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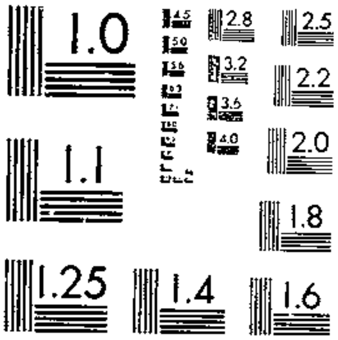

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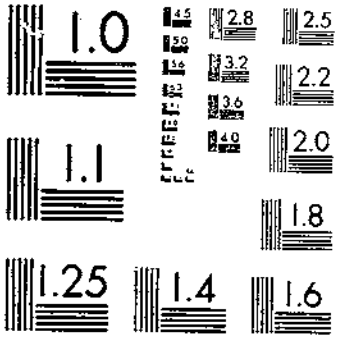

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SULFUR CONTENT of Rainwater and Atmosphere in Southern States

as related to crop needs

Technical Bulletin No. 1196

UNITED STATES DEPARTMENT OF AGRICULTURE
in cooperation with
State Agricultural Experiment Stations

CONTENTS

This study was made possible by the cooperation of personnel of the United States Department of Agriculture and the Agricultural Experiment Stations of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia who supervised collection of rainwater and precipitation records (see fig. 1).

Special acknowledgment is made to Marvin Gieger, chemist, Mississippi Agricultural Experiment Station, in whose laboratory many of the chemical determinations were made. Samples of rainwater from Alabama and Virginia were analyzed in laboratories at Auburn and Blacksburg, respectively.

Special acknowledgment is also made to J. M. Brown and J. B. Martin, Jr., assistant agronomists, Alabama Agricultural Experiment Station, who were responsible for the collection of rainwater samples in the vicinity of an electric steam plant near Tuscumbia, Ala.

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SULFUR CONTENT of Rainwater and Atmosphere in Southern States

as related to crop needs

By Howard V. Jordan and Charles E. Bardsley, Jr., soil scientists, Soil and Water Conservation Research Division, Agricultural Research Service; L. E. Ensminger, soil chemist, Alabama Agricultural Experiment Station; and J. A. Lutz, Jr., agronomist, Virginia Agricultural Experiment Station

The Southeastern United States is a region of potential sulfur deficiency. Soils are highly weathered, and there is only minor industrial activity to contribute sulfur to the atmosphere and precipitation. Crop production has been sustained in the past, to a considerable extent, by sulfur applied incidentally in fertilizers. With the present trend toward use of fertilizers low in sulfur, this contribution can be expected to diminish, resulting in increase of sulfur deficiency in the soils of the region.

The Southern Regional Sulfur Project was begun in 1953 to study this problem. It was established as a cooperative research effort among the Soil and Water Conservation Research Division, Agricultural Research Service; the Agricultural Experiment Stations of 12 Southern States; and the Soils and Fertilizer Research Branch, Agricultural Relations Division, Tennessee Valley Authority. The project was designed to study sulfur supply as well as sulfur requirements of crops in the 12 States that participated in the study.

Accretions of sulfur in rainwater, which constitute one source of sulfur supply, were measured over a 3-year period. The data obtained were supplemented by measurements of sulfur in the atmosphere. Many of these data have been summarized in separate reports. Bulletins issued by the Alabama (*13*) [1] and the Virginia (*28*) Agricultural Experiment Stations present results from those two States. Results from other States have been summarized in research reports.[2] The

[1] Italic numbers in parentheses refer to Literature Cited, p. 14.

[2] JORDAN, H. V., and BARDSLEY, C. E., JR., compilers. [1953, 1954, AND 1955] PROGRESS REPORT[S] FOR THE SOUTHERN REGIONAL SULFUR PROJECT. Soil and Water Conserv. Res. Br., Agr. Res. Serv., Res. Rpts. 279, 286, and 297. 1954–56. [Processed.]

purpose of this bulletin is to bring together all the data and to determine the regional pattern.

There are several potential sources of sulfur in atmosphere and precipitation. The principal source, especially in the winter months, is believed to be the discharge of combustion gases from burning coal and wood. Near seacoasts, sulfur is probably carried inland as spray. Upon anaerobic decomposition, as in swamps, organic matter gives off hydrogen sulfide. This atmospheric sulfur is periodically carried to the earth in rainwater. Indirect evidence of sources of sulfur in atmosphere and precipitation was obtained in this study.

Measurements and possible significance of atmospheric sulfur are discussed in this publication. Major emphasis in the study was placed on measuring sulfur accretions in rainwater, as these represent tangible additions to the soil-plant system and can readily be measured. Contributions of atmospheric sulfur to plants, other than that carried to the earth in rainwater, are more difficult to evaluate.

SULFUR ACCRETIONS IN RAINWATER

The essential role of sulfur in the nutrition of plants was established a century and a half ago, and the contributions of sulfur in rainwater were studied as early as 1884 (*18*). Since that time numerous studies have been made in the United States and other countries.

In the United States, studies of sulfur in rainwater have been made in Alabama (*37*), Georgia (*37*), Illinois (*11, 35*), Indiana (*4, 11*), Iowa (*38*), Kentucky (*23*), Minnesota (*1*), Mississippi (*37*), New York (*9, 26, 39*), Oklahoma (*20, 22*), Oregon (*34*), Tennessee (*29, 37*), Texas (*16*), Virginia (*12*), Washington (*14, 33*), and Wisconsin (*21*). Studies in other countries have been reported from France (*5, 6*), Germany (*27*), Great Britain (*10*), Russia (*25*), New Zealand (*18*), and Japan (*30*). As most of the results of these studies are summarized by Eriksson (*15*), they are not reviewed here.

In certain earlier studies, the recording of excessively high values may have been attributable to the fact that rainwater was collected in containers made of corrodible metal. In 1937 Alway and coworkers (*1*) noted that such metals react with atmospheric sulfur. This reacted sulfur is washed into the collecting vessel and determined as sulfate in rainwater. Alway found errors ranging up to sixfold from rainwater collectors of this type.

Seasonal trends in precipitation of sulfur were noted in several investigations. Leland (*26*) found that sulfur in rainwater at Ithaca, N. Y., averaged 37.63 pounds per acre for the 6 months from November to April and 11.23 pounds for the 6 months from May to October. Johnson (*23*) measured sulfur in rainwater by quarters at 7 locations in Kentucky with the following results: From January through March, 13.33 pounds per acre; from April through June, 7.09 pounds; from July through September, 6.36 pounds; and from October through December, 9.34 pounds. The high values in the winter months were attributed in both studies to higher consumption of coal for home heating. Other investigators have noted similar trends.

A change in concentration of sulfur in response to changing conditions has also been observed. Wilson (*39*) found that sulfur in rainwater at Ithaca, N. Y., ranged from 25 to 36 pounds per acre per year in the period from May 1918 to May 1923. A new coal-burning heating plant was placed in operation near the rain collector in the fall of 1923. Subsequently, sulfur accretions ranged from 46 to 65 pounds per acre per year.

These investigations, as well as others, reflect the dominant influence of combustion gases as a source of sulfur in rainwater in the continental United States.

Near seacoasts, other factors may be important. Investigators in Australia (*2*), New Zealand (*18*), the West Coast of Africa (*7*), and Japan (*30*) emphasize the importance of spray from the sea as a source of sulfur in precipitation. In fact, Eriksson (*15, p. 285*) states that "it can be concluded that a great part of sulfur in precipitation is of oceanic origin either brought into the air by spray or as H_2S [hydrogen sulfide] formed by reduction of sulfate in the sea."

Experimental Procedures

Rainwater for this study was collected at 109 locations (fig. 1). The collection stations were all in rural areas, mostly at main or branch State Agricultural Experiment Stations.

Gages of noncorrodible metal were used to measure the rainwater. In Virginia these gages were made of aluminum; at all other locations, they were made of stainless steel. The water was collected and stored in glass containers. It was composited by quarters—December through February, March through May, June through August, and September through November. Water from all the locations except those in Alabama and Virginia was shipped to the Mississippi Agricultural Experiment Station, where it was analyzed for sulfur. Water from Alabama and Virginia was shipped, respectively, to the Agri-

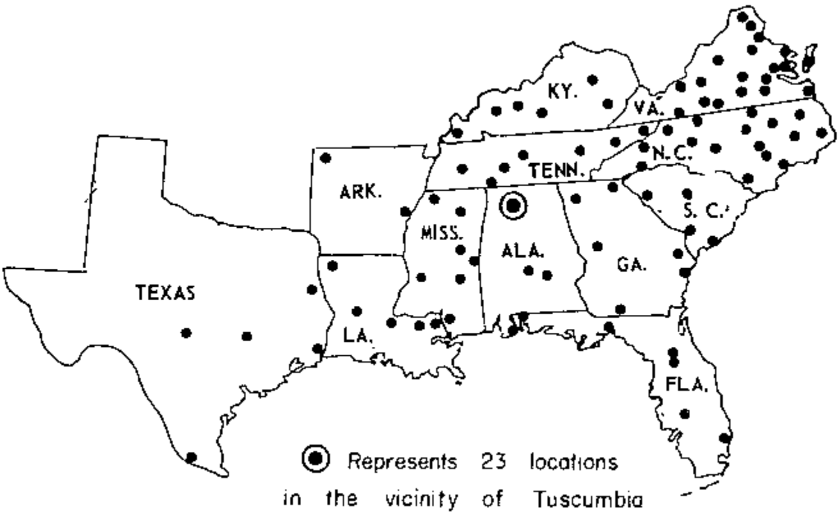

FIGURE 1.—Location of rainwater-collection points in the Southern States.

cultural Experiment Stations of those two States, where it was analyzed.

At the laboratories of the Mississippi and Alabama Experiment Stations, water was analyzed by a modification of the turbidimetric method of Chesnin and Yien (*8*). A quantity of 100 milliliters (ml.) of water was evaporated to 25 ml. in a porcelain dish containing 0.5 gram of potassium chloride. After cooling, 10 ml. of saturated bromine water was added, and the contents were evaporated to dryness in a sulfur-free hood. The dish and residue were dehydrated for 1 hour in an electric oven; the residue was then taken up with Morgan's solution (*31*), after which it was filtered and washed. To a measured portion of this solution, 2 ml. of acacia solution was added, and the whole was made to volume of 25 ml. Sulfate was precipitated by addition of 1 gram of barium chloride crystals; the whole was stirred for 1 minute, and allowed to stand for 20 minutes; and the turbidity was read on a colorimeter.

In Virginia, sulfur was determined by the method of the Association of Official Agricultural Chemists (*3*). Sulfur was precipitated as barium sulfate ($BaSO_4$) and determined gravimetrically.

Control samples were analyzed in the laboratories of the Agricultural Experiment Stations of Mississippi, Alabama, and Virginia, and data were found to be comparable.

As collections were not initiated at all locations in the first quarter of 1953, data are not complete for that year. However, complete data were recorded for virtually all locations in 1954 and 1955.

Results of Experiments

Sulfur Accretions Recorded

Data collected in this study as a whole are reported in table 1.

In Kentucky, Tennessee, and Virginia, sulfur accretions in rainwater were found to be higher than in the nine other Southern States covered by this study (table 2). The reason for this may have been a greater consumption of coal for industrial and heating purposes in those three States.

Within the nine other Southern States covered by this study, a few locations recorded abnormally high sulfur accretions. At Cantonment, Fla., sulfur added in rainwater amounted to 47.0, 29.5, and 13.2 pounds per acre in 1953, 1954, and 1955, respectively. The gage at Cantonment was located about 1 mile from a paper mill; this may have accounted for the high values. At Bogalusa, La.—some 3 miles from a paper mill—sulfur in rainwater amounted to 12.4 pounds per acre in 1955.

Sulfur accretions at Statesville, N. C., were 12.7, 11.3, and 17.3 pounds per acre, respectively, for the 3 years of the study. Similar high values were obtained at Apex, N. C., in 1953; also, at Blackville, S. C., and Beaumont, Tex., in 1955. Industrial activity at or near these locations probably accounts for the high values.

Disregarding the locations mentioned in the preceding paragraph, the average annual accretions of sulfur in rainwater in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas were 5.8, 4.1, and 6.3 pounds per acre in 1953, 1954, and 1955, respectively. The general average of 5.4 pounds per

TABLE 1.—*Sulfur collected in rainwater during 3-year period* [1] *December 1952 to November 1955, inclusive*

Collection location	Amounts of elemental sulfur collected during the period—			Average annual accretion
	December 1952 through November 1953	December 1953 through November 1954	December 1954 through November 1955	
	Pounds per acre	*Pounds per acre*	*Pounds per acre*	*Pounds per acre*
Alabama:				
Prattville	----------	[2] 3.0	[2] 3.6	3.3
Tuscumbia	----------	[3] 4.8	[4] 10.6	7.8
Arkansas:				
Fayetteville	----------	3.4	4.7	4.1
Marianna	----------	2.3	2.4	2.4
Florida:				
Cantonment	47.0	29.5	13.2	29.9
Gainesville	7.1	8.6	8.1	7.9
Homestead	----------	2.4	3.2	2.8
Jay	2.9	2.9	3.7	3.2
Ona	----------	2.0	3.9	2.5
Quincy	----------	1.6	2.1	1.9
Waldo tract [5]	5.8	3.0	3.0	3.9
Georgia:				
Blairsville	----------	----------	10.3	----------
Calhoun	----------	5.7	7.8	6.8
Experiment	----------	6.9	6.1	6.5
Fleming	----------	4.0	12.4	8.2
Tifton	----------	2.5	4.9	3.7
Watkinsville	----------	5.6	5.8	5.7
Kentucky:				
Campbellsville	----------	3.6	12.1	7.9
Greenville	----------	11.3	14.6	13.0
Lexington	----------	8.0	15.8	11.9
Mayfield	----------	8.3	19.9	14.1
Princeton	----------	10.2	14.4	12.3
Quicksand	----------	11.3	----------	----------
Louisiana:				
Baton Rouge	----------	2.0	4.8	3.4
Bogalusa	----------	----------	12.4	----------
De Ridder	----------	1.9	7.0	4.5
Franklinton	----------	----------	8.5	----------
Homer	----------	5.6	11.1	8.4
Mississippi:				
Brooksville	6.8	1.7	6.1	4.9
Holly Springs	7.3	3.0	8.0	6.1
Newton	9.0	3.5	1.4	4.6
Oakley	6.5	2.3	.7	3.2
Pontotoc	6.9	5.9	8.6	7.1
Poplarville	3.4	1.4	3.1	2.6
State College	----------	1.3	4.8	3.1
North Carolina:				
Apex	9.0	2.1	8.9	6.7
Faison	4.0	2.2	5.3	3.8
Greenville	----------	3.0	4.9	4.0
Hendersonville	----------	4.2	13.0	8.6
Jackson Springs	3.5	9.3	7.7	6.8

[1] Data are omitted where records for year are incomplete.
[2] Average of 2 locations.
[3] Average of 19 locations.
[4] Average of 20 locations.
[5] 11 miles north of Gainesville, Fla.

TABLE 1.—*Sulfur collected in rainwater during 3-year period [1] December 1952 to November 1955, inclusive*—Continued

Collection location	Amounts of elemental sulfur collected during the period—			Average annual accretion
	December 1952 through November 1953	December 1953 through November 1954	December 1954 through November 1955	
	Pounds per acre	*Pounds per acre*	*Pounds per acre*	*Pounds per acre*
North Carolina—Continued				
Laurel Springs		1.9	9.6	5.8
Lewiston	4.1	1.8	5.2	3.7
Oxford	5.4	1.3	6.0	4.2
Plymouth	5.4	7.7	8.7	7.3
Rocky Mount		3.1	5.5	4.3
Rural Hall	5.4	2.8	6.3	4.8
Statesville	12.7	11.3	17.3	13.8
Waynesville	5.6	2.9	7.9	5.5
Whiteville	3.3	2.5	7.9	4.6
Willard	3.6	5.4	4.7	4.6
Wilmington	3.2	5.2	8.5	5.6
South Carolina:				
Blackville		4.1	15.8	10.0
Clemson	7.4		8.5	8.0
Columbia	2.8	2.9	5.7	3.8
Summerville	4.0	3.9	7.3	5.1
Tennessee:				
Columbia			9.4	
Crossville			14.3	
Greenville			11.8	
Harriman			19.1	
Jackson			11.3	
Lawrenceburg		3.0	12.1	7.6
Springfield			12.0	
Texas:				
Beaumont		8.9	12.6	10.8
College Station		6.7	6.7	6.7
Temple		2.8	6.3	4.6
Tyler		4.2	4.5	4.4
Weslaco		3.7	5.3	4.5
Virginia:				
Ashland		9.7	16.9	13.3
Blacksburg		18.1	18.4	18.3
Buckingham		11.0	11.9	11.5
Chantilly			27.7	
Chatham		10.6	15.5	13.1
Charlotte Courthouse		9.2	13.5	11.4
Fredericksburg		13.5	25.2	19.4
Halifax		10.7	12.2	11.5
Hillsville		7.5	12.9	10.2
Kenbridge		15.3	16.8	16.1
Mattoax		20.3		
Middleburg		15.3	22.6	19.0
Norfolk		29.8	33.0	31.4
Onley			30.8	
Orange		13.2	22.6	17.9
Saint Stephens Church			14.9	
Salem			25.8	
Staunton		24.0	14.8	19.4
Warsaw		9.8	19.0	14.4

TABLE 2.—*Sulfur accretions in rainwater collected in Kentucky, Tennessee, and Virginia, and averages for the nine other Southern States* [1] *covered by this study, 1953–55*

	Sulfur in rainwater in—		
	1953	1954	1955
	Pounds per acre	*Pounds per acre*	*Pounds per acre*
Kentucky	[2] 8. 5	8. 8	15. 4
Tennessee			12. 9
Virginia	[3] 12. 2	14. 5	19. 7
Nine other Southern States,[1] average	5. 8	4. 1	6. 3

[1] Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas.
[2] Record for 9 months, calculated on a 12-month basis.
[3] Record for 16 months, calculated on a 12-month basis.

acre should be a good estimate of the annual accretion of sulfur in rainwater for rural locations in this region. By comparison, sulfur in rainwater near Gary, Ind., which is a highly industrialized locality, was measured (*4*) as 127 pounds per acre annually. Measurements made near Ithaca, N. Y. (*26*) and Lafayette, Ind. (*4*), which are moderately industrialized, were 49 and 22 pounds per acre, respectively.

Effects of Steam-Plant Effluents

A cooperative project between the Alabama Agricultural Experiment Station and the Tennessee Valley Authority was initiated in 1951 to study the effects of steam-plant effluents on soils and vegetation. Rainwater samples were also collected during the time the units were being put into use and for a period of 1 year after all 4 units were in full operation.

The effects of the steam plant on sulfur in rainwater are presented in table 3. For the period December 1953 through November 1954, which preceded operation of the steam plant near Tuscumbia, Ala., an average of 4.8 pounds of sulfur was brought down in rainwater. During the next year, when the steam plant was being put into operation, the average amount of sulfur increased to 10.6 pounds. During the last period—the first year in which all units were in operation—the sulfur in rainfall averaged 9.8 pounds. Although the steam-plant effluents about doubled the sulfur brought down in rain, the amounts measured were relatively low compared with those reported for certain industrial areas.

Based on the average sulfur content of coal burned in 1956, it was estimated that 89,000 tons of sulfur was given off by the steam plant. Evidently, the stacks were high enough to cause the effluents to be distributed over a wide area. Locations of the collection points are shown in figure 2. It is apparent from the data that there is no relationship between the amount of sulfur brought down in rainwater and the distance or direction of collection points from the steam plant. (See table 3.)

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TABLE 3.—*Effect of steam-plant effluents on sulfur content of rainwater collected in the vicinity of Tuscumbia, Ala., December 1953 to November 1956, inclusive*

Tracts where rainwater was collected [1]	Sulfur in rainwater [2] from—		
	December 1, 1953 through November 30, 1954	December 1, 1954 through November 30, 1955	December 1, 1955 through November 30, 1956
	Pounds per acre	*Pounds per acre*	*Pounds per acre*
1. Dotson	5.9	10.1	10.1
2. McBride	4.1	14.5	7.7
3. McGavack	5.7	11.7	12.0
4. Foster	----------	5.7	9.9
5. Hester	3.4	10.5	9.1
6. Rutland	----------	13.7	11.6
7. Gilbert	4.3	11.6	9.9
8. Moody	4.4	10.2	8.4
9. Watkins Cemetery	4.8	----------	11.4
10. Bockwell	6.0	8.2	10.0
11. Ethridge	4.6	----------	7.5
12. Nelson	5.6	12.8	9.2
13. Harris	4.6	8.6	6.7
14. Campbell	6.1	11.4	9.1
15. Haraway	----------	12.2	8.2
16. Thompson	5.4	10.9	5.8
17. Ingram	4.4	9.3	7.3
18. Haddock	4.6	9.0	9.6
19. Whitten	5.3	9.2	8.0
20. Darby	2.8	----------	12.1
21. Do	4.3	11.9	14.8
22. Howard	----------	10.3	14.3
23. Young	5.4	9.7	12.5
Average	4.8	10.6	9.8

[1] Locations with respect to the steam plant are shown (fig. 2).

[2] The first unit of the steam plant was put into operation in January 1955, the second in February of that year, the third in July, and the fourth and final unit in October.

Effects of Seasons

Only minor seasonal changes in the amount of sulfur in rainwater were recorded in the States covered by this study. Average data by quarters for nine Southern States are given in table 4. The highest values were recorded in the December-through-February and the March-through-May quarters, but actual differences for all quarters were small. Lack of more pronounced seasonal effects in those nine States was probably occasioned by the relatively small amount of home heating.

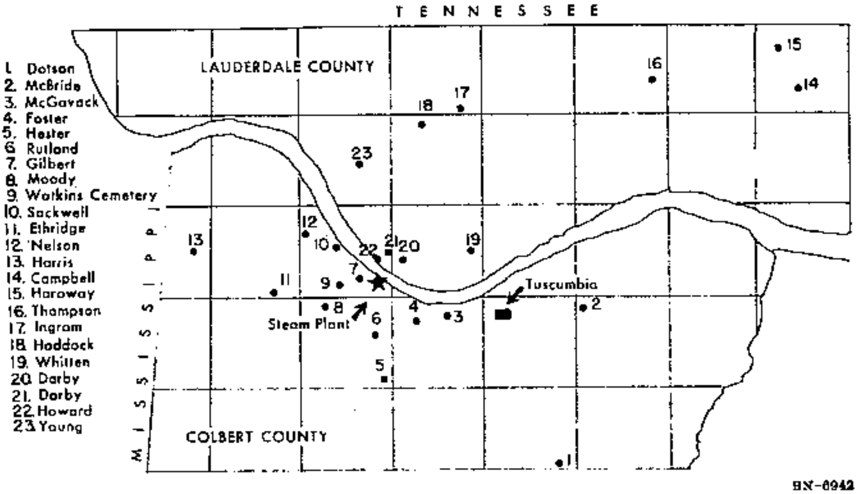

FIGURE 2.—Location, with respect to electric steam plant, of points in the vicinity of Tuscumbia, Ala., where rainwater was collected for determination of sulfur content. The map shows two Alabama counties. (See also table 3.)

TABLE 4.—*Sulfur accretions in rainwater averaged by quarters for nine of the Southern States* [1] *covered by this study, 1953–55*

Year	Sulfur in rainwater for the quarter—			
	December through February	March through May	June through August	September through November
	Pounds per acre	*Pounds per acre*	*Pounds per acre*	*Pounds per acre*
1953	1.8	1.8	1.0	0.6
1954	1.2	.9	.9	1.1
1955	1.4	2.6	1.3	1.0
Average	1.5	1.8	1.1	.9

[1] Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas.

The data indicate that sulfur accretions in rainfall are correlated to some extent with frequency of rains. The following hypothesis is suggested: A moderate rainfall, perhaps 0.5 inch, removes practically all sulfur from the atmosphere. If the rain continues to a total of 2 inches, the latter 1.5 inches serves only to dilute the concentration of sulfur. Thus, 4 intermittent rains of 0.5 inch each may bring down more sulfur than a single rain of 2 inches.

This is illustrated by data from Homestead, Fla. (table 5). Rainfall in the last 2 quarters was predominantly in rains of 1 to 3 inches each.

Table 5.—*Relationship between frequency and volume of rains and accretions of sulfur in rainwater, Homestead, Fla., by quarters, December 1954 through November 1955*

	Total rainfall	Total rainfall from rains in excess of 0.5 inch each	Sulfur in rainfall	Sulfur accretion from total rainfall
	Inches	*Inches*	*P. p. m.*	*Pounds per acre*
December 1954 through February 1955	2. 42	0	1. 41	0. 77
March 1955 through May 1955	6. 72	3. 68	1. 32	2. 01
June 1955 through August 1955	25. 66	19. 40	. 04	. 23
September 1955 through November 1955	16. 66	13. 65	. 06	. 23

Effects of Sea Spray

No clear evidence was found during these investigations to indicate that sea spray contributed to sulfur in precipitation, although opportunity to measure this influence was limited. Homestead, Fla., and Wilmington, N. C., are near the coast where sea spray might be a factor. At neither of these locations were sulfur-accretion values found to be appreciably different from those at similar locations farther from the coast.

SULFUR IN THE ATMOSPHERE

Sulfur contributed to the soil-plant system by rainwater, as discussed in the preceding section, is dissolved initially from the atmosphere. Surface soils and plants also take up atmospheric sulfur. Thus, the concentration of sulfur in the atmosphere has a direct relationship to the sulfur nutrition of plants. It is difficult, however, to measure and evaluate this contribution.

Alway and coworkers (*1*) concluded that sulfur absorbed from the atmosphere by surface soils made an appreciable contribution to plant requirements. Fried (*17*) and Turrell and Weber (*36*) demonstrated by use of radioactive sulfur (S–35) that alfalfa and lemon trees can absorb sulfur directly through their leaves.

A method of assessing atmospheric sulfur was devised in Great Britain (*19, p. 14*) in a study of air pollution. This method, which consisted of absorbing atmospheric sulfur on cylinders coated with lead peroxide, was adapted for use in several investigations in the United States and was used in the present study.

Alway and coworkers (*1*) used the lead-peroxide-cylinder method of measurement in Minnesota and calculated sulfur reacted as pounds per acre of exposed surface. Values ranged from 343 pounds of sulfur per acre of surface in a 10-month period in Minneapolis to 2 pounds per acre at Becida, a rural post office 12 miles from the nearest town or railroad. Alway concluded that sulfur in the atmosphere varies in somewhat the same way as sulfur brought down in rainwater, but that it is of less value to crops.

Kelly and Midgley (*24*) conducted a similar study in Vermont. Atmospheric sulfur available for absorption ranged from annual equivalents of 43 to 13 pounds per acre of exposed surface at 5 locations in the State. They concluded that Vermont atmosphere contains sufficient sulfur to supply crop needs. It has been estimated (*32*) that around 650,000 tons of sulfur trioxide (SO_3) are liberated in the atmosphere of New England each year from burning coal. This is the equivalent of 13.3 pounds of sulfur above each acre in the region. No comparable estimate is available for the Southeast.

Experimental Procedures

Lead-peroxide cylinders were exposed at 8 locations in Alabama and 19 locations in Virginia where sulfur accretions in rainwater were also measured. The locations in Alabama were in the vicinity of Tuscumbia, and the records cover the period March 1, 1956, through February 28, 1957. During this period sulfur in rainwater near Tuscumbia was higher than during an earlier period because of operation of the electric steam plant. (See table 1.)

The cylinders were covered with cotton fabric having a surface area of 100 $cm.^2$, which was coated with lead-peroxide paste. At intervals the fabric and coating were removed from the cylinders, the amount of sulfate was determined, and new fabric surfaces were exposed. The cylinders were exposed freely to the air but were protected from rain by a cowl.

Results of Experiments

The lead-peroxide-cylinder data for 1 year, as well as sulfur accretions in rainwater, are shown in table 6 for each location in Alabama and Virginia.

Although considerable variation was noted in both States, atmospheric sulfur, as measured by absorption on cylinders was generally found to be at higher concentrations at locations sampled in Virginia than at the Alabama locations. Annual averages were 22.8 mg. per 100 $cm.^2$ in Virginia and 16.7 mg. per 100 $cm.^2$ in Alabama. This difference corresponds with the higher accretions of sulfur recorded in rainwater in Virginia than in the other Southern States. (See table 2.) This may also have been a factor in the lack of crop response to sulfur applications in Virginia (*28*) and in the response obtained in Alabama (*13*).

Although sulfur carried to the earth in rainwater is derived from atmospheric sulfur, the amount in rainwater is dependent on the frequency of rains. (See table 5.) For this reason, only a general correlation exists between sulfur absorbed on cylinders and sulfur accretions in rainwater.

Table 6.—*Comparative amounts of atmospheric sulfur absorbed by surfaces of lead-peroxide cylinders and sulfur collected in rainwater, at various locations in Alabama and Virginia, by quarters*

ALABAMA (IN VICINITY OF TUSCUMBIA)

Location	Sulfur absorbed on cylinders during period—					Sulfur in rain for year	
	March through May 1956	June through August 1956	September through November 1956	December 1956 through February 1957	Total for year	Average	Total accretion
	Mg. per 100 cm.²	*Mg. per 100 cm.²*	*Mg. per 100 cm.²*	*Mg. per 100 cm.²*	*Mg. per 100 cm.²*	*P. p. m.*	*Pounds per acre*
Gilbert	0. 2	0. 1	4. 0	1. 3	5. 6	1. 0	11. 2
Moody	1. 3	5. 1	7. 1	2. 9	16. 4	. 8	9. 4
Foster	. 9	4. 6	2. 6	2. 9	11. 0	. 9	10. 5
McGavack	1. 9	3. 4	4. 2	2. 5	12. 0	1. 1	12. 3
Howard	6. 1	. 9	5. 5	2. 8	15. 3	1. 2	13. 6
Darby	9. 1	3. 3	6. 1	7. 9	26. 4	1. 4	15. 7
Darby	6. 3	6. 9	6. 7	7. 1	27. 0	1. 2	14. 4
Wright	5. 1	. 2	7. 0	7. 9	20. 2	------	------

VIRGINIA (IN VICINITY OF TOWNS NAMED)

Location	March through May 1955	June through August 1955	September through November 1955	December 1954 through February 1955	Total for year	Average	Total accretion
	Mg. per 100 cm.²	*Mg. per 100 cm.²*	*Mg. per 100 cm.²*	*Mg. per 100 cm.²*	*Mg. per 100 cm.²*	*P. p. m.*	*Pounds per acre*
Ashland	3. 8	1. 9	3. 1	8. 2	17. 0	1. 7	16. 9
Blacksburg	5. 4	2. 6	8. 4	7. 3	23. 7	1. 6	18. 4
Buckingham	3. 5	2. 0	4. 4	6. 9	16. 8	1. 8	11. 9
Chantilly	7. 8	3. 9	8. 6	11. 6	31. 9	3. 9	27. 7
Chatham	4. 6	1. 7	5. 7	3. 0	15. 0	2. 1	15. 5
Charlotte Courthouse	3. 4	1. 6	4. 4	4. 4	13. 8	1. 7	13. 5
Emory	2. 2	1. 5	5. 1	--------	--------	------	------
Fredericksburg	5. 2	3. 8	6. 3	13. 5	28. 8	3. [illegible]	25. 2
Halifax	2. 0	1. 9	3. 4	3. 4	10. 7		12. 2
Hillsville	2. 1	1. 8	4. 8	4. 8	13. 5	1. [illegible]	12. 9
Kenbridge	2. 7	1. 0	3. 9	5. 0	12. 6	1. 3	16. 8
Middleburg	7. 4	3. 3	7. 3	14. 7	32. 7	2. 9	22. 6
Norfolk	12. 4	5. 3	10. 2	26. 9	54. 8	3. 7	33. 0
Onley	5. 4	. 9	4. 7	--------	--------	5. 2	30. 8
Orange	2. 7	1. 9	4. 7	8. 5	17. 8	2. 9	22. 6
Saint Stephens Church	4. 2	1. 5	3. 7	--------	--------	1. 6	14. 9
Salem	5. 6	4. 7	11. 8	12. 5	34. 6	4. 2	25. 8
Staunton	4. 5	1. 6	4. 9	8. 2	19. 2	2. 4	14. 8
Warsaw	5. 1	2. 6	5. 1	9. 6	22. 4	2. 1	19. 0

DISCUSSION

Crops commonly grown in the Southeast, such as clover, alfalfa, and cotton, require from 15 to 25 pounds of sulfur per acre for normal production. Vegetable crops of the Cruciferae and Liliaceae families have even higher sulfur requirements. Corn and grasses require 10 pounds per acre or less.

Surface soils in the Southeast characteristically contain 3 parts per million (6 pounds per acre) of extractable sulfur or less, although there are accumulations of larger amounts in lower soil horizons. Such soils are potentially deficient in sulfur. Production has probably been maintained on many of these soils by incidental additions of sulfur in fertilizers and rainwater and, to some extent, by direct uptake of atmospheric sulfur by soils and plants.

This study showed that at locations removed from industry in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas, the annual contributions of sulfur from rainwater are small. Undoubtedly, runoff and leaching cause losses of sulfur that sometimes equal or exceed the amounts added from the atmosphere.

Limited measurements indicated higher concentrations of sulfur in the atmosphere in Virginia than in Alabama.

The results of this study emphasize the importance of soil-management practices that include additions of sulfur in fertilizer or other amendments in the nine Southern States mentioned in the preceding paragraph. A planned program of sulfur applications should replace dependence on incidental additions.

SUMMARY

During the investigations covered by this publication, rainwater was collected at 109 locations in the Southern United States and was analyzed for sulfur during the 3-year period, 1953–55.

Rainwater collected in Virginia, Kentucky, and Tennessee was found to contain more sulfur than did that from the other States included in the investigations—Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas. In those nine States, a few locations had high sulfur-accretion values because of their proximity to industrial establishments.

In the rural areas of the nine States just named, average accretions of sulfur in rainwater were 5.8, 4.1, and 6.3 pounds per acre in 1953, 1954, and 1955, respectively. (See table 2.) The general average for the 3 years was 5.4 pounds per acre.

The principal source of sulfur in atmosphere and rainwater, especially in the winter months, is probably the discharge of combustion gases from burning coal and wood. Seasonal variations in the sulfur content of rainwater are small.

Sulfur in rainwater makes only a minor contribution to the sulfur required by crops in the nine cooperating Southern States other than Virginia, Kentucky, and Tennessee.

In this study, sulfur in the atmosphere was measured at 8 locations in Alabama and at 19 locations in Virginia. As in rainwater, sulfur in the atmosphere was generally found to be higher at the Virginia locations.

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