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Sulfur Fertilization of an Annual-Range Soil During Years of Below-Normal Rainfall[1]

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Sulfur is a major limiting factor in forage production on many range soils in California (Martin, 1958). Leaching loss of available sulfur in the form of sulfate from slightly acid, coarse textured soils has been recognized as a problem in fertility management. Gypsum (calcium sulfate) is a source of sulfur readily available to plants, but is highly susceptible to leaching loss (McKell and Williams, 1960). Elemental sulfur is more slowly available since it must be oxidized, usually microbially, to sulfate before becoming usable by plants. Elemental sulfur also is less susceptible to leaching.

A series of lysimeter studies was started at the San Joaquin Experimental range in the Sierra Nevada foothills 25 miles north of Fresno, California, in 1957. In the first year of study, various rates of gypsum labeled with sulfur-35 were applied, and the subsequent distribution of natural and applied sulfur was determined in the plants, soil, air, rain and percolate during a season of above-normal rainfall. Percolating water carried 77 percent of the applied sulfur out of the root zone by the end of the season (McKell and Williams, 1960), most of it being lost before rising temperatures permitted appreciable growth of the seeded clover (McKell and Wilson, 1963).

Lobb and Bennetts (1957) have recommended the use of elemental sulfur in preference to gypsum in sulfur-deficient soils of New Zealand in which excessive leaching occurs. Hence, an experiment was initiated to compare elemental sulfur and gypsum as sources of sulfur on an annual-range soil in an environment typical of much of California's foothill range country. Sulfur-35 was used to distinguish the applied sulfur from naturally occurring sulfur.

Methods

The lysimeters, soil, and general procedures used in this study were the same as those described in detail for the first experiment (McKell and Williams, 1960). In brief, the experiment was conducted on Vista sandy loam soil in lysimeters six feet in diameter and two feet deep. Major soil characteristics were pH 6.2, cation exchange capacity 4.16 me./100g., and organic matter 0.6 percent. At the conclusion of the first experiment the lysimeters were divided into three stratified groups based on their residual sulfur content, with each replication of the treatments assigned to a group of lysimeters and the treatments randomly assigned within the replicate. The treatments comprised control, finely ground elemental sulfur applied at the rate of 60 pounds per acre and gypsum at 300 pounds per acre to obtain equivalent sulfur[2]. The treatments were applied, and the lysimeters seeded to rose clover (*Trifolium hirtum* All.), in October 1958. Yield, percolate, and precipitation were sampled over a three-year period.

Results

Clover Response

During the series of relatively dry years in which this study was conducted, clover production was influenced greatly by the amount and distribution of rainfall. No yield response to sulfur or gypsum application was detectable in 1959 or 1961 when rainfall was very limited (10.42 and 12.36 inches in the respective seasons, Figure 1). Dry-matter production was 1,000 pounds per acre or less regardless of treat-

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Table 1. Yield and sulfur content of rose clover following application of elemental sulfur and gypsum in autumn 1958.

Treatment	1959	1960	1961
	(Pounds per Acre)		
Control	340	3,120*	620
Elemental S	410	4,490	990
Gypsum	580	4,240	1,040
	(Total sulfur percent)		
Control	0.09	0.05*	0.06*
Elemental S	.10	.10	.11
Gypsum	.26*	.10	.11
	(Sulfur from fertilizer percent)		
Control	0	0	0
Elemental S	40	51	26
Gypsum	55*	56	26

*Value significantly different (five percent level) from other treatment means in the same year (zero values were excluded from the analysis of variance).

ment (Table 1). In 1960, the second year after application of the fertilizer, both the elemental sulfur and gypsum increased yield by approximately 1,000 pounds per acre over the control yield of 3,100 pounds per acre. Substantial rain the previous September, along with adequate rain in March and April 1960 (seasonal total 15.54 inches, Figure 1), made moisture conditions more favorable than in 1959 and 1961, thus permitting the expression of a sulfur response.

During each year of the experiment, the sulfur percentage in the rose clover at harvest time (bloom stage) was influenced by treatment. In 1959 the clover grown on the gypsum-treated lysimeters contained almost three times as much sulfur as either the control or elemental sulfur treatments (Table 1). In the respective treatments the proportion of total sulfur derived from gypsum was significantly greater than the sulfur obtained from the elemental sulfur applied. In 1960 and 1961 the sulfur percentage in the clover produced on lysimeters treated either with gypsum or elemental sulfur was nearly double the sulfur percentage in the controls. The proportion of sulfur in the plants from the two sources was not significantly different, but declined from a range of 48 to 56 percent in 1960 to 24 to 26 percent in 1961.

Loss of Sulfur by Percolation

Percolation of rain water through the soil columns amounted to 2.5, 2.4, and 1.7 inches in the first, second, and third seasons, respectively. The only major loss of sulfur during this period occurred in the first year when 16.0 pounds per acre appeared in the percolate of the gypsum treatment (Figure 2). Of this loss 65 percent came from the gypsum, but this amounted to only 17 percent of the total of 61.1 pounds of sulfur per acre applied in the gypsum. The loss from the elemental sulfur treatment due to leaching in the first year amounted to only 3.9 pounds of sulfur per acre, of which less than one pound was from the applied total of 59.7 pounds per acre. The loss of sulfur from the controls amounted to 3.5 pounds per acre for the same interval of time.

Sulfur Balance Sheet

A sulfur balance sheet was constructed for each treatment using the data collected for additions to and losses from the soil columns (Table 2). Additions considered were from the fertilizer treatments and from rain. Previously it has been shown that additions of sulfur from air contact and seed are negligible (McKell and Williams, 1960). Losses were from clover removed and deep percolation.

Total sulfur addition from rainfall over the three-year period was 8.7 pounds per acre. Sulfur removal in the clover forage amounted to: control 2.3, elemental sulfur treatment 5.1, and gypsum treatment 6.0 pounds per acre. Sulfur lost in percolating water amounted to: control 4.7, elemental sulfur treatment 9.5, and gypsum treatment 22.0 pounds per acre. It was calculated by difference that sulfur was retained by the soil in the amount of: control 1.8, elemental sulfur treatment 53.3, and gypsum 40.9 pounds per acre.

The absorbed sulfate in samples from the soil columns was extracted with sodium acetate at pH 4.8 at the beginning and end of the experiment. The sulfate-sulfur content of the soil declined in all treatments in the following amounts: control 28,

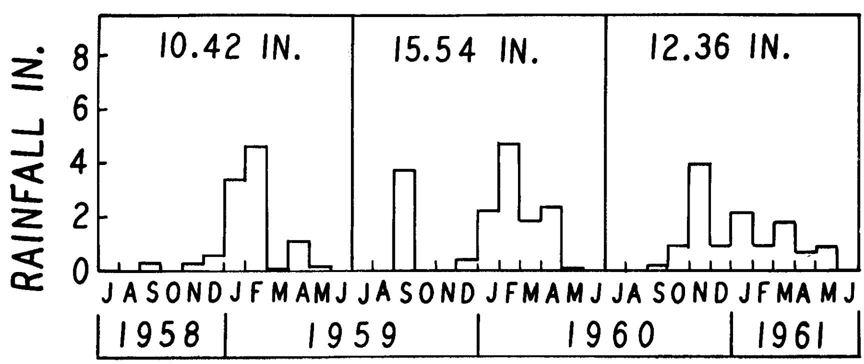

FIGURE 1. Monthly and seasonal-total rainfall at study site (mean seasonal 19.9 inches).

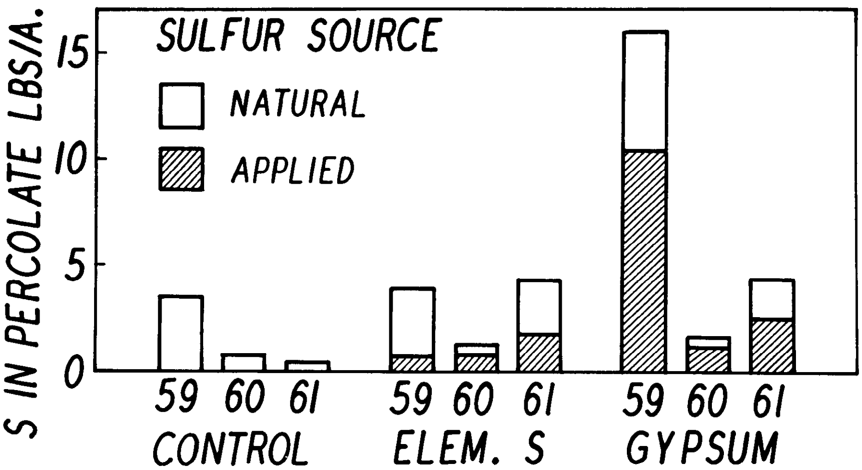

FIGURE 2. Amount and source of sulfur in percolating water from soil columns treated with elemental sulfur and gypsum.

elemental sulfur 17, and gypsum 18 pounds per acre (Table 3). The sum of the respective values and the calculated sulfur-retention value for the treatment is the amount of sulfur "apparently immobilized" in the soil. These amounts are control 30, elemental sulfur 71, and gypsum 58 pounds per acre.

Discussion

During the first growing season (1958-59), a drier one than normal, some sulfur from the elemental sulfur application was taken up by the clover plants. However, the amount was not sufficient to increase their total sulfur content relative to the controls. Neither did appreciable amounts of sulfate ion percolate through the soil columns. The environment (mainly low soil moisture) was not conducive to microbiological oxidation of elemental sulfur to sulfate, the form most readily taken up by plants (Starkey, 1950). However, clover took up a sizeable amount of sulfate from the gypsum, as indicated both by higher total sulfur content and by the substantial fraction of labeled sulfur present. Also an appreciable amount of labeled sulfur appeared in the percolate. Although the initial response to elemental sulfur was markedly slower than to gypsum, the moisture limitation was so extreme that no yield response was obtained from either treatment in 1959.

At another location with more favorable precipitation Walker and Williams (1963) observed that elemental sulfur caused increases in forage yield equal to that produced by gypsum on annual-type range during the season the application was made. Presumably moisture conditions favorable to microbiological oxidation of elemental sulfur are concomitant with moisture conditions favorable to vigorous annual-range plant growth and vice versa.

In the second season (1959-60) the rainfall total, although again subnormal, was more favorable, especially as regards distribution. Clover production improved greatly. Significant and approximately equal yield responses were obtained from the elemental sulfur and gypsum treatments. Thus the sulfur not lost nor removed in plant tissue in the first season was effective in the second season. Uptake of sulfur, both labeled and natural, was about the same where either source of sulfur was used, but much enhanced relative to the control. Walker (1958) also observed a carry-over effect of gypsum after a dry year, although with substantially smaller applications (rates equivalent to five and 15 pounds of sulfur per acre).

Unfortunately in the third growing season (1960-61) rainfall shortage again imposed a

Table 2. Sulfur balance sheet for Vista sandy loam treated with elemental sulfur and gypsum.

Source	Sulfur disposition Control	Elemental Sulfur	Gypsum
	— — — (Pounds per acre)	— — —	
Sulfur added from:			
Fertilizer 1958	0	59.7	61.1
Rain 1958-59	3.2	3.2	3.2
1959-60	4.1	4.1	4.1
1960-61	1.4	1.4	1.4
Total sulfur added	8.7	68.4	69.8
Sulfur removed in:			
Clover 1959	0.3	0.4	1.5
1960	1.6	4.2	4.3
1961	0.3	1.0	1.1
Clover total	2.2	5.6	6.9
Percolate 1959	3.5	3.9	16.0
1960	.8	1.3	1.6
1961	.4	4.3	4.4
Percolate total	4.7	9.5	22.0
Total sulfur removed	6.9	15.1	28.9
Calculated sulfur retention by soil: (sulfur added-sulfur removed)	1.8	53.3	40.9

Table 3. Extractable sulfur content of Vista sandy loam treated with elemental sulfur and gypsum, and apparent immobilization of sulfur.

Treatment	Extractable sulfur 1958	Extractable sulfur 1961	Extractable sulfur Decrease	Calculated retention (from balance sheet)	Apparent immobilization (decrease + retention)
	(Pounds per acre)				
Control	47	19	28	1.8	30
Elemental S	41	23	18	53.3	71
Gypsum	41	24	17	40.9	58

very low ceiling on clover production, but sulfur uptake continued at an enhanced level from both sulfur sources, indicating that the applied materials were at least somewhat available to the plants at that time.

The approximate equivalence of uptake of sulfur from the two sources in the second and third seasons after application is at variance with the observations of Jordan and Baker (1959) in a field experiment with alfalfa. Their results showed an increased uptake of sulfur from gypsum relative to elemental sulfur persisting over a three-year period after application. The mean uptake of fertilizer-sulfur as a percent of total plant uptake was 15 percent from gypsum and 4 percent from elemental sulfur. The peak uptake from both materials occurred in the second year of their experiment.

The inference that can be made concerning the fate of the applied sulfur remaining in the soil at the conclusion of the present experiment is worthy of note. The sulfur balance sheet calculations show that a very high proportion of the applied elemental sulfur and a somewhat lesser, yet substantial, amount of gypsum-sulfur was retained by the soil at the end of the three-year period. Extraction by sodium acetate at pH 4.8 (Ensminger, 1954 and 1958; Kamprath et al., 1956 and 1957; and Bardsley and Jordan, 1957) demonstrated that the adsorbed sulfur content of the soil columns was low, even lower than at the beginning of the experiment. It is hypothesized, therefore, that either immobilization through biological activities, reduction to metallic sulfides, or reduction to hydrogen sulfide occurred. The two reduction processes seem to be unlikely possibilities in view of the limited rainfall of the period, the well-drained character of the soil profile, and the consequent low probability of the existence of reducing conditions during the experiment.

Immobilization appears to be a more likely possibility. Walker (1957) has pointed out that sulfur may be immobilized through the activities of microorganisms in a manner similar to the immobilization of nitrogen and phosphorus. Some sulfur might have been immobilized during decomposition of root tissue remaining in the soil from the 1957 experiment and from the sizeable clover crop produced in the second season of the experiment reported here. The supposition that substantial immobilization occurred in the second season is supported by leaching evidence of the gypsum treatment. Very little of the applied sulfate appeared in the percolate in the second season, although about as much percolation occurred in the season as in the first, and about 80 percent of the applied gypsum remained in the soil at the beginning of the season.

Since (1) only small amounts of sulfur were removed in the clover, (2) relatively small amounts occurred in the percolate, and (3) adsorbed sulfate sulfur in the soil declined in the course of the experiment, it was deduced that substantial immobilization occurred in all treatments. The apparent immobilization was greatest for the elemental sulfur treatment, intermediate for the gypsum treatment, and least for the control. It is evident that sulfur immobilization is a factor requiring further study, especially as it is influenced by rate and frequency of application of various sulfur sources under various climatic and soil conditions.

Application of Results

Under excessively deficient moisture conditions response of clover to sulfur fertilization on a sulfur deficient soil may be nil. Even so, some sulfate from gypsum may be lost through deep percolation, as demonstrated by the results in 1959 in this experiment. However, in contrast to the great loss of gypsum in a high rainfall season shown previously (McKell and Williams, 1960,) loss in percolating water in a series of dry years was low. Percolation loss from elemental sulfur was inconsequential.

Sulfur carried over to the second year either as the elemental form or as sulfate may be utilized in the event of more favorable moisture conditions for the enhancement of forage production as was illustrated by the 1960 results.

No significant difference in yield response to the two forms of sulfur was detected in this experiment.

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