production. The annual rates for 1980 in North America ranged from 0.5 to slightly above $10\,\mathrm{kg\,S\,ha^{-1}}$, which are much below those required by agronomic crops. Therefore, atmospheric sources are important components in meeting crops S requirements and should be considered in benefit-cost analyses relating to S emissions.

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