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TEXAS AGRICULTURAL EXPERIMENT STATION

A. B. CONNER, DIRECTOR
COLLEGE STATION, BRAZOS COUNTY, TEXAS

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DIVISION OF CHEMISTRY

POSSIBILITIES OF SULPHUR AS A SOIL AMENDMENT

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Sulphur is an essential plant food. Chemical analyses show that alfalfa, cabbage, cotton, onions, and turnips take up much larger quantities of sulphur than corn, rice, oats, and wheat. Some Texas soils are low in sulphur. Sulphur is brought down by rain and also is supplied by irrigation water and in most commercial fertilizers. The amount brought down by rain in Texas averages 4 to 12 pounds a year on each acre, varying with different sections.

Pot experiments show that sulphur alone gave very poor results but when it was used to supplement a complete fertilizer in pots watered with distilled water which contained no sulphur, it gave, in some cases, increases in yield of crops. Additions of sulphur did not increase the amounts of nitrogen or potash taken up by crops in pot experiments, although they increased the sulphur taken up and slightly increased the phosphoric acid. There was a tendency for the sulphur removed by crops to increase as the sulphur content of the soil increased. Oxidation of sulphur had practically no effect upon the active phosphoric acid or active potash in the soils tested, but increased the permeability of some of the soils to water.

Sulphur is not recommended as a fertilizer on soils in Texas, since a sufficient amount of sulphur is present in the soils, or is supplied by rain or irrigation water or by commercial fertilizers carrying plant food. Sulphur or gypsum may be recommended in special cases on soils which run together under irrigation, or which contain black alkali. It is possible that the use of concentrated commercial fertilizers containing little or no sulphur may cause a deficiency of sulphur in soils in some sections of the country, especially for crops which require comparatively large amounts of sulphur, such as alfalfa, cotton, cabbage, and onions. The conclusion that sulphur is not needed as a fertilizer on Texas soils confirms the conclusions of the Division of Agronomy, Texas Agricultural Experiment Station, recently reported.

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POSSIBILITIES OF SULPHUR AS A SOIL AMENDMENT

G. S. FRAPS

For a long time it has been known that sulphur, like nitrogen, phosphoric acid, potash, and some other materials, is essential to plant life. Sulphur, however, is not considered to be an essential constituent of commercial fertilizers, the constituents recognized by both law and usage being nitrogen, phosphoric acid, and potash. This usage is based upon extensive field experiments and the experience of nearly a century, which are taken to mean that one or more of these constituents is needed when a soil needs plant food. On the other hand, applications of nitrogen, phosphoric acid, and potash are usually accompanied by applications of sulphur; the nitrogen frequently being used as a sulphate of ammonia, the phosphoric acid usually as superphosphate made by the action of sulphuric acid upon phosphate rock or bone, and the potash sometimes as sulphate of potash or accompanied by sulphate in some form. Sulphur in the form of gypsum has been applied to soils for a long time, but has not been used extensively since commercial fertilizers came into use.

Fraps (18, 22), in 1900, called attention to the fact that the percentage of sulphur in plants was higher than was generally supposed. Hart and associates (34, 35) first emphasized the importance of sulphur as a plant food and the possibility of its being needed by the soil. Numerous other workers have studied various phases of the subject. Some of these studies will be referred to later in the publication. Extensive references are given by Joffe (41), McKibbin (56), Lomanitz (49), and Cubben (13).

In recent years, it has been found that some soils in the State of Washington (78) and Oregon (64) respond markedly to applications of sulphur, either as such or as gypsum (sulphate of lime). Improved methods of analysis have shown plants to contain more sulphur than was formerly supposed. Concentrated fertilizers which contain little or no sulphur are coming on the market. These facts render it important to know whether there are other soils, in addition to those in Washington or Oregon, which respond to applications of sulphur. It is also necessary to know if soils treated with any new concentrated fertilizers containing only small amounts of sulphur, will need sulphur after continued usage. Other questions related to the use of sulphur in the soil need to be answered. These questions are especially important in Texas, on account of the large deposits of native sulphur being mined in the State, and the deposits of gypsum and, in some cases, mixtures of gypsum and sulphur, found in the western part of the State.

Sulphur and Sulphur Ores in Texas

Sulphur is found chiefly as elemental sulphur, as iron pyrites, and as sulphate of lime (gypsum or anhydrite). Iron pyrites is not suitable for agricultural purposes, though it is used for the manufacture of sulphuric acid. Native sulphur and gypsum are used to some extent for agricultural purposes and large deposits of both occur in Texas. Pyrites occur in small quantity in many parts of the state, frequently associated with lignite. They have a yellow color and being sometimes mistaken for gold, are called "fool's gold." The pyrite deposits in Texas are usually too small to be of commercial value.

Gypsum. Gypsum (82, 83) is a hydrous calcium sulphate, occurring abundantly in many parts of Texas in various forms—as rock gypsum, as gypsite or earth gypsum, as mica-like selenite, and as satin spar.

The most valuable deposit of gypsum in Texas lies just below, and parallel to, the line of the Cap Rock in a belt about fifty miles wide in Western Texas, extending from Hardeman County through Foard, Stonewall, Nolan, and other counties to Sterling County. The strata of rock gypsum are often fifty or more feet thick and there are deep deposits of gypsite with little overburden. This stratum of gypsum continues westward from the line of the belt mentioned, but it dips under the Cap Rock and at most points on the high plains it is too far below the surface to allow mining.

There is a large area of gypsum and gypsite in the northern part of Hudspeth County west of the Guadalupe Mountains and another in the Malone Mountains in the extreme southern part of the county.

There is an extensive deposit of gypsum several hundred feet in thickness near Falfurrias in Brooks County. There are many deposits of gypsum throughout the Gulf Coastal Plains, but usually they are far below the surface. Gypsiferous marls and clays abound throughout central and eastern Texas, but usually they are not in workable form and quality.

Mixtures of sulphur, gypsum, and earth are found in El Paso County (66, 75).

Elemental Sulphur. Native or free sulphur in Texas is at present mined chiefly on the Gulf Coast, in Brazoria, Matagorda, and Wharton Counties. The sulphur is melted by superheated water, and forced to the surface, where it is allowed to cool. In this form it is called crude sulphur, although it has a high degree of purity. The quantity mined is quite large, being estimated at nearly two million tons yearly.

There are two kinds, and many varieties of sulphur.

Sulphur is purified by sublimation. The sulphur is melted and vaporized, the vapors being condensed in large brick chambers. Part of the sulphur is condensed as a fine dust, known as flowers of sulphur. The degree of fineness depends on the size and shape of the chamber in which the vapors are condensed and on the rate of heating the sulphur. In general there are two grades, the fine flowers of sulphur, and the extra light flowers of sulphur. Some of the sublimed sulphur melts, and is cast into candles, bars, or other shapes, or allowed to solidify in the sublimation chamber, after which it is broken into lumps. A large number of different grades and preparations of sulphur are made for various commercial uses.

Both the crude and the sublimed sulphur may be ground to a very fine powder; which is called flour of sulphur. Usually there are two grades, the finely ground and the very finely ground. The direct agricultural use of elemental sulphur is chiefly for the treatments of plant diseases and the control of insects. Large amounts of sulphur are used in the manufacture of superphosphates. About one-fourth the total domestic production of sulphur is used directly or indirectly for agricultural purposes.

Sulphur Content of Crops

Fraps, in 1900 (18, 21, 22, 23), redirected attention to the fact that the sulphur in the ash of plants may be much below the amount actually present in the plants. As Referee on Ash of the Association of Official Agricultural Chemists, Fraps (19, 20, 23) began studies of methods to estimate sulphur in plants which have been continued by referees on Inorganic Plant Constituents more or less intermittently up to the present time. Withers and Fraps (87) determined the sulphur content of a number of materials. Determinations have also been reported by Hart and Peterson (34), Powers (64), Shedd (72), and others.

A number of determinations of the sulphur content of various plants and plant-products were made in the course of the work here presented. These results together with some of those from elsewhere are given in Table 1. The Texas estimations are marked with an asterisk and some are averages. The sulphur was estimated by the A. O. A. C. method (4, page 44), which uses fusion with sodium carbonate and sodium peroxide in a nickel crucible.

Table 1—Sulphur content of various crops and plant materials. (Texas results marked*)

Crop	Sulphur, per cent	Crop	Sulphur, per cent
Alfalfa hay*	0.300	Lettuce leaves	.013
Alfalfa seed	.292	Limes and seed	.047
Apple and seed	.043	Linseed meal*	.390
Asparagus	.088	Loco weed, dried	.232
Barley*	.200	Mesquite grass, dried*	.108
Barley straw	.147	Millet seed*	.132
Beans (white)	.232	Milo grain*	.098
Beets and tops	.028	Milo fodder, dried*	.087
Beet pulp, dried*	.200	Milo heads, dried*	.086
Bermuda hay*	.176	Needle grass	.097
Blackberries	.040	Oak leaves dried*	.092
Bluegrass	.134	Oats	.189
Brown corn seed*	.073	Oat straw	.195
Buckwheat*	.118	Okra	.054
Buffalo grass hay*	.192	Onions	.568
Cabbage	.819	Orange	.026
Cactus, dried*	.140	Parsley	.070
Cantaloupe seed	.065	Parsnip	.046
Carrot	.042	Peach	.014
Carrot tops	.114	Peach seed	.041
Celery	.053	Peas	.069
Cherries, including seed	.108	Pea pods	.043
Clover, red	.164	Pepper, green bell	.040
Clover, sweet flowering stage	.082	Pepper fruit, dried*	.276
Corn stover	.126	Pepper plants, dried*	.532
Corn, white	.170	Pepper, red bell	.043
Corn, grain*	.120	Pineapple	.039
Corn, yellow	.139	Pineapple cone	.059
Cotton, leaves (dried)*	.952	Potatoes	.137
Cotton lint, fresh sample	.014	Plum, California	.023
Cotton seed*	.204	Plum seed, California	.020
Cottonseed hulls*	.084	Radish, including leaves	.066
Cottonseed meal	.487	Rape tops	.988
Cottonseed meal*	.395	Raspberry, black	.035
Cotton stem, dried	.146	Rhode grass hay*	.192
Cowpea seed	.111	Rice*	.126
Cowpea seed*	.248	Rice bran*	.152
Cowpea vine, green	.077	Rice hulls*	.064
Cucumber	.062	Rutabagas	.817
Currant, red	.056	Rye	.123
Cymlings	.035	Rye, heading stage	.120
Dewberries	.037	Rye, straw	.049
Egg plant, dried*	.300	Sacchuista grass*	.167
Egg plant, fruit, dried*	.308	Sorghum hay or fodder*	.090
Feterita chops*	.120	Sorghum seed*	.088
Fillere weed, dried*	.212	Sorghum silage, dried*	.113
Flax plant, by-product*	.236	Soy bean	.341
Grapefruit and seed	.065	Spinach	.063
Goat weed, dried*	.158	Sudan grass hay*	.116
Gooseberries	.012	Sugar beet	.138
Goose grass, dried*	.107	Sugar beet tops	.433
Grass, Texas pasture*	.131	Sweet potato	.021
Grass, range*	.138	Tallow weed, dried*	.338
Hay, mixed	.160	Timothy	.190
Hemp	.107	Tobacco: average of 40 varieties	.458
Hungarian millet, green	.033	Tomatoes, ripe	.010
Kafir grain*	.121	Turnips	.740
Kafir fodder*	.168	Turnip tops	.900
Kafir heads*	.124	Vetch, flowering stage	.107
Kafir head stems*	.084	Wheat	.170
Kafir silage, dried*	.105	Wheat gray shorts*	.180
Kale	.220	Wheat white shorts*	.116
Lemon and seed	.022	Wheat straw	.119

Sulphur Withdrawn by Crops

The amount of sulphur taken up by a crop varies to a considerable extent, depending upon the size of the crop and the percentage of sulphur contained in it. The percentage of sulphur depends upon the nature of the crop, but also to some extent upon the sulphur in the soil, as will be shown later. Any estimate of the amount of sulphur or other materials taken up by a crop is, of course, only approximate. Estimates of the amount of sulphur taken up by crops have been made by Hart and Peterson (14).

Table 2—Plant food removed by crops in pounds per acre

	Sulphur (S)	Nitrogen	Phosphoric Acid	Potash
Alfalfa, 4 tons	22	183*	50	143
Cabbage, 14,800 pounds	39	60	20	80
Corn, 40 bushels (in corn and cob)	3	38	19	13
Corn (in stalk and leaves)	3	22	6	29
Cotton (in seed and lint, 600 pounds)	1	13	6	7
Cotton (in stalk, burs and leaves—2,400 lbs)	12	50	10	20
Oats, 40 bushels (in the grain)	3	25	10	7
Oats (in the straw)	4	10	4	21
Onions, 30,000 pounds	23	57	27	60
Potatoes, Irish (100 bushels in the tubers)	2	20	10	36
Potatoes, sweet (200 bushels in the tubers)	2	28	20	72
Rice, 1,900 pounds (in the grain)	2	23	12	5
Rice (in 2,250 pounds straw)	1	14	3	37
Sorghum, 3 tons dried	5	84	29	134
Sugar cane, 20 tons	3	153	15	44
Turnips, leaves	14	....	11	....
Turnips, roots	23	....	22	....
Wheat, 25 bushels (in the grain)	2	29	13	9
Wheat (in the straw)	3	13	5	14

*A part of this nitrogen comes from the air.

Table 2 contains estimates of sulphur removed by crops, based upon analyses in Table 1, the table of Hart and Peterson, and other analyses and data available. The amounts of nitrogen, phosphoric acid, and potash removed by crops are also given for purposes of comparison. It will be noted that alfalfa, cabbage, cotton, onions, and turnips take up greater amounts of sulphur than the other crops. The quantity of sulphur taken up is lower than that of nitrogen, phosphoric acid, or potash, except for cabbage and turnips.

Sulphur in Rain Water

Sulphur is brought to the soil by rain or snow, chiefly in the form of sulphates. The amounts may be considerable, especially where much coal is burned.

Estimations of the amount of sulphur brought down by rain and snow have been made at a number of places; see Joffe (41, page 9) and Wilson (86). The quantities of sulphur brought down in a year on an acre were reported to be 6 to 8 pounds at Rothamsted, England; Catarinia, Sicily; Lincoln, New Zealand; Wisconsin and some other places; while 38 to 72 pounds per acre came down at Garforth, England; Leeds, England; Urbana, Illinois; and Petrograd, Russia (U. S. S. R.). MacIntire and Young (55) found that 12.7 to 232.4 pounds per acre of sulphur were brought down by the rain in various parts of Tennessee, the smallest being at Crossville and the largest at Copperhill.

Sulphur in Texas Rain Water. For the purpose of estimating the sulphur brought down by rain and snow in Texas, samples of rain water were collected by the superintendents of the various Texas substations, and at the Main Station, and sent in monthly if the rainfall was one inch or more; otherwise the sample was held for a longer period. The analysis was made on a volume of 1000 cc., if possible, and checked by analyses of other portions, usually smaller. The water was evaporated to dryness on an electric stove in a room as free as possible from sulphur, apart from the regular laboratory, and in which no gas was used. The residue was taken up in acid and water, filtered, and the sulphates precipitated in the usual way.

A few of the samples were lost by breakage in transit or otherwise, in which case the results are interpolated. The results by months are given in tables. A summary is given in Table 3.

Table 3—Sulphur (S) in pounds per acre, brought down by rain or snow, in Texas

Substations	1924 9 months	1925 12 months	1926 12 months	1927 12 months	1928 7 months	Assumed yearly average
Angleton No. 3	6.84	12.12	10.01	7.92	3.58	9.47
Balmorhea No. 9	1.96	3.14	5.84	4.68	1.56	4.07
Beaumont No. 4	12.72	12.13	18.50	15.92	6.92	15.36
Beeville No. 1	5.57	8.80	6.77	4.29	2.94	6.56
Chillicothe No. 12	....	8.26	13.05	7.12	7.45	10.00
College Station (Main) No. 10	12.00	9.56	13.61	11.82	8.82	12.66
Denton No. 6	7.54	7.38	11.31	12.46	13.93	11.82
Lubbock No. 8	3.29	4.52	10.30	5.56	33.59	12.01
Nacogdoches No. 11	11.83	10.96	12.41	9.79	7.93	12.00
San Antonio	....	2.40*	7.04	7.21	7.34	8.22
Spur No. 7	3.24	6.56	10.29	5.00	10.14	7.98
Temple No. 5	5.84	5.45	11.00	9.68	6.69	8.88
Troup No. 2	6.39	6.38	10.93	8.90	7.07	9.08
Weslaco No. 15	....	10.37*	6.02	9.24	9.30	15.46

*4 months only.

A comparison of this table with Table 2 shows that rain may bring down more than enough sulphur to supply the needs of all the crops mentioned in the table except alfalfa, cabbage, onions, turnips, and in most cases, cotton. The sulphur brought down by rain seems sufficient to supply crops with low sulphur requirements, such as corn, oats, potatoes, rice, sorghum, sugar cane, and wheat. The sulphur brought down by rain is not all at the disposal of plants, since some is carried away in the run-off and some is lost by percolation.

The locations in Texas fall into three groups with respect to the sulphur brought down annually by rain.

Group 1, average quantity of sulphur brought down about 12 pounds yearly; Beaumont, College Station, Denton, Nacogdoches, and Weslaco.

Group 2, average quantity of sulphur brought down about 8 pounds yearly; Angleton, Beeville, Chillicothe, San Antonio, Spur, Temple, and Troup.

Group 3, average quantity of sulphur brought down about 4 pounds yearly; Balmorhea.

It must be remembered that the location of the rain gauge with respect to sources of sulphur, such as combustion of oil, gas, coal, or lignite, has something to do with the amount of sulphur brought down, so that the figures given above cannot be taken to represent the exact amount of sulphur in the rain in all the surrounding country.

The sulphur in the rainfall by months is given in Tables 4 to 8, inclusive. While a portion of the sulphur is brought down during the growing season, a considerable quantity is brought down during other periods of the year, and part is lost by percolation and run-off.

Sulphur Lost by Percolation. Sulphur is washed out of the soil by percolation of rain water through the soil and the quantities lost in this way may be large. The amounts vary with the physical character of the soil, the rainfall, the slope of the land, temperature, amount of sunshine, and other conditions. Estimates have been made by Lyon and Bizzell (50, 51), MacIntire (53), and others, which are summarized by Joffe (41). The annual amounts of sulphur in drainage water were 8 to 28 pounds per acre.

Ellett and Hill (17) in 1929 found, with an average annual precipitation, 17 pounds of sulphur yearly per acre for six years, an average outgo of about 19 pounds of sulphur from lysimeters one foot deep, 14 pounds for lysimeters two feet deep, and 5 pounds from lysimeters three feet deep. While one-foot lysimeters lost sulphur, the two-foot lysimeter retained about 17 per cent, and the three-foot lysimeter retained 70 per cent of the sulphur in the rainfall.

The amount and composition of the water which goes through a soil in a drain gauge may be quite different from that which percolates from a field where part of the water has opportunity to run off and part of the water is used by crops.

Sulphur in Irrigation Waters

Drainage waters and irrigation waters in Texas usually contain sulphates, sometimes in considerable amounts. The water

Table 4.—Sulph ur (S) in rainfall by months (1924) for Texas stations in pounds per acre.

Substations		April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total nine months
Angleton	No. 3	.42	1.71	.92	.19	.73	.34	0	.48	2.05	6.84
Balmorhea	No. 9	.20	0	0	.69	.10	.33	.30	0	.34	1.96
Beaumont	No. 4	3.87	.66	2.03	1.13	.20	1.46	.24	.92	2.20	12.71
Beeville	No. 1	.52	3.22	1.04	.03	.00	.21	0	.03	.51	5.56
College Station (main Station)		1.73	4.98	1.42	.92	.08	.66	.15	.81	1.25	12.00
Denton	No. 6	2.13	1.22	.60	.38	.70	.71	0	.17	1.62	7.53
Lubbock	No. 8	.37	.39	.80	.37	.54	.56	.22	.02	.02	3.29
Nacogdoches	No. 11	3.84	2.06	1.22	.08	.03	1.34	.03	1.24	1.98	11.82
Spur	No. 7	.39	1.08	.20	.56	.24	.55	.22	0	0	3.24
Temple	No. 5	.98	1.33	.33	.06	.15	1.33	.08	.77	.08	5.83
Troup	No. 2	1.81	3.15	.23	.00	.08	.28	.02	.18	.63	6.38

Table 5.—Sulphur in rainfall by months in 1925 for Texas stations, in pounds per acre.

Stations		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	12 months
Angleton	No. 3	1.55	.13	.38	.59	.90	.86	.98	.70	1.77	2.04	1.17	1.07	12.14
Balmorhea	No. 9	0	0	0	.75	.47	.03	.51	.53	.35	.49	0	.02	3.15
Beaumont	No. 4	.65	.78	.54	.98	.09	.88	1.24	.75	1.28	2.86	1.21	.85	12.11
Beeville	No. 1	.06	.03	1.00	.65	3.75	.24	.74	.40	.76	.53	.19	.45	8.80
Chillicothe	No. 12	.07	.01	.03	.39	1.88	.84	.68	.75	3.31	.12	.13	.03-	8.24
College Station	No. 10	.81	.66	.31	.97	.01	.64	.42	.32	.57	3.00	1.27	.59	9.57
Denton	No. 6	1.07	.46	.03	1.14	.79	.24	.21	1.59	.53	.80	.52	.00	7.38
Lubbock	No. 8	.31	.00	.00	.51	.80	.29	.31	.30	1.62	.30	.02	.06	4.52
Nacogdoches	No. 11	1.17	1.58	.76	.58	.74	.10	1.07	.76	.71	1.67	1.18	.64	10.96
San Antonio		.....	.....	.....	.....	.....	.....	.....	.....	1.44	.31	.32	.33	2.40
Spur	No. 7	.10	.10	.10	2.53	1.45	.21	.47	.87	.43	.20	.06	.06	6.58
Temple	No. 5	.61	.08	0	.88	1.16	.18	.30	.29	.58	.68	.56	.13	5.45
Troup	No. 2	.50	.84	.39	.29	.64	.21	.84	.13	.35	.96	.94	.30	6.39
Weslaco		.....	.....	.....	.....	.....	.....	.....	.....	5.05	1.39	.42	3.51	10.37

Table 6.—Sulphur (S) in rainfall by months, 1926, in pounds per acre for Texas stations.

Stations	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Angleton . . . . No. 3	1.10	.30	2.09	.84	1.53	.48	1.12	.60	.36	.82	.18	.59	10.01
Balmorhea . . . . No. 9	.44	0	1.29	.58	1.16	.10	.03	.62	.47	.61	.09	.45	5.84
Beaumont . . . . No. 4	1.63	.61	3.62	1.54	1.14	1.59	2.70	1.31	.53	1.17	.82	1.84	18.50
Beeville . . . . No. 1	2.74	.06	.94	.49	.45	.37	.06	.05	.04	.87	.10	.58	6.75
Chillicothe . . . . No. 12	1.30	0	1.95	5.18	.87	.72	.52	.44	.60	.18	.02	1.24	13.02
College . . . . No. 10	1.21	.06	2.64	1.33	.67	.25	.81	.58	.47	1.42	.79	3.39	13.62
Denton . . . . No. 6	1.36	.13	1.28	.82	.89	1.32	.77	.52	.38	1.65	.29	1.92	11.33
Lubbock . . . . No. 8	.79	.06	2.26	.26	.82	.18	.42	.40	.60	1.94	.29	2.28	10.30
Nacogdoches . . . . No. 11	1.55	.74	2.10	.82	.96	1.04	.95	.82	.43	.65	.80	1.55	12.41
San Antonio	.66	.02	1.53	1.07	.56	.13	.21	.36	.45	.41	.64	.98	7.02
Spur . . . . No. 7	.18	.01	.45	.95	1.42	.75	1.94	.94	2.04	.89	.12	.60	10.29
Temple . . . . No. 5	1.68	.05	1.84	2.19	.80	.68	.55	.52	.30	1.07	.20	1.12	11.00
Troup . . . . No. 2	1.16	.55	1.63	.48	1.61	1.45	1.11	.08	.34	.68	.58	1.25	10.92
Weslaco . . . . No. 15	.67	0	.62	.50	.46	.64	.84	.38	.77	.46	.68	0	6.02

Table 7.—Sulphur (S) in rainfall by months, 1927, in pounds per acre for Texas stations.

Substations	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Angleton . . . . No. 3	.32	.50	.40	.88	.02	.86	.67	.02	1.54	.34	.82	1.56	7.93
Balmorhea . . . . No. 9	.17	.58	.81	0	.46	.47	.82	.08	.72	.22	0	.35	4.68
Beaumont . . . . No. 4	.83	1.15	1.78	1.21	.62	2.37	2.15	.03	.46	.36	.76	4.19	15.92
Beeville . . . . No. 1	.12	.26	.76	.14	.07	1.00	.44	.14	.52	.44	.12	.28	4.29
Chillicothe . . . . No. 12	.67	.40	.62	.46	.59	.70	.61	.46	.78	.89	.37	.58	7.13
College Station . . . . No. 10	1.10	2.10	1.37	1.56	.74	.80	.70	.04	.58	1.16	.12	1.55	11.82
Denton . . . . No. 6	.97	1.75	1.02	1.45	.38	1.56	1.05	.26	.95	1.47	.01	1.59	12.46
Lubbock . . . . No. 8	.89	.40	0	.44	0	1.98	.51	.28	.55	.17	0	.34	5.56
Nacogdoches . . . . No. 11	.61	1.26	1.47	1.40	.60	1.25	.23	.66	.49	.82	.44	.56	9.79
San Antonio	.30	1.00	.74	.60	.87	1.44	.11	.17	.41	.51	0	1.05	7.20
Spur . . . . No. 7	.40	.10	.38	.15	.24	1.68	.39	.44	.85	.28	0	.10	5.01
Temple . . . . No. 5	.89	1.28	.77	1.17	1.07	2.23	.29	.01	.49	.77	.07	.64	9.68
Troup . . . . No. 2	.55	1.03	.11	2.56	.60	.74	.72	0	.54	.84	.48	.73	8.90
Weslaco . . . . No. 15	.11	.51	.09	1.02	1.08	.97	.96	.21	2.95	.46	.08	1.21	9.24

Table 8.—Sulphur (S) in rainfall by months, 1928, in pounds per acre at Texas Stations.

Substation		Jan.	Feb.	Mar.	April	May	June	July	Total seven months
Angleton	No. 3	.16	1.35	.17	.29	.55	1.01	.05	3.58
Balmorhea	No. 9	.00	.08	.03	.24	.81	.40	0	1.56
Beaumont	No. 4	.18	1.10	.80	.83	.06	3.18	.78	6.92
Beeville	No. 1	.20	.82	.46	.13	.21	1.04	.07	2.93
Chillicothe	No. 12	.42	2.30	.53	.58	1.61	.85	1.16	7.45
College Station		.15	1.62	1.19	1.47	.62	2.65	1.13	8.83
Denton	No. 6	.19	1.45	.29	3.94	4.98	2.49	.59	13.93
Lubbock	No. 8	.13	.95	....	.07	1.89	3.15	4.16	10.35
Nacogdoches	No. 11	.10	1.30	2.00	.57	1.05	1.37	1.53	7.92
San Antonio		.38	1.44	.66	.70	2.36	.58	1.21	7.33
Spur	No. 7	.05	.23	.08	.36	7.11	.49	1.81	10.13
Temple	No. 5	.46	1.66	.14	1.14	.32	1.72	1.26	6.70
Troup	No. 2	.19	1.15	.78	1.07	1.46	2.01	.41	7.07
Weslaco	No. 15	1.58	3.70	.12	.46	2.51	.84	.08	9.29

of the Rio Grande river varies in composition, but near Brownsville (25) it contains over 75 parts per million of sulphur (S) in the form of sulphates, which is equivalent to about 200 pounds of sulphur per acre-foot of water. Many irrigation waters in the western part of the United States contain more sulphur than the Rio Grande, while a few contain less. The water in the Pecos River near Barstow, Texas (11), contains about 500 parts per million of sulphur or about 1350 pounds per acre-foot. The water of Lake Kemp in Wichita County, Texas, contains about 180 parts per million or 400 pounds per acre-foot. Since crops which have high requirements for sulphur, as alfalfa, cotton, cabbage, and onions, require less than 40 pounds of sulphur per acre, it is obvious that the irrigation waters in western Texas supply an abundance of sulphur for the crops grown under irrigation.

Some of the river waters used for irrigation of rice in Texas (24) contain only 4 to 11 parts per million of sulphur, or 12 to 33 pounds per acre-foot, but a crop of rice requires only about 3 pounds of sulphur to the acre.

Sulphur in Soils

The sulphur in soils may be present as organic compounds, as pyrites, and as sulphates, such as calcium or barium sulphate. It may be found in the interior of soil particles and not be exposed to the action of plant roots or soil moisture.

Hart and Peterson (34), Brown and Kellogg (6), Ames and Boltz (2), Shedd (71), and others found that the sulphur content of many soils is low, and may be lower than the content of phosphoric acid.

Sulphur in Texas Soils. Analyses were made of a number of Texas soils, selected so as to represent various geological origins and various climatic conditions. The estimation was made by the A. O. A. C. method (28, p. 30). Sodium peroxide was used in a room free from sulphur, so far as possible. Electric heating appliances were used to avoid the presence of sulphur from gases. The analyses, averaged by counties, are given in Table 9. The content of sulphur is, as a rule, lower than that of nitrogen or phosphoric acid. The soils of Cameron and of Jefferson counties contain more sulphur than the others. The group of counties where soils average smaller amounts of sulphur includes Archer, Dallam, Eastland, Freestone, Harris, and Washington counties. Some samples are quite low in sulphur. This is shown by reference to the analyses of some soils of Harris County (Table 10) and of Freestone County (Table 11).

Table 9—Average percentage of sulphur, nitrogen and phosphoric acid in Texas soils

		Sulphur (S)	Nitrogen	Total phosphoric acid	Number of soils averaged
Archer county	surface	.0152	.076	.053	11
	subsoil	.0236	.043	.048	8
Bowie county	surface	.0308	.067	.061	45
	subsoil	.0144	.039	.055	54
Brazoria county	surface	.0264	.142	.048	14
	subsoil	.0212	.110	.044	10
Cameron county	surface	.0640	.112	.180	21
	subsoil	.0344	.053	.108	20
Dallam county	surface	.0132	.070	.057	3
	subsoil	.0160	.063	.063	5
Dallas county	surface	.0292	.122	.095	14
	subsoil	.0368	.077	.099	13
Denton county	surface	.0276	.091	.080	47
	subsoil	.0356	.057	.054	47
Dickens county	surface	.0272	.019	.074	11
	subsoil	.1460	.058	.061	23
Eastland county	surface	.0132	.066	.042	11
	subsoil	.0176	.062	.049	11
Ellis county	surface	.0324	.155	.124	13
	subsoil	.0312	.137	.125	13
Freestone county	surface	.0148	.063	.044	28
	subsoil	.0160	.045	.044	37
Harris county	surface	.0128	.147	.026	13
	subsoil	.0196	.051	.036	19
Hays county	surface	.0324	.180	.101	6
	subsoil	.0276	.073	.163	3
Jefferson county	surface	.0668	.146	.046	23
	subsoil	.0496	.081	.061	25
Lee county	surface	.0192	.035	.032	5
	subsoil	.0116	.039	.029	3
Lubbock county	surface	.0200	.111	.072	18
	subsoil	.0192	.068	.061	18
Red River county	surface	.0188	.079	.063	23
	subsoil	.0168	.047	.066	17
San Saba county	surface	.0180	.090	.068	23
	subsoil	.0176	.075	.066	21
Smith county	surface	.0256	.049	.044	24
	subsoil	.0176	.039	.044	23
Washington county	surface	.0148	.082	.047	9
	subsoil	.0188	.089	.048	9

Table 10—Percentages of sulphur, nitrogen, and phosphoric acid in some soils of Harris County

Laboratory No.	Description	Sulphur (S)	Nitrogen	Total phosphoric acid
20037	Acadia clay	.0232	.109	.032
20038	Acadia clay subsoil	.0240	.169	.045
20021	Acadia clay loam	.0160	.054	.017
20022	Acadia clay loam subsoil	.0140	.035	.015
20023	Acadia clay loam subsoil	.0088	.023	.012
20027	Orangeburg fine sandy loam	.0052	.026	.023
20028	Orangeburg fine sandy loam subsoil	.0084	.021	.023
20029	Orangeburg fine sandy loam subsoil	.0088	.037	.031
20030	Orangeburg fine sandy loam subsoil	.0068	.035	.028
20031	Lake Charles fine sandy loam	.0116	.053	.015
20032	Lake Charles fine sandy loam subsoil	.0024	.028	.011
20033	Lake Charles fine sandy loam subsoil	.0140	.057	.019
2844	Moderate soil	.0068	.089	.030
2845	Subsoil to 2844	.0088	.041	.015
3409	Moderate upland	.0040	.147	.062
3410	Subsoil to 3409	.0020	.090	.045
20039	Norfolk fine sandy loam	.0164	.063	.023
20040	Norfolk fine sandy loam subsoil	.0092	.022	.011
1333	Sheldon rice soil	.0160	.100	.020
23123	Surface soil	.0092	.054	.028
23124	Subsoil to 23123	.0068	.038	.016
20017	Victoria clay	.0232	.119	.027
20018	Victoria clay subsoil	.0152	.059	.016
20019	Victoria clay subsoil	.0112	.045	.015
20020	Victoria clay subsoil	.0120	.039	.015

Table 10—Percentages of sulphur, nitrogen, and phosphoric acid in some soils of Harris County—Continued.

Laboratory No.	Description	Sulphur (S)	Nitrogen	Total phosphoric acid
20024	Victoria clay loam	.0176	.063	.018
20025	Victoria clay loam subsoil	.0092	.042	.011
20026	Victoria clay loam subsoil	.0036	.021	.012
20034	Fine sandy loam	.0084	.050	.018
20035	Fine sandy loam subsoil	.0060	.031	.012
20036	Fine sandy loam subsoil	.0188	.053	.020

Table 11.—Percentage of sulphur, nitrogen and phosphoric acid in some soils of Freestone County.

Laboratory No.	Description	Sulphur (S)	Nitrogen	Total phosphoric acid
15041	Norfolk fine sandy loam	.0092	.043	.074
15042	Subsoil to 15041	.0140	.034	.022
15037	Norfolk sand	.0076	.039	.041
15038	Subsoil to 15037	.0100	.019	.037
16110	Norfolk sand	.0072	.046	.019
16111	Subsoil to 16110	.0072	.021	.048
16083	Norfolk sandy loam	.0096	.024	.021
16084	Norfolk sandy loam	.0100	.032	.015
16112	Ochlockonee clay	.0268	.144	.101
16113	Subsoil to 16112	.0204	.105	.075
16119	Ochlockonee silty clay loam	.0340	.200	.106
16120	Subsoil to 16119	.0296	.144	.096
15035	Orangeburg fine sandy loam	.0132	....	.050
15036	Subsoil to 15035	.0104	.044	.030
16072	Ruston fine sandy loam	.0112	.037	.038
16073	Subsoil to 16072	.0136	.050	.038
3397	Bowie fine sandy loam, probably	.0240	.055	.072
3398	Subsoil to 3397	.0148	.041	.082
16064	Bowie fine sandy loam	.0136	.044	.024
16065	Subsoil to 16064	.0144	.027	.020
16077	Cahaba fine sandy loam	.0100	.025	.025
16078	Subsoil to 16077	.0124	.045	.027
16114	Cahaba sand (subsoil)	.0048	.019	.023
15024	Crockett fine sandy loam	.0164	.050	.040
15025	Subsoil to 15024	.0204	.058	.043
15026	Deep subsoil to 15024	.0300	.029	.041
15021	Crockett loam	.0260	.131	.057
15022	Subsoil to 15021	.0224	.048	.023
15023	Deep subsoil to 15021	.0300	.032	.037
16102	Houston clay loam	.0232	.133	.062
16104	Subsoil to 16102	.0156	.039	.044
16079	Kalmia fine sandy loam	.0076	.024	.021
16080	Subsoil to 16079	.0112	.034	.052
15027	Kirven gravelly fine sandy loam	.0124	.043	.040
15028	Subsoil to 15027	.0196	.069	.057
15033	Lufkin fine sandy loam	.0196	.083	.046
15034	Subsoil to 15033	.0168	.055	.061
15039	Norfolk fine sand	.0104	.015	.033
16081	Sumter clay	.0280	.114	.107
16069	Susquehanna clay loam	.0164	.036	.013
16070	Subsoil to 16069	.0176	.047	.050
3401	Susquehanna fine sandy loam	.0160	.049	.077
3402	Subsoil to 3401	.0040	.041	.090
16105	Susquehanna fine sandy loam	.0140	.049	.042
16106	Subsoil to 16105	.0112	.035	.024
16107	Deep subsoil to 16105	.0124	.034	.030
16117	Susquehanna fine sandy loam	.0120	.040	.020
16118	Subsoil to 16117	.0184	.033	.035
16085	Susquehanna gravelly fine sandy loam	.0128	.060	.018
15029	Tabor fine sandy loam	.0096	.029	.115
15030	Subsoil to 15029	.0168	.041	.093
16121	Tabor fine sandy loam	.0160	.091	.012
16122	Subsoil to 16121	.0156	.050	.026
15018	Wilson silt loam	.0268	.134	.059
15019	Subsoil to 15018	.0204	.082	.033
15020	Deep subsoil to 15018	.0180	.041	.040

Soils of Oregon (64) which respond to sulphur contained as much sulphur as some of those of Texas (Table 12). It is to be noted that the Oregon soils are high in phosphoric acid. The rainfall in Oregon where these soils occur contains only a few pounds of sulphur per acre per year. Percolation experiments on the soils, however, indicate that the soils are losing sulphur, in spite of the small amounts present.

Table 12.—Percentage of sulphur in Oregon soils which respond to applications of sulphur.

	Sulphur, per cent	Nitrogen, per cent	Phosphoric acid, per cent	Increase of alfalfa due to sulphur, pounds per acre
Salem fine sandy loam surface	.015	.081	.174	2080
Salem fine sandy loam subsoil	.030	.025	.181	
Antelope clay adobe surface	.020	.117	.147	4800
Antelope clay adobe subsoil	.027	.074	.151	
Phoenix clay adobe surface	.021	.117	.110	4004
Phoenix clay adobe subsoil	.020	.074	.165	
Salem clay loam surface	.027	.140	.114	1700
Salem clay loam subsoil	.024	.055	.165	
Barron coarse sand surface	.028	.052	.176	2166
Barron coarse sand subsoil	.015	.015	.204	
Tolo loam surface	.029	.148	.149	1532
Tolo loam subsoil	.013	.039	.140	
Medford sandy loam surface	.032	.107	.119	
Medford sandy loam subsoil	.016	.026	.142	
Willemette clay loam (did not respond)	.030	....	....	0

Sulphur as a Fertilizer

Sulphur, in the form of gypsum, which is sulphate of lime, was at one time used extensively on soils, usually in combination with manure, and especially for such legumes as clovers. It was used in France, England, and Germany during the last half of the eighteenth century and was introduced into the United States by Benjamin Franklin. The use of gypsum has now been almost discontinued. Knowledge of the nature of plant nutrition at that time was very slight. Definite information regarding the elements essential to plants, and knowledge regarding the deficiencies of the soil were later secured, beginning with the early part of the nineteenth century. Commercial fertilizers came into use for supplying the soil's known deficiencies in nitrogen, phosphoric acid, or potash. As gypsum alone did not supply any of the plant foods ordinarily deficient, the soil would become deficient in nitrogen, phosphoric acid, or potash; or a deficiency already existing would become more pronounced.

It is obvious that gypsum or sulphur cannot correct deficiencies of nitrogen, phosphoric acid, or potash. It should also be clear that sulphur is not needed as a plant nutrient in soils which contain an abundant supply of sulphur or to which sufficient amounts are provided by rain, irrigation water, or by fertilizers which incidentally carry sulphur.

There still remains the fact that under some special conditions sulphur may be needed as a plant nutrient or that sulphur or gypsum may exert a favorable effect upon the physical or chemical character of the soil. Joffe (42, p. 20) has summarized the results given in a number of investigations.

Sulphur or gypsum has given favorable results in some parts of Washington and Oregon. Experiments conducted at the Oregon Experiment Station for more than 10 years and discussed by Powers (64) show that 100 pounds of sulphur to the acre may give increases in yields for three to five years on the red hill soils of Western Oregon. Alfalfa, red clover, and alsike clover have given marked increases in yield on soils treated with sulphur or fertilizers containing sulphur. Moderate increases have been obtained with wheat and potatoes. Little increase has been secured on field peas, beans, corn, kale, rape, or sunflowers. From a study of the literature and inquiry of experiment stations, Powers (64) concludes that the basaltic region of the Pacific Northwest affords the greatest field for the profitable use of sulphur as a fertilizer. Soils receiving large quantities of irrigation waters containing sulphates, those high in organic matter, and those containing saline sulphates in the Great Basin regions, are plentifully supplied with sulphur. The soils in the eastern and southern states receive a fair supply of sulphur in fertilizer, manures, and in rain, especially in the sections where coal and oil are burned in large quantity as a fuel.

Shedd (72, 73), in pot experiments, found that sulphur alone decreased the yield of tobacco, but when added to a soil which received potassium nitrate, calcium phosphate, and calcium carbonate, sulphur produced a decided increase in yield over the pot which received the additions without the sulphur. Sulphur increased the yields of soy beans, turnips, and mustard but gave no increase in the yields of clover, cabbage, or radishes.

Recommendations by Experiment Stations Regarding the Use of Sulphur or Gypsum

The following information was secured chiefly by correspondence with the Experiment Stations in the states named. The use of sulphur or gypsum as a fertilizer is not recommended by the following states:

Alabama	Georgia	Louisiana
Arizona	Illinois	Maine
Arkansas	Indiana	Maryland
Colorado	Iowa	Massachusetts
Connecticut	Kansas	Michigan
Florida	Kentucky	Mississippi

Missouri	North Dakota	Utah
Nebraska	Ohio	Vermont
New Hampshire	Oklahoma	Virginia
New Jersey	Pennsylvania	Wisconsin
New Mexico	Rhode Island	Wyoming
New York	Tennessee	
North Carolina	Texas	

It is believed in many cases that commercial fertilizers are more generally needed than sulphur, and where they are used supply all the sulphur needed. The rain also brings down enough sulphur in some cases.

Arkansas and Nebraska tried sulphur at a number of points and secured no benefit. Kansas (79) found sulphur to decrease the production of alfalfa hay. Iowa (15) on some fields secured increases of alfalfa, clover, and oats with gypsum, while on other fields there were no increases. In some cases, the increase was small; in others, it was large enough to make the application profitable. They do not recommend the use of gypsum but suggest that farmers try it out on a small scale on alfalfa. The Georgia Station states that some farmers use gypsum on peanuts with apparently good results, but other farmers fail to get any benefit from it.

Gypsum is used for peanuts in Virginia with slight increases in yield, but it is believed that superphosphate would give the same result. Experiments in North Carolina with gypsum on peanuts gave only a slight increase in yield.

Idaho (52) recommends the use of 200 pounds of gypsum on legumes on all cut-over lands and on most of the farms in the northern part of the state. Sulphur gives good results but gypsum is more economical. On the arid soil (63) no marked effect was produced on alfalfa.

In Pennsylvania, gypsum was used in fertilizer experiments for over 40 years, and there was no apparent benefit from it as measured either by crop growth or reaction of the soil. A mixture of sulphur and rock phosphate gave some indication of beneficial action.

Illinois (77) found little need for sulphur. There was no benefit to roses and carnations in greenhouse work (Illinois, 84).

Montana recommends sulphur or gypsum for clover and alfalfa in the western part of the state. In some cases, yields are doubled and the feeding value of the hay increased.

A number of experiments in Indiana (12) gave no increases for additions of sulphur.

There was apparently no need for sulphur in Rhode Island (36) when sulphur had been omitted from the fertilizer on a number of plats for ten years.

Experiments in Oklahoma (61) for eight years gave no appreciable gain for gypsum on alfalfa, oats, cotton, corn, or cowpeas.

California recommends sulphur or gypsum chiefly in connection with the amelioration of alkali soils. In general, however, gypsum is used to counteract sodium carbonate in the soil. It is also used to promote permeability in soils where there is very little alkali, when the soil is not readily penetrated by water. It is employed as a soil amendment to increase the growth of alfalfa, partly with the idea that it releases potassium and partly as a means of supplying sulphur. Sulphur is recommended in spots where the soil contains insufficient sulphur for the growth of the plant and for neutralizing black alkali. It seems advantageous in this kind of difficulty to use sulphur first in order to neutralize a good deal of the alkalinity before any leaching is begun. If the alkalinity is first neutralized by an acid, such as is produced by sulphur when it is oxidized, the humus and some other valuable substances of the soil are not so likely to be washed away when leaching is begun.

Washington (78) states that sulphur or gypsum causes increase in yields of legumes in some places, but that in other places they are of doubtful benefit. For this reason, farmers are advised to try out sulphur or gypsum on a small scale before making extensive applications, at the rate of 200 pounds of gypsum or 50 pounds of sulphur per acre, in the spring. It is pointed out that the increased yield will increase the draft on the other plant food and require the applications of other fertilizer elements in the near future.

Oregon states that good results are secured from gypsum at the rate of 200 pounds per acre on soils low in sulphur, as is the case with some soils in Southern and Central Oregon. The continued use of gypsum on light sandy soils that are not fertile will generally result in rapid depletion of the soil in other forms of plant food, such as phosphoric acid or potash.

According to Russel (69) sulphur has not proved especially effective to crops in England.

In Massachusetts (37) (60) no indication of shortage of sulphur was observed after 30 years of cultivation and the use of fertilizers containing little or no sulphur.

In Utah (33), sulphur is not at present a limiting factor but may be in time.

Pot and field experiments on Maryland soils with various crops are reported by McKibbin (56). Sulphur alone gave increased yields with buckwheat, corn (2 in 3 tests), cotton, soy beans (2 in 4 tests), sweet clover, and tomatoes (1 in 3 tests); decreases or no increase with alfalfa, corn, lettuce, peas, sweet potatoes, Irish potatoes, soy beans (2 in 4 tests), tomatoes (2 in

3 tests). Sulphur added to raw rock phosphate gave increase in 12 of 17 cases. Sulphur added to superphosphate gave decreases in 13 out of 19 cases. Inoculated sulphur gave about the same results as non-inoculated sulphur. McKibbin attributes the increased yields to the beneficial effect of increased acidity upon the soil solution or upon the crop grown, rather than to an increase in water-soluble sulphates, of which there seemed to be a supply already in the soil adequate to the growth of any crop. He concludes that light application of elemental sulphur, less than 100 pounds, on specific crops, may give increased yields in many cases, but it should not be applied mixed with superphosphate.

Reynolds, at the Texas Station (65), reports on extensive field experiments with sulphur. "The use of sulphur in amounts ranging from 50 to 10,000 pounds per acre on soils at Temple, Angleton, Beeville, College Station, Nacogdoches, and Troup, Texas, did not produce significant or profitable increases in the yield of cotton, corn, cowpeas, or oats. The work was conducted over a period of six years at Temple, four years at Angleton and Troup, three years at Nacogdoches, and two years at Beeville and College Station. The results indicate that the soils on which the experiments were conducted are not deficient in sulphur and consequently the use of sulphur alone as a fertilizer would not be profitable in farm practice. Sulphur applied at rates ranging from 50 to 10,000 pounds per acre each year to the dark calcareous soil at Temple did not bring about an acid condition in the soil during the six years of the experiment. The rate of application of sulphur apparently had no appreciable effect on the development or control of root-rot disease of cotton on this soil, indicating that sulphur should be of little practical value in controlling the disease on highly calcareous soils, such as the black waxy soils in the Blackland region of Central Texas."

Pot Experiments with Sulphur

Pot experiments have been made with sulphur or gypsum by investigators in various states. Some workers have reported marked increases in yield of crops, especially on certain Washington and Oregon soils, while others have had very poor results. Lomanitz (49) found little benefit from sulphur on Texas soils.

Texas Experiments. Pot experiments were made to test the action of sulphur alone or in combination with other materials upon growing plants. A variety of soils was used. In the check experiments, made in the absence of sulphur, the materials used were analyzed to see that no appreciable amounts of sulphur were contained in them, and the plants were watered with distilled water because the cistern water usually used was found to contain some sulphur. The experiments were conducted in 8-inch galvanized iron pots, with 5 kilograms of soil in a greenhouse, as has been previously described (27).

Sulphur Alone in Pot Experiments. The use of sulphur alone, as such or in gypsum, was tried in some pot experiments, for the purpose of ascertaining whether such applications would give responses similar to those given by the usual plant foods, nitrogen, phosphoric acid, and potash.

Table 13 contains the results of some pot experiments made in 1924, with corn, sorghum, cotton, and alfalfa, in which sulphur alone is compared with ammonium nitrate and potassium sulphate (NK) or with ammonium nitrate, dicalcium phosphate, and potassium sulphate (NPK). The complete fertilizer in practically all cases gave higher yields than the incomplete fertilizer, or the application of sulphur alone. The application of sulphur usually gave lower yields than the fertilizer containing nitrogen and potash, but no phosphoric acid or sulphur. The results with sulphur are especially low, as compared with the regular fertilizer on the Norfolk fine sand, on the Norfolk sandy loam, and on the Orangeburg sandy loam, which represent soils on which commercial fertilizers are extensively used in East Texas. The growth of crops on soil treated with the sulphur averaged about 40 per cent of that with the complete fertilizer and 60 per cent of that with the nitrogen and potash.

Table 14 contains the results of pot experiments conducted in 1925, in which sulphur was compared with nitrogen and potash and with a complete fertilizer. The results are similar to those presented in Table 13. The soil treated with sulphur produced about 35 per cent as much as the soil treated with a complete fertilizer and 60 per cent as much as the soil treated with nitrogen and potash.

Table 15 contains the results of an experiment somewhat different from the preceding. The application of sulphur is here compared with untreated soil and with a complete fertilizer. The sulphur gave practically the same results as no fertilizer and averaged about 43 per cent of that with a complete fertilizer.

Sulphur alone had little or no effect on the yields of crops grown in the pot experiments just discussed, while fertilizers containing nitrogen, phosphoric acid, and potash gave very decided increases in yield of crops on many of the soils. Sulphur alone, therefore, cannot be expected to give results on these soils, or to take the place of the ordinary commercial fertilizers.

Table 13.—Crops grown in pot experiments with nitrogen and potash with and without sulphur.

No.		Crop	Weight of crop in grams				Grams P_2O_5	
			Sulphur added	NK added	NKP added	Per cent S in soil	Average with sulphur	Average KN
9690	Surface soil, Wise Co., 0″–8″	Corn	12.2	13.2	24.6	....	.0549	.0589
9690	Surface soil, Wise Co., 0″–8″	Sorghum	28.7	31.5	34.5	.037	.0718	.0897
20197	Abilene silty clay loam, Coleman Co., 8″–30″	Corn	11.7	9.9	19.7	....	.0304	.0263
20197	Abilene silty clay loam, Coleman Co., 8″–30″	Sorghum	8.2	21.7	27.1	.024	.0287	.0499
20198	Abilene silty clay loam, Coleman Co., 30″–36″	Corn	5.0	5.4	8.2	....	.0140	.0135
20198	Abilene silty clay loam, Coleman Co., 30″–36″	Sorghum	7.0	10.0	22.0	.021	.0168	.0200
21779	Victoria clay loam, 0″–18″	Corn	46.6	46.6	49.0	....	.2200	.2132
21779	Victoria clay loam, 0″–18″	Sorghum	27.1	29.2	35.5	.033	.1458	.1606
21781	Harlingen clay, Cameron Co., 0″–8″	Corn	20.2	28.0	30.4	....	.0727	.0949
21781	Harlingen clay, Cameron Co., 0″–8″	Sorghum	11.5	28.4	26.5	.031	.0633	.0738
21783	Norfolk fine sand, Henderson Co., 0″–10″	Corn	7.5	39.0	41.8	....	.0413	.1040
21783	Norfolk fine sand, Henderson Co., 0″–10″	Sorghum	4.8	19.4	23.5	.009	.0341	.0908
21784	Norfolk fine sand, Henderson Co., 10″–36″	Corn	3.0	27.9	44.8	....	.0216	.0763
21784	Norfolk fine sand, Henderson Co., 10″–36″	Sorghum	0.5	8.9	6.8	.006	.0051	.0433
21785	Norfolk fine sandy loam, Henderson Co., 0″–18″	Corn	4.9	9.3	33.0	....	.0125	.0194
21785	Norfolk fine sandy loam, Henderson Co., 0″–18″	Sorghum	3.1	7.8	10.1	.006	.0141	.0198
21785	Norfolk fine sandy loam, Henderson Co., 0″–18″	Cotton	4.6	11.2	27.9	....	.0198	.0273
21786	Norfolk fine sandy loam, Henderson Co., 18″–36″	Corn	4.7	2.9	27.5	....	....	.0047
21786	Norfolk fine sandy loam, Willacy	Sorghum	2.5	4.1	21.0	.016	.0078	.0078
22121	Orangeburg sandy loam, Nacogdoches	Corn	10.5	13.8	30.0	....	.0263	.0372
22121	Orangeburg sandy loam, Nacogdoches	Sorghum	4.7	24.1	17.7	.010	.0212	.0578
22121	Orangeburg sandy loam, Nacogdoches	Cotton	12.6	24.3	31.5	....	.0441	.0658
22122	Subsoil to 22121, Nacogdoches	Corn	4.4	3.8	24.2	....	.0092	.0077
22122	Subsoil to 22121, Nacogdoches	Sorghum	4.0	5.0	15.5	.021	....	.0110
22141	Surface soil, Pecos	Alfalfa	14.0	15.3	18.3	.041	.0427	.0466
22142	Subsoil to 22141, Pecos	Alfalfa	7.0	7.6	14.0	.047	.0210	.0190
	Average	....	10.4	17.2	25.7	....	.0433	.0554

Table 14.—Weight, in grams, of crops grown with sulphur alone compared with crops grown with fertilizer.

No.		Crop	Sulphur	Nitrogen and potash	Nitrogen phosphoric acid and potash	Percentage sulphur (S) in soil
22225	Derby loamy very fine sand, Wichita Co., 7″–19″	Corn	10.0	12.8	44.4	.009
22225	Derby loamy very fine sand, Wichita Co., 7″–19″	Kafir	4.3	16.9	35.3	
22225	Derby loamy very fine sand, Wichita Co., 7″–19″	Cotton	8.5	18.8	36.0	
22226	Vernon very fine sandy loam, Wichita Co., 0″–7″	Corn	17.7	30.7	48.1	.013
22226	Vernon very fine sandy loam, Wichita Co., 0″–7″	Kafir	10.2	27.7	39.0	
22230	Kirkland clay loam, Wichita Co., 0″–7″	Corn	25.3	27.2	45.1	.019
22230	Kirkland clay loam, Wichita Co., 0″–7″	Kafir	13.0	25.4	29.7	
22232	Yahola very fine sandy loam, Wichita Co., 0″–7″	Corn	17.7	30.4	27.7	.023
22232	Yahola very fine sandy loam, Wichita Co., 0″–7″	Kafir	15.0	13.9	9.0	
22234	Miller silty clay loam, Wichita Co., 0″–7″	Corn	17.6	24.1	33.1	.027
22234	Miller silty clay loam, Wichita Co., 0″–7″	Kafir	10.2	21.9	30.8	
22236	Calumet very fine sandy loam, Wichita Co., 0″–7″	Corn	18.8	30.6	39.0	.019
22236	Calumet very fine sandy loam, Wichita Co., 0″–7″	Kafir	7.2	20.3	43.2	
22236	Calumet very fine sandy loam, Wichita Co., 0″–7″	Cotton	9.5	28.4	27.9	
22237	Calumet very fine sandy loam, Wichita Co., 7″–19″	Corn	10.0	8.7	34.0	.080
22237	Calumet very fine sandy loam, Wichita Co., 7″–19″	Kafir	4.0	13.5	43.2	
22238	Kirkland very fine sandy loam, Wichita Co., 0″–7″	Corn	18.9	30.1	43.9	.009
22238	Kirkland very fine sandy loam, Wichita Co., 0″–7″	Kafir	15.4	25.6	45.2	
22239	Kirkland very fine sandy loam, Wichita Co., 7″–19″	Cotton	12.5	13.2	25.2	.026
22904	Surface soil, Jasper Co	Corn	14.0	16.5	37.3	.011
22904	Surface soil, Jasper Co	Kafir	5.5	16.8	36.6	....
	Average	....	12.6	21.6	35.9	
23971	Houston black clay, Milam Co., 7″–19″	Corn	31.2	48.1	....	.025
23971	Houston black clay, Milam Co., 7″–19″	Kafir	5.7	5.1	....	....

Table 15.—Crops, in grams, grown in pot experiments with sulphur compared with no additions and with complete fertilizer.

No.		Sulphur added	No additions	Nitrogen phosphoric acid and potash	Crop grown	Percentage sulphur (S) in soil
23125	Surface soil, Harris	5.5	6.3	23.4	Corn	.010
23972	Trinity clay, Milam, 0″–7″	25.8	24.7	32.0	Corn	.025
23972	Trinity clay, Milam, 0″–7″	3.3	2.6	5.7	Kafir	....
23206	Hidalgo fine sandy loam, Hidalgo, 0″–7″	11.0	12.8	30.9	Corn	.015
23206	Hidalgo fine sandy loam, Hidalgo, 0″–7″	3.9	4.7	20.2	Kafir	....
23323	Harlingen clay, surface, Hidalgo	31.0	32.9	53.2	Corn	.035
23323	Harlingen clay, surface, Hidalgo	2.6	2.7	21.9	Kafir	....
23971	Houston black clay, gravelly phase, Hidalgo, 0″–7″	13.7	12.0	10.0	Kafir	....
23123	Surface soil, loin disease pasture, Harris	13.5	13.2	29.5	Corn	.009
23246	Brennan fine sandy loam, Hidalgo, 7″–19″	10.9	9.3	66.3	Corn	.010
23246	Brennan fine sandy loam, Hidalgo, 7″–19″	3.1	2.5	14.2	Kafir	....
23960	Bell clay, Milam, 0″–7″	14.5	13.5	15.4	Corn	.014
23960	Bell clay, Milam, 0″–7″	2.5	2.7	31.0	Kafir	....
	Average corn	16.0	16.1	35.8	....	....
	Average kafir	4.9	4.5	17.2	....	....

Sulphur in Combination with Nitrogen, Phosphoric Acid, and Potash. The previous experiments showed that while the soils tested gave practically no response to sulphur alone, they responded to the usual fertilizer materials. This response involves a greater draft on the sulphur of the soil. The question arises whether this increased growth may not bring about a greater demand for sulphur than the soil could supply, thereby causing a response to applications of sulphur.

Pot experiments were made in which the effect of sulphur in combination with nitrogen, phosphoric acid, or potash, was compared with the same materials without sulphur. Table 16 contains the results of experiments with cotton made in 1925 and 1926. They are usually averages of two pots. The differences are in the limit of error, except with a Norfolk subsoil of Cass county, a sample of Norfolk fine sandy loam of Nacogdoches county, and Milam fine sandy loam of Milam county. Two of these soils were very low in sulphur.

Table 17 contains the results of experiments in which a fertilizer containing nitrogen, phosphoric acid, and potash, free from sulphur, was compared with the same fertilizers plus calcium sulphate. There are indications that sulphur was effective, to some extent, with Crockett fine sandy loam (subsoil) 23955, of Milam county, Norfolk fine sandy soil 23963 of Milam county, Ruston fine sandy loam 24009 of Nacogdoches county, Nueces fine sand, shallow phase, of Willacy County, both surface and subsoil 25783-4, and Irving clay 25959 of Navarro county.

Table 18 contains another set of experiments conducted in 1926. The sulphur had no effect on the yield of cotton although it increased the percentage of sulphur and total amount of sulphur in the crop.

These experiments indicate that when a complete fertilizer free of sulphur is used on some sandy soils low in sulphur, and the crops are watered with distilled water free from sulphur, there will be a response to sulphur fertilization in some cases. Under natural conditions, the rain contains sulphur, and the fertilizer usually contains it. Fertilizers containing little or no sulphur are now coming on the market. It seems probable that crops which require large amounts of sulphur and which receive fertilizers low in sulphur, and are grown on soils low in sulphur and not irrigated, may need fertilization with sulphur. This possibility needs to be further investigated in connection with the use of the new concentrated commercial fertilizers some of which may contain little sulphur. Sulphur may be needed after such fertilizers are used for a few years on non-irrigated land, especially for such crops as cotton, cabbage, turnips, and onions.

Table 16.—Average weight of cotton in grams, with and without sulphur, 1925 and 1926.

No.	Soil type, depth, county	PK	SPK	NK	SNK	NP	SNP	NPK	SNPK	Per cent S in soil
22223	Wichita very fine sandy loam, 7″–19″, Wichita	15.9	17.6	14.4	14.0	....	....	26.5	28.0	.015
22227	Vernon very fine sandy loam, 7″–19″, Wichita	14.2	13.7	12.0	13.8	....	....	29.4	30.8	.016
22822	Surface soil, Franklin	....	....	23.0	20.5	....	....	30.9	32.0	.074
22911	Soil, Smith	11.6	11.2	21.8	20.0	....	....	27.7	29.7	.017
22918	Yellow subsoil, probably Norfolk, Cass	....	....	....	....	....	....	20.7	35.2	.006
22962	Surface soil, Rusk	....	....	....	....	....	....	35.0	34.2	.010
22963	Subsoil to 22962, Rusk	....	....	....	....	....	....	34.0	35.4	.008
23245	Brennan fine sandy loam, 0″–7″, Hidalgo	11.6	10.0	21.6	24.7	25.3	24.0	19.1	18.8	.010
23361	Duval fine sandy loam, 0″–7″, Hidalgo	11.2	9.0	13.9	14.2	19.2	17.1	18.9	19.7	.010
23362	Duval fine sandy loam, 7″–19″, Hidalgo	10.4	8.6	8.6	10.4	24.2	22.2	21.9	19.6	.010
23551	Norfolk fine sandy loam, 0″-7″, Nacogdoches	....	....	10.4	14.0	....	....	19.6	25.4	.012
23948	Gause fine sandy loam, 0″–7″, Milam	11.3	12.3	15.0	19.7	....	....	22.6	20.0	.005
23959	Wilson clay loam, 7″–19″, Milam	11.3	14.0	14.8	15.5	....	....	23.8	22.5	.020
23966	Milam fine sandy loam, 0″–7″, Milam	9.4	7.9	13.6	13.5	....	....	18.0	25.7	.012
23967	Milam fine sandy loam, 7″–19″, Milam	8.2	7.9	7.5	8.0	....	....	17.7	14.2	.010
24004	Ochlockonee fine sandy loam, 7″–19, Nacogdoches	14.4	13.6	9.2	12.6	....	....	16.2	24.8	.012
23960	Bell clay, 0″–7″, Milam	....	....	16.5	16.0	....	....	15.4	....	.014
22222	Wichita fine sandy loam, 0″–7″, Wichita	....	....	31.4	33.4	....	....	....	....	.016
22224	Derby loamy very fine sand, 0″–7″, Wichita	....	....	26.2	31.4	....	....	....	....	.011
23960	Bell clay, 0″–7″, Milam	9.9	9.4	26.1	25.7	....	....	....	....	.014

Table 17.—Crops grown in pot experiments with complete fertilizer with and without sulphur.

No.	Soil type, depth, county	Crop	Weight of crop		Per cent sulphur (S) in soil
			NPK	NPKS	
23954	Crockett fine sandy loam, 0″–7″, Milam	Corn	2.5	1.6	.011
23954	Crockett fine sandy loam, 0″–7″, Milam	Kafir	15.8	7.9	
23955	Crockett fine sandy loam, 7″–19″, Milam	Corn	24.3	34.2	.012
23955	Crockett fine sandy loam, 7″–19″, Milam	Kafir	34.4	31.7	
23962	Norfolk fine sand, 0″–7″, Milam	Corn	24.7	32.3	.007
23962	Norfolk fine sand, 0″–7″, Milam	Kafir	19.1	29.3	
23962	Norfolk fine sand, 0″–7″, Milam	Cotton	23.5	7.5	
23963	Norfolk fine sand, 7″–19″, Milam	Corn	15.7	29.5	.005
23963	Norfolk fine sand, 7″–19″, Milam	Kafir	21.3	2.4	
23964	Kirvin fine sandy loam, 0″–7″, Milam	Corn	40.0	36.0	.016
23964	Kirvin fine sandy loam, 0″–7″, Milam	Kafir	38.5	38.2	
23965	Kirvin fine sandy loam, 7″–19″, Milam	Corn	12.6	19.6	.014
23965	Kirvin fine sandy loam, 7″–19″, Milam	Kafir	32.7	30.2	
24005	Kirvin clay loam, 0″–7″, Nacogdoches	Kafir	36.3	31.1	
24007	Kirvin fine sandy loam, 0″–7″, Nacogdoches	Corn	24.8	18.5	.014
24007	Kirvin fine sandy loam, 0″–7″, Nacogdoches	Kafir	22.9	34.6	
24009	Ruston fine sandy loam, 0″–7″, Nacogdoches	Corn	30.5	36.5	.006
24009	Ruston fine sandy loam, 0″–7″, Nacogdoches	Kafir	13.4	31.5	
24011	Susquehanna fine sandy loam, 0″–7″, Nacogdoches	Corn	35.5	40.5	.014
24011	Susquehanna fine sandy loam, 0″–7″, Nacogdoches	Kafir	31.2	36.7	
25783	Nueces fine sand (shallow phase) 0″–7″, Willacy	Corn	32.0	33.7	.010
25783	Nueces fine sand (shallow phase) 0″–7″, Willacy	Kafir	19.2	34.2	
25783	Nueces fine sand (shallow phase) 0″–7″, Willacy	Cotton	20.5	26.0	
25784	Nueces fine sand (shallow phase) 7″–19″, Willacy	Corn	30.2	40.5	.009
25784	Nueces fine sand (shallow phase) 7″–19″, Willacy	Kafir	28.8	33.5	
25784	Nueces fine sand (shallow phase) 7″–19″, Willacy	Cotton	26.5	24.0	
25785	Willacy fine sandy loam, 0″–7″, Willacy	Corn	36.8	40.6	.014
25785	Willacy fine sandy loam, 0″–7″, Willacy	Kafir	44.6	45.7	
25959	Irving clay, 0″–7″, Navarro	Corn	31.2	36.3	.012
25959	Irving clay, 0″–7″, Navarro	Kafir	25.3	41.9	
25969	Crockett fine sandy loam, 0″–7″, Navarro	Corn	44.1	41.1	.010
25969	Crockett fine sandy loam, 0″–7″, Navarro	Kafir	28.7	21.1	

Table 18.—Effect of sulphur in addition to nitrogen, phosphoric acid and potash, on cotton.

No.	Soil	Weight of crops in grams		Per cent sulphur (S) in crops		Grams sulphur (S) in crops		Per cent sulphur (S) in soil
		NPK	NPKS	NPK	NPKS	NPK	NPKS	
23205	Brown fine sandy loam, 0″–7″, Hidalgo	23.2	23.5	.236	.568	.0550	.1335	.020
23321	Victoria fine sandy loam, surface, Hidalgo	24.8	23.5	.392	.676	.0976	.1576	.019
23322	Victoria fine sandy loam, 7″–19″, Hidalgo	24.4	25.1	.284	.576	.0700	.1428	.016
23549	Norfolk fine sand No. 1, 0″–7″, Nacogdoches	14.7	10.0	.168	.896	.0247	.0896	.006
23550	Norfolk fine sand No. 2, 7″–19″, Nacogdoches	10.2	7.7	.220	1.268	.0224	.0983	.006
23552	Norfolk fine sandy loam No. 4, 7″–19″, Nacogdoches	17.7	19.8	.276	.540	.0488	.1069	.007
24008	Kirvin fine sandy loam, 7″–19″, Nacogdoches	16.0	15.3	.472	.864	.0751	.1317	.014
24010	Ruston fine sandy loam, 7″–19″, Nacogdoches	18.5	13.0	.348	.824	.0644	.1071	.010
24012	Susquehanna fine sandy loam, 0″–7″, Nacogdoches	5.2	7.4	.268	.516	.0139	.0382	.014

Effect of Sulphur on the Composition of Crops

It has been shown by several workers that sulphur may affect the composition of crops. Hart and Tottingham (54) reported that applications of sulphur increased the sulphur content of clover, rape, and other crops. Miller (58) found that sulphur increased the sulphur and nitrogen content of clover plants. Neidig and others in Idaho (63) found that sulphur and certain of its compounds produced an increase in the percentage of sulphur and nitrogen in alfalfa. Neller, in Washington (62), reported that sulphur in pot and field experiments increased the percentage of sulphur and nitrogen of alfalfa, while it apparently decreased the percentage of lime. The results were much less pronounced in field experiments than in pot tests. Shedd in Kentucky (74) found a larger percentage of sulphur in soybean plants grown on soils to which sulphur was added in pot experiments than on untreated soil; this did not hold for nitrogen.

Texas Experiments. Chemical analyses of the crops grown in the pot experiments with and without sulphur showed that the addition of sulphur made a decided increase in the percentage of sulphur. Some illustrations are given in Table 19. It would seem that sulphur, like potash, and, to a less extent, like nitrogen, can be taken up by the plant in excess. This also occurs in field experiments, as is shown in the analyses of field crops also given in Table 19. Sulphur did not favorably influence the yields, though some of it was taken up by the crop.

Table 19.—Effect of sulphur on the percentage of sulphur in crops.

No.		No sulphur	Sulphur added
22223	Cotton, pot experiment	.332	.784
22227	Cotton, pot experiment	.336	.676
22911	Cotton, pot experiment	.248	.792
22918	Cotton, pot experiment	.236	.724
22962	Cotton, pot experiment	.216	.808
22222	Cotton, pot experiment	.520	1.012
	Cotton leaves, Temple, 500 pounds sulphur per acre	1.336	1.992
	Cotton leaves, College, 200 pounds sulphur per acre	.964	.956
	Cotton leaves, Beeville, 200 pounds sulphur per acre	.952	1.172
	Cotton stems, Beeville	.148	.212
	Cotton stems, Temple	.300	.396
	Cotton stems, College	.228	.220
	Pepper plants, field grown	.432	.460
	Pepper plants, field grown	.512	.552

More nearly complete analyses were made of certain crops grown in the pot experiments with and without sulphur, for the purpose of seeing what effect the high percentages of sulphur had upon the other ingredients. The average results are presented in Table 20. The crop with high sulphur averaged 0.82 per cent total sulphur (S), of which 0.70 per cent was water-soluble and precipitated directly with barium sulphate. The low-sulphur plants also contained water-soluble sulphates, but much smaller amounts. The excess sulphur was almost entirely in the form of sulphates. The high sulphur content was accompanied by a higher ash, which was chiefly accounted for by the sulphates. The phosphoric acid, the potash, and the insoluble ash also averaged higher in the high-sulphur plants, while the nitrogen and lime were lower. The increase in bases did not correspond to the increase in sulphur; consequently, the high-sulphur plants had a more acid ash. Plants can apparently take up sulphur compounds readily when accessible. It is possible that high sulphur may be of advantage to tobacco or perhaps other plants under special conditions.

Table 20.—Average composition of cotton plants grown in pot experiments with and without sulphur.

	No sulphur per cent	Sulphur added per cent
Total sulphur (S)	.24	.82
Water-soluble sulphur (S)	.14	.70
Ash	9.26	11.31
Phosphoric acid	.66	.72
Potash	2.92	3.50
Nitrogen	1.30	1.18
Lime	2.34	2.12
Magnesia	.63	.63
Insoluble ash	1.10	1.32
Ash not shown in analysis	1.01	.98
Number averaged	8	8

Effect of Sulphur on Plant Food in the Soils

Erdman (14) found that gypsum in some soils made both phosphoric acid and potash of the soil slightly more soluble in water, but little or no effect was observed on other soils. Gypsum at the rate of 200 pounds per acre was beneficial to clover and alfalfa in some cases. Other workers have reported on this subject (2, 5, 67, 74).

Cubben (13) and Erdman (14) both pointed out that contrasting results were secured by some workers on the effect of calcium sulphate on the potash dissolved from the soil. While appreciable amounts were dissolved in some cases, in other cases the calcium sulphate did not increase the amount of potash brought into solution in water. Cubben did not secure a marked liberation of potash.

While sulphate of lime or other salts may increase the amounts of potash dissolved by water from some soils, it does not necessarily follow that plants will take more potash from such soils. It is quite possible that the active potash may enter the plants as readily from a soil low in water-soluble potash as from a soil containing larger amounts. A series of pot experiments was conducted at the Texas Experiment Station (26) using, among other additions, 400, 500, 1000, or 10,000 parts per million of gypsum in addition to fertilizer. There was no gain in dry matter of the crop caused by gypsum on any of the ten soils used. The gypsum was injurious in some cases. There was a slight gain in the potash taken up on two of the ten soils; this difference is within the limit of error. There was thus no evidence that the addition of gypsum increased the availability of the potash of the soil or caused plants to take up larger quantities of potash.

Effect of Sulphur on the Nitrogen, Phosphoric Acid and Potash Taken Up by Crops

Some workers have found that applications of sulphur increased the quantity of plant food taken up by some crops.

If sulphur causes an increase in the size of a crop on a soil deficient in sulphur but containing good supplies of nitrogen, phosphoric acid, or potash, the increased crop will necessarily take up a larger quantity of these plant foods, though not necessarily a larger percentage. Such an increase does not mean that the sulphur rendered any of the plant food available. The deficiency of sulphur limited the ability of the crop to use the other materials, already in forms suitable for plant use. While the use of sulphur on a soil deficient in sulphur may have increased the amount of other plant foods taken up, it does not necessarily follow that it changes or increases the assimilability of these plants foods in the soil.

Analyses were made of some of the plants grown in the pot experiments already discussed, for the purpose of seeing whether or not the addition of sulphur had any effect upon the amount of the particular plant food taken from the soil by the crop. The analysis was made for the particular material not added. Thus if nitrogen and potash were used, with and without sulphur, analysis was made of the crop for phosphoric acid, to see if the addition of the sulphur aided the plant to secure additional supplies of phosphoric acid from the soil.

Effect on nitrogen. Table 21 shows the effect of sulphur upon the percentage of nitrogen and weight of nitrogen in some crops grown on soils receiving phosphoric acid and potash but no nitrogen. It is seen that the addition of sulphur did not increase the amount of nitrogen taken up, and consequently the availability of nitrogen, except possibly on one soil; but even this is doubtful. Most of these soils are low in nitrogen, so that the sulphur had opportunity to be effective.

Table 21.—Grams of nitrogen removed by cotton grown in pot experiments (in 1926) with and without sulphur.

No.	Soil	PK added	PKS added	Per cent sulphur (S) in soil
23245	Brennan fine sandy loam, 0″–7″, Hidalgo	.0724	.0677	.010
23361	Duval fine sandy loam, 0″–7″, Hidalgo	.0991	.1128	.010
23362	Duval fine sandy loam, 7″–19″, Hidalgo	.0770	.0686	.010
23948	Gause fine sandy loam, 0″–7″, Milam	.0947	.0959	.005
23959	Wilson clay loam, 7″–19″, Milam	.1379	.1120	.020
23966	Milam fine sandy loam, 0″–7″, Milam	.0733	.0482	.012
23967	Milam fine sandy loam, 7″–19″, Milam	.0525	.0632	.010
24004	Ochlockonee fine sandy loam, 7″–19″, Milam	.1051	.1020	.012

Effect on phosphoric acid. Tables 13 and 22 show the effect of sulphur on phosphoric acid on soils receiving potash and nitrogen but no phosphoric acid. There seems to be some tendency of the sulphur to increase the amount of phosphoric acid taken up.

Table 13 contains some experiments with corn and kafir, recording similar results.

Table 22.—Grams of phosphoric acid removed by cotton grown in pot experiments in 1926 with and without sulphur.

No.	Soil	Average KN	Average KNS	Per cent sulphur in soil
23245	Brennan fine sandy loam, 0″–7″, Hidalgo	.0839	.0951	.010
23361	Duval fine sandy loam, 0″–7″, Hidalgo	.0241	.0252	.010
23362	Duval fine sandy loam, 7″–19″, Hidalgo	.0199	.0275	.010
23551	Norfolk fine sandy loam, 0″–7″, Nacogdoches	.0260	.0361	.012
23948	Gause fine sandy loam, 0″–7″, Milam	.0435	.0466	.005
23959	Wilson clay loam, 7″–19″, Milam	.0397	.0405	.020
23966	Milam fine sandy loam, 0″–7″, Milam	.0460	.0360	.012
23967	Milam fine sandy loam, 7″–19″, Milam	.0129	.0155	.010
24004	Ochlockonee fine sandy loam, 7″–19, Nacogdoches	.0257	.0396	.012
23960	Bell clay, 0″–7″, Milam	.0970	.0906	.014
	Average	.0419	.0453	....

Effect on potash. Table 23 contains a few experiments on the effect of sulphur on the removal of potash from soils receiving nitrogen and phosphoric acid but no potash. The results are not adequate to draw definite conclusions but there seems to be little or no effect of sulphur on the amount of potash taken up by crops.

Table 23.—Grams of potash removed by cotton in pot experiments in 1926 with and without sulphur

No.		Average NP	Average NPS	Per cent sulphur in soil
23245	Brennan fine sandy loam, 0″–7″, Hidalgo	.6899	.6216	.024
23361	Duval fine sandy loam, 0″–7″, Hidalgo	.4318	.4364	.026
23362	Duval fine sandy loam, 7″–19″, Hidalgo	.4242	.4117	.025

Reciprocal Relation of Sulphur to Nitrogen and Sulphur to Phosphoric Acid

It has been shown by Mitscherlich (59) and others, that the growth of plants is influenced by other conditions in addition to the one supposed to be at a minimum. Thus, if both nitrogen and phosphoric acid in varying amounts are added to a soil deficient in these elements, the response in crop growth to increased amounts of nitrogen will increase as the quantity of phosphoric acid increases, as long as both are below the optimum. That is to say, with a given increment of nitrogen, the increase in plant growth will depend upon the amount of phosphoric acid added, and will be different for additions of different quantities of phosphoric acid. Thus neither nitrogen nor phosphoric acid is an absolute limiting factor, but the response to the one will depend to a certain extent on the supply of the other, and the soil will respond to either, applied separately. The fact has been known for a long time in connection with field experiments, and accounts for the fact that additions of either superphosphate or nitrogenous fertilizer alone may result in increased yields.

Experimental work. Two series of experiments were made to ascertain the relation of sulphur to nitrogen and to phosphoric acid, not only in plant growth but in the percentages and quantities taken up.

Sulphur and nitrogen. Three pots of sand were used for each application. The pots contained 5,000 grams of sand, and each received 1 gram of potassium phosphate, 1 gram of potassium chloride, and 1 gram of calcium carbonate. Ammonium nitrate containing 0.3 gram of nitrogen was the basal nitrogen application, and 0.2 gram of sulphate of lime the basal sulphur application. Large quantities of nitrogen and sulphur were applied to several sets of pots. Each application was made on three pots. Cotton was the crop grown.

The results are given in Table 24, each being the average of three pots. The nitrogen added is shown in the lines at the head of the table, while the sulphate of lime added is shown in the column so designated. Thus the pots receiving 0.6 gram of nitrogen also received 0, 0.2, 0.4, 0.8, or 2.0 grams of sulphate of lime, respectively. The results are irregular but the fact that each addition influenced the other is indicated by the weights of the crops secured, and the weights of sulphur and nitrogen removed from the soil. That the weight of the crop increased as the sulphur increased is brought out more clearly in the pots receiving 0.6 gram of nitrogen, while the increase in the weight of the crop when the nitrogen is increased is brought out, somewhat irregularly, with 0.2 gram of calcium sulphate. There is a slight tendency for the percentage of sulphur in the crops and the weight of sulphur taken up to increase with the increased applications of nitrogen. There is a tendency for percentages of nitrogen and grams of nitrogen to increase as the applications of sulphur are increased. The irregularities in the results, probably caused by the fact that the sand used was not very good for pot experiments, obscure these relations.

Table 24.—Effect of varying quantities of sulphur and nitrogen on cotton in pot experiments.

Soil 22194	Sulphate of lime, grams	Nitrogen added, grams			
		0	0.3N	0.6N	1.2N
Average weight of crops, grams	0	5.8	7.5	9.5	4.7
	0.2	5.1	8.9	5.6	13.0
	0.4	....	8.5	7.9	5.9
	0.8	....	7.6	12.4	4.0
	2.0	....	....	10.9	6.7
Average per cent SO_3 in crop	0	1.34	1.05	.80	1.39
	0.2	1.06	.86	1.48	1.26
	0.4	....	.89	1.11	1.47
	0.8	....	1.20	1.39	1.67
	2.0	....	....	1.54	1.04
Average SO_3 removed (grams)	0	.0808	.0805	.0729	.0778
	0.2	.0594	.0739	.1524	.1652
	0.4	....	.0659	.1123	.0935
	0.8	....	.0917	.2431	.0670
	2.0	....	....	.1624	.0645
Average per cent N in crops	0	.60	1.12	1.02	1.44
	0.2	.80	.94	1.52	1.60
	0.4	....	.90	1.55	1.87
	0.8	....	.91	1.26	2.01
	2.0	....	....	1.20	1.87
Average N in grams	0	.0357	.0815	.1026	.0614
	0.2	.0403	.0825	.0842	.2071
	0.4	....	.0762	.1062	.1123
	0.8	....	.0704	.1512	.0804
	2.0	....	....	.1234	.1223

Sulphur and phosphoric acid. These experiments were similar to the ones just discussed, three pots of each application being used, with additions of ammonium nitrate, potassium chloride, and calcium carbonate to all the pots. Varying amounts of sulphur were added as flowers of sulphur and phosphoric acid as dicalcium phosphate. The results are given in Table 25. Increasing the amounts of sulphur increased the effect of the phosphoric acid on the weight of the crops, and increasing the amount of phosphoric acid increased the effect of the sulphur. Each had an influence on the other. Increased amounts of phosphoric acid seemed to decrease slightly the percentage of sulphur in the crop with the low applications and to increase it with the high ones. Increasing the phosphoric acid increased the quantity of sulphur taken up by the crop. Increasing the sulphur tended to decrease the percentage of phosphoric acid in the crops.

Table 25.—Effect of varying quantities of sulphur and phosphoric acid on the crop in pot experiments.

Soil 22194	Sulphur added, grams	Phosphoric acid added, grams			
		0	0.10	0.20	0.40
Average weight crop, grams	0	3.4	6.0	7.8	12.9
	.05	2.7	8.7	10.5	17.0
	.10	....	9.4	12.1	....
	.20	....	6.9	12.5	14.5
	.50	....	5.1	8.8	4.2
Average per cent SO_3 in crop	0	2.3	2.0	2.1	1.7
	.05	2.6	2.1	1.8	1.3
	.10	....	2.0	1.9	....
	.20	....	2.3	2.0	1.9
	.50	....	2.4	1.9	2.8
Average SO_3 removed (grams)	0	.1043	.1186	.1607	.2142
	.05	.0896	.1812	.1867	.2213
	.10	....	.1909	.2208	....
	.20	....	.1585	.2482	.2667
	.50	....	.1230	.1661	.1153
Average per cent P_2O_5 in crops	0	.364	.256	.271	.302
	.05	.299	.297	.263	.259
	.10	....	.190	.239	....
	.20	....	.200	.206	.227
	.50	....	.186	.170	.264
Average P_2O_5 in grams	0	.0116	.0141	.0210	.0379
	.05	.0072	.0246	.0277	.0438
	.10	....	.0177	.0285	....
	.20	....	.0141	.0256	.0258
	.50	....	.0101	.0149	.0111

Relation of the Sulphur Taken Up by Crops to the Sulphur Content of the Soil

It has been shown in previous bulletins that the percentages of total nitrogen (28), active phosphoric acid (27), and active potash (29, 30) of the soil are related to the quantities of nitrogen, phosphoric acid, or potash removed by crops in pot experiments. Similar experiments have been made with sulphur, though to a more limited extent. All the pots received nitrogen, phosphoric acid, and potash, in a form free from sulphur.

The pots in the experiment were arranged in groups according to the sulphur content of the soils. The average results for corn are given in Table 26; for kafir, which followed corn in the same pots, in Table 27; and for cotton, in different pots, in Table 28.

In all three of the tables in the first three groups, the sulphur removed by the crops increases with the sulphur content of the soil, but thereafter as the percentage of sulphur increases the results are irregular. This may be partly due to the small number of experiments in each of these groups.

If corn is assumed to require 6 pounds of sulphur for 40 bushels and cotton 13 pounds of sulphur for 200 pounds of lint, the corn possibility can be calculated from the quantities of sulphur withdrawn. The corn possibility is given in Tables 26-27 and the cotton possibility in Table 28.

Table 26.—Average relation of sulphur taken up by corn to the sulphur in soil.

Group according to percentage of sulphur (S) in soil	Number of soils	Weight crops in grams, NPK	Per cent S in crops	Grams S in crops	Per cent S in soil	Corn possibility of sulphur taken up in bushels per acre
Group .004-.008......	5	22.0	.105	.0198	.006	53
Group .008-.012......	14	35.3	.089	.0306	.010	82
Group .012-.016......	7	30.9	.129	.0791	.014	103
Group .016-.020......	2	35.8	.089	.0319	.018	83
Group .020-.024......	2	36.6	.084	.0322	.022	84
Group .024-.028......	2	17.5	.116	.0200	.027	33
Group .028-.032......	4	24.6	.098	.0257	.030	39
Group .032-.036......	2	23.3	.125	.0290	.033	76

Table 27.—Average relation of sulphur taken up by kafir to the sulphur in soil.

Group according to the percentage of sulphur in the soil	Number of soils	Weight crop in grams	Per cent S in crops	Grams S in crops	Total S in soil per cent	Corn possibility of sulphur in bushels per acre
Group .004-.008......	6	20.6	.106	.0198	.006	53
Group .008-.012......	18	24.5	.107	.0237	.010	70
Group .012-.016......	7	32.9	.104	.0338	.014	90
Group .016-.020......	2	37.5	.074	.0281	.018	74
Group .020-.024......	4	23.8	.120	.0230	.022	61
Group .024-.028......	2	21.0	.108	.0228	.027	61
Group .028-.032......	4	22.9	.170	.0219	.031	58
Group .032-.036......	2	25.7	.083	.0198	.033	52

Table 28.—Average relation of sulphur taken up by cotton to the sulphur in soil.

Group based on percentages of sulphur in the soils	Number of soils	Weight crop in grams	Per cent S in crops	Grams S in crops	Total S in soil	Cotton possibility pounds lint per acre
Group .004-.008......	4	20.6	.141	.0296	.006	178
Group .008-.012......	13	20.2	.232	.0462	.010	277
Group .012-.016......	4	18.3	.326	.0568	.014	341
Group .016-.020......	2	23.8	.230	.0549	.020	330
Group .020-.024......	1	45.5	.097	.0440	.022	264

According to these figures, while the corn possibility is good, the cotton possibility is low, which is evidence that cotton may need sulphur fertilizer in addition to nitrogen, phosphoric acid, and potash.

Effect of Fertilizer on Quantity of Sulphur Taken Up by Crops. As pointed out previously, addition of sulphur to the soil increases the amount of sulphur taken up by the crop in pot experiments. The percentage of sulphur in the crop thus depends, to a certain extent, upon the size of the crop and the quantity available in the soil. It thus happens that while applications of nitrogen, phosphoric acid, or potash may increase the size of the crop grown in pot experiments, they may not increase the quantity of sulphur taken up by the crop. This is shown in Table 29. It is noted that where there is a decided increase in crop, the percentage of sulphur decreases and the amount of sulphur taken up does not vary as widely as might be expected, and also that the addition of sulphur increases the amount taken up.

Oxidation of Sulphur in the Soil

It has been known for a long time, that flour of sulphur or other free sulphur placed in the soil, is slowly oxidized. A number of workers have studied this from various angles (1, 42). Sulphuric acid is produced which may be neutralized by the bases in the soil, producing neutral sulphates. The sulphuric acid may make the soil acid if insufficient amounts of the bases are present. The oxidation may be effected chiefly by microorganisms, but a slight amount is also produced by chemical action. See, McIntire, Gray and Shaw (54).

The rate of oxidation of sulphur depends upon the temperature, moisture, physical character of the soil, and other conditions. The effect on the soil depends upon the buffer capacity of the soil for acids, and the amount of sulphuric acid produced (31).

Effect of Oxidation on Active Phosphoric Acid and Potash. It has been claimed that sulphur renders plant food available. Experiments were made to test the effect of oxidation of the sulphur upon the active phosphoric acid and potash of the soils. To portions of 1000 grams of soil, 0.1, 0.2, and 1.0 gram of sulphur was added. This was equal to 100, 200, and 1000 parts per million, or 200, 400, and 2000 pounds of sulphur to two million pounds of soil. One portion received no additions. The soils were mixed with water equal to one-third the saturation capacity, and kept at room temperature, beginning in June, for twelve weeks, water being added to restore the loss by evaporation every two weeks. The results of the analyses are given in Table 30.

The oxidation of the sulphur had practically no effect on the active phosphoric acid or active potash. Some effect apparently occurred in another series in which a check sample of soil was not carried in the experiment, but the difference may be due to slight differences in the samples.

Table 29.—Grams of sulphur removed from soils by cotton in pot experiments.

No.		Average NK	Average NKS	Average PK	Average PKS	Average NP	Average NPS	Average NPK	Average NPKS
23245	Brennan fine sandy loam, 0″–7″, Hidalgo	.1471	.4236	.1955	.1726	.1214	.5400	.1552	.3005
23361	Duval fine sandy loam, 0″–7″, Hidalgo	.1560	....	.1988	.0496	.1468	.4577	.1478	.5013
23362	Duval fine sandy loam, 7″–19″, Hidalgo	.0804	.2794	.0707	.0854	.1152	.6099	.1027	.3900
23551	Norfolk fine sandy loam, 0″–7″, Nacogdoches	.0874	.3626	.0911	....	....	....	.1196	.4623
23948	Gause fine sandy loam, 0″–7″, Milam	.0770	.3559	.0850	.2214	....	....	.0986	.4152
23959	Wilson clay loam, 7″–19″, Milam	.0962	.3990	.1254	.1120	....	....	.1373	.3707
23966	Milam fine sandy loam, 0″–7″, Milam	.0801	.3443	.1363	.1114	....	....	.1008	.4832
23967	Milam fine sandy loam, 7″–19″, Milam	.0746	.1832	.0697	.0932	....	....	.1062	.2201
24004	Ochlockonee fine sandy loam, 7″–19″, Nacogdoches	.1251	.4360	.0936	.2394	....	....	.0940	.4588
23960	Bell clay, 0″–7″, Milam	.1452	.3856	....	....	....	....	.1371	....

Table 30.—Average effect of oxidation of sulphur on the active phosphoric acid and potash of the soil in parts per million.

	Group 1	Group 2
Number of soils	17	12
Active phosphoric acid—no addition	60	....
Active phosphoric acid—sulphur 100 parts per million	59	30
Active phosphoric acid—sulphur 200 parts per million	59	....
Active phosphoric acid—sulphur 500 parts per million	....	28
Active phosphoric acid—sulphur 1000 parts per million	59	....
Active potash—no addition	229	....
Active potash—sulphur 100 parts per million	229	97
Active potash—sulphur 200 parts per million	227	....
Active potash—sulphur 500 parts per million	....	89
Active potash—sulphur 1000 parts per million	224	....

Effect of Sulphur and Sulphates on Percolation of Water

It has been shown by Kelly and others that the oxidation of sulphur in the soil or the addition of gypsum, increases the permeability of soil to water on certain soils, especially clay soils containing much soluble salts (alkaline soils).

The effect of sulphur and gypsum on the permeability of soil to water was studied in several experiments. The method of measuring the percolation is as follows:

Select glass tubes one inch in diameter, measuring each tube. Tie a piece of cheesecloth over the bottom. Weigh out 100 grams of soil. Make such additions as may be assigned. Begin percolating with distilled water in the morning, and record time of percolating of each 25 cc. until 100 cc. have percolated, or for three days. If the percolation is not finished by 4 p. m., measure the amount percolated and record with the time. Then add enough water to percolate during the night. Measure the quantity percolated in the morning if it exceeds 25 c.c.; otherwise proceed as directed above. The final record is the number of cc. percolated per hour calculated from the rate of percolation of 100 cc.

The method is, of course, purely arbitrary, and not especially accurate. The statement in terms of cubic centimeters of water an hour is made so that the figures will become larger as the permeability of the soil becomes greater.

Effect of Gypsum and Limestone. In this experiment, 0.1 gram of calcium sulphate or calcium carbonate was thoroughly mixed with the dry soil, and percolated as described above. The results are given in Table 31.

While the addition of gypsum increased percolation with some of the soils, with others there was a decrease, and with others, little or no effect. The same is true of carbonate of lime, but the decrease in percolation averaged more with the addition of carbonate of lime.

It is possible that different results could be secured if more time were allowed for the sulphate or carbonate of lime to react with the soil before the percolation took place.

Table 31.—Effect of carbonate of lime and sulphate of lime on percolation in cubic centimeters per hour.

No.		No addition	With sulphate of lime	With carbonate of lime
12649	Miller clay, 0″–6″, Brazos Co.	10.5	10.3	10.6
12651	Yahola silt loam, 0″–10″, Brazos Co.	14.3	7.6	11.7
12643	Trinity clay, 0″–6″, Brazos Co.	1.3	.3	.2
12645	Pledger clay, 0″–8″, Brazos Co.	.8	.2	.7
12641	Trinity fine sandy loam, 0″–12″, Brazos Co.	151.5	200.0	200.0
12647	Miller fine sandy loam, 0″–10″, Brazos Co.	80.0	80.0	63.3
12652	Yahola silt loam, 10″–20″, Brazos Co.	9.0	10.1	9.7
12653	Bastrop fine sandy loam, 0″–12″, Brazos Co.	50.0	50.0	52.4
12654	Bastrop fine sandy loam, 0″–12″, Brazos Co.	52.4	41.1	38.8
12663	Crockett clay, 0″–6″, Brazos Co.	4.2	1.5	1.5
12667	Crockett loam, 0″–8″, Brazos Co.	24.0	26.1	22.2
12657	Bell clay, 0″–8″, Brazos Co.	11.8	9.4	5.2
12659	Wilson clay loam, 0″–8″, Brazos Co.	6.9	5.6	6.7
12642	Trinity fine sandy loam, 12″–24″, Brazos Co.	12.7	12.7	10.0
12680	Wilson fine sandy loam, 10″–20″, Brazos Co.	5.0	7.2	5.0
21773	Laredo silty clay loam, 0″–15″, Cameron Co.	12.5	8.3	7.7
12409	Surface soil, 0″–8″, Bell Co.	28.5	33.3	26.1
12640	Wilson clay, 12″–24″, Brazos Co.	3.0	3.5	2.9
12648	Miller fine sandy loam, 10″–20″, Brazos Co.	21.4	28.5	11.1
12650	Miller clay, 6″–16″, Brazos Co.	4.1	4.2	4.1
12407	Surface soil, 0″–9″, Bell Co.	28.6	25.0	14.3
12408	Subsoil, 9″–18″, Bell Co.	19.4	19.4	8.3
12676	Ochlockonee fine sandy loam, 12″–24″, Brazos	100.0	133.3	92.6
21782	Harlingen clay, 8″–36″, Cameron Co.	0	0	0
12395	Surface soil, 0″–7″, Bell Co.	12.1	10.6	9.4
12397	Surface soil, 0″–10″, Bell Co.	20.2	17.7	12.5
12678	Lufkin clay loam, 0″–6″, Brazos Co.	.5	1.0	.1
12679	Wilson fine sandy loam, 0″–10″, Brazos Co.	30.0	33.3	22.6
12672	Susquehanna fine sandy loam, 10″–20″, Brazos	2.1	.9	.6
12674	Lufkin fine sandy loam, 12″–20″, Brazos	12.9	14.3	11.1
21775	San Benito clay, 0″–12″, Cameron Co.	.2	1.0	.7
21777	Rio Grande silty clay loam, 0″–15″, Cameron Co.	.9	2.8	2.6
21781	Harlingen clay, 0″–8″, Cameron Co.	1.4	1.5	1.0
12582	Ennis clay, 0″–6″, Ellis Co.	12.4	7.1	2.3
12578	Susquehanna fine sandy loam, 0″–12″, Ellis Co.	400.0	400.0	333.3
12579	Susquehanna fine sandy loam, 12″–24″, Ellis Co.	151.6	120.5	100.0
21776	San Benito clay, 12″–36″, Cameron	1.2	2.4	1.8
21778	Rio Grande silty clay loam, 15″–26″, Cameron	7.8	14.3	5.5
21779	Victoria clay loam, 0″–18″, Cameron	6.5	21.8	5.2
21780	Victoria clay loam, 18″–36″, Cameron	6.2	6.3	7.1
12568	Houston clay, 0″–12″, Ellis Co.	4.9	2.9	lost
12569	Houston clay, 12″–18″, Ellis Co.	1.6	2.6	1.4
12581	Trinity clay, 6″–12″, Ellis Co.	4.0	3.0	2.5
12583	Ennis, 6″–18″, Ellis Co.	1.3	2.0	2.0
12584	Durant loam, 0″–8″, Ellis Co.	32.4	30.0	18.2
23095	Subsoil, Dallas Co.	.2	2.0	.4
12571	Houston stony clay, 4″–8″, Ellis Co.	109.9	120.5	66.6
12572	Crawford loam, 0″–12″, Ellis Co.	6.1	5.4	4.9
12575	Durant clay, 8″–16″, Ellis Co.	2.8	3.5	3.2

Effect of Oxidation of Sulphur on Percolation. The soils used in this experiment received 1 gram of sulphur to 1000 grams of soil, and were allowed to remain at summer temperature for 12 weeks, the water lost by evaporation being replaced every two weeks. The samples were then dried and prepared for analysis. The results of the percolation are given in Table 32. The results of this experiment are different from those of the preceding one. The oxidation of the sulphur has increased the permeability of several of the soils. As the permeability is low, the effect is favorable. It confirms the work of Kelly previously cited.

Table 32.—Effect of oxidation of sulphur on percolation.

No.	Description, location, and depth	No sulphur c. c. per hour	Sulphur added c. c. per hour
7172	Surface soil, Calhoun Co., 6″–16″	0.3	0
7181	Houston black clay, Dallas Co., 0″–11″	4.4	36.3
7225	Surface soil, moderate, Jasper Co., 0″–9″	16.7	23.9
7242	Surface soil, moderate, Comanche Co., 7″–19″	33.8	54.6
7244	Surface soil, moderate, Colorado Co., 0″–14″	44.4	33.3
7345	Surface soil, good, Liberty Co., 0″–5″	36.3	70.5
7347	Surface soil, Liberty Co., 0″–6″	46.2	70.5
7357	Lake Charles clay, probably, Harris Co., 0″–12″	3.6	12.0
7230	Surface soil, poor, Fannin Co., 8″–20″	6.0	26.4
7241	Surface soil, Comanche Co., 0″–7″	38.7	60.2
6977	Surface soil, valley land, Wichita Co., 10″–28″	2.0	30.0
6882	Blackland surface, Walker Co., 0″–6″	2.5	4.5
6732	Subsoil, Zamora Ranch, Willacy Co., 6″–18″	14.5	57.2
6731	Surface, Zamora Ranch, Willacy, Co., 0″–6″	14.5	109.9
3332	Travis gravelly loam, McLennan, 12″–24″	62.5	48.0
6681	Surface soil, Chambers Co., 7″–19″	13.4	92.6
17746	Surface soil, Colorado Co., 0″–6″	47.2	100.0
7373	Surface soil, Victoria Co., 0″–6″	6.6	31.2
7092	Surface soil, Victoria Co., 12″–24″	14.4	92.8
7118	Surface soil, Fayette Co., 0″–10″	15.0	17.1
7129	Surface soil, Bastrop Co., 0″–8″	11.0	2.0
7157	Surface soil, Wharton Co., 0″–12″	25.3	30.7
7159	Surface soil, Madison Co., 0″–8″	75.1	151.5
7160	Surface soil, Madison Co., 8″–20″	1.4	8.5
7169	Norfolk fine sandy loam, Upshur Co , 0″–6″	11.4	18.1

Percolation of Soils Used in Pot Experiments. Soils to which sulphur was added in pot experiments were prepared for analysis and subjected to percolation, with the results given in Table 33. Here, again, the sulphur increased the permeability of the soil to water. The amount of sulphur used was 1 gram to 5000 grams of soil, or 200 parts per million.

Table 33.—Effect of sulphur on percolation on soils used in pot experiments, cubic centimeters of water percolated per hour.

Soil		Before cropping	After cropping
21779	Victoria clay loam, 0″–18″, Cameron Co	6.5	22.6
21779	Victoria clay loam, 0″–18″, Cameron Co	6.5	27.1
21781	Harlingen clay, 0″–8″, Cameron	1.4	7.5
21785	Norfolk fine sandy loam, 0″–18″, Henderson Co	16.9	31.6
21785	Norfolk fine sandy loam, 0″–18″, Henderson Co	16.9	21.8
21785	Norfolk fine sandy loam, 0″–18″, Henderson Co	16.9	26.1
21786	Norfolk fine sandy loam, 18″–36″, Henderson Co	18.1	32.4
9690	Surface soil, 0″–8″ or 9″, Wise Co	3.4	7.3

Percolation of Field Soils. Samples of soils were taken from the field experiments at Substation No. 5, Temple, Texas. The soil is a heavy limestone soil. The results of the tests are given in

Table 34. Each figure represents a different piece of land. While there appears to be a tendency for the applications of sulphur to increase the permeability of the soil for water, the results are so erratic that it is not possible to draw a definite conclusion. The irregularity is probably due in part to variations of the physical character of the soil in the different parts of the field.

Table 34.—Percolation of soils from field experiments, Substation No. 5, Temple, in cubic centimeters per hour (each quantity a separate sample).

No sulphur added	23.5	5.2	7.8	9.7
	15.6	16.5	22.2	11.7
	18.1	13.1	3.1	4.1
	9.4	8.3	4.1	14.2
	8.3	....	....	....
500 pounds per acre	7.8	8.3	9.5	9.2
2500 pounds per acre	17.3	6.6	12.5	12.5
4000 pounds per acre	26.6	22.2	....	....
5000 pounds per acre	12.9	4.1	14.5	18.1
10000 pounds per acre	33.7	27.3	15.1	15.4

Effect of Oxidation of Sulphur on the Availability of Phosphoric Acid in Rock Phosphate

It has been proposed to take advantage of the bacterial oxidation of sulphur to sulphuric acid for the purpose of rendering the phosphoric acid of rock phosphate available. For this purpose, mixtures were to be made consisting of sulphur, earth, and rock phosphate, kept moist, and allowed to act for several months. Some workers have claimed that an appreciable amount of phosphoric acid was made available.

This procedure was suggested by Lipman (47, 48). It was studied by Ames and Richmond (3), Brown and Warner (8), Brown and Gwinn (7), and McLean (44), Ellett and Harris (16), among others (32, 68) as well as Joffe (41), who secured a comparatively high degree of solubility.

Experimental. Under the direction of the Division of Agronomy of the Texas Agricultural Experiment Station (80) in 1918, composts of rock phosphate, sulphur, Lipman's starter, and several types of soil were made, in accordance with a centralized plan from the Office of Experiment Stations of the United States Department of Agriculture and in cooperation with the Council of National Defense. In 1919, it was reported (81) that the study showed no practical gain in availability of plant food by the composting. The field applications showed gains in some cases.

Some chemical analyses of these composts are given in Table 35. It is to be noted that there are some losses of total phosphoric acid in some of the composts, either due to improper mixing or sampling. The basicity of the composts, expressed

Table 35.—Effect of composting with sulphur on available phosphoric acid of rock phosphate.

	Compost Number	Available phosphoric acid per cent			Total phosphoric acid, per cent		Basicity in carbonate of lime per cent	
		Before	After	Gain	Before	After	Before	After
Main Station	A	2.60	2.15	.00	16.50	13.35	1.81	0
	B	0.90	0.80	.00	17.25	12.50	1.71	.65
Station No. 1	A	1.60	1.43	.00	18.39	16.15	2.27	2.35
	B	0.55	1.32	.77	17.00	16.77	1.86	1.05
Station No. 2	A	1.10	1.03	.00	17.15	16.83	2.07	1.05
	B	1.97	1.40	.00	18.87	18.20	1.61	.95
Station No. 3	A	0.83	1.90	1.07	17.50	18.00	2.37	.99
	B	2.43	1.40	.00	18.73	18.45	2.07	.68
Substation No. 4	A	1.18	1.65	.47	19.03	18.05	2.26	2.15
	B	1.78	1.35	.00	18.23	18.20	2.01	.95
Substation No. 5	A	1.08	1.15	.07	18.23	15.45	8.18	7.05
	B	0.74	0.78	.04	17.75	15.28	4.85	2.60
Substation No. 6	A	1.26	.95	.00	17.95	16.05	4.11	3.88
	B	1.11	1.00	.00	16.14	14.70	1.86	1.11
Substation No. 7	A	0.92	1.30	.38	17.97	17.30	3.51	2.85
	B	1.95	1.40	.00	18.25	18.00	3.20	1.27
Substation No. 8	A	1.50	1.05	.00	16.85	12.85	3.88	1.96
	B	1.60	.95	.00	18.20	12.00	2.06	1.11
Substation No. 9	A	0.60	0.85	.25	17.10	15.25	7.41	7.43
	B	0.22	1.75	1.53	17.22	14.80	4.72	1.37
Substation No. 11	A	1.18	1.90	.72	17.38	17.80	2.05	1.64
	B	2.25	1.60	.00	17.25	18.05	1.95	1.00
Substation No. 12	A	1.88	1.65	.00	18.75	17.70	3.03	2.10
	B	1.75	1.35	.00	18.35	17.95	2.71	.80

as carbonate of lime, was measured by the amount of 0.2N nitric acid neutralized. It is to be noted that many of the soils contained basicity, which, though partly neutralized by the oxidation of sulphur, was not completely neutralized in some cases. In other cases, however, the basicity was very low. After all the facts are considered, the conclusion is reached that the amount of phosphoric acid made available was not sufficient to pay for the cost of either the sulphur or the labor.

Sulphur in Fertilizers

Table 36 shows the percentage of sulphur found in fertilizers sold in Texas.

Table 36.—Percentage of sulphur (S) in some fertilizers.
(Each set of figures is a separate sample.)

Superphosphate, 20 per cent (6 samples)	11.20	11.71	10.34	....	....
Superphosphate, 20 per cent	11.04	10.99	10.98	....	....
Sulphate of ammonia (4 samples)	23.96	23.90	23.38	23.33	....
0–15–0 fertilizer	7.84	....	....	....	....
3–10–3 fertilizer	7.65	....	....	....	....
4–8–4 fertilizer (4 samples)	8.62	8.30	9.28	7.31	....
4–8–6 fertilizer	9.66	....	....	....	....
4–10–7 fertilizer	10.77	....	....	....	....
4–12–4 fertilizer (8 samples)	10.83	11.25	11.63	10.94	....
4–12–4 fertilizer	11.71	8.06	11.52	9.84	....
5–15–5 fertilizer	10.61	....	....	....	....
6–10–7 fertilizer	11.48	....	....	....	....
6–12–6 fertilizer (5 samples)	11.18	7.52	11.34	12.58	12.24
9–27–9 fertilizer	5.54	....	....	....	....
16–20–0	14.34	....	....	....	....
Kainit (2 samples)	5.98	.93	....	....	....
Nitrate of soda (4 samples)	.08	.25	0	.32	....
Muriate of potash (3 samples)	.85	.51	1.00	....	....

Sulphur and Gypsum for Alkali Soils

When alkali soils are flooded to wash out the soluble salts, it frequently happens that the soil runs together so that the water percolates very slowly. The removal of the injurious saline salts may take place very slowly, or be almost stopped, so that the possibility of putting the land in cultivation may be much retarded, or even rendered impossible.

This impermeable condition may exist in the surface, so that a hard crust is formed, or it may occur in the subsoil, producing an impervious layer rendering under-drainage difficult or impossible. This impermeable condition is believed to be caused by replacement of calcium by sodium in complex soil silicates, producing finely divided deflocculated particles which retard the flow of water. Hence, if the sodium is replaced by calcium, flocculation occurs and the soil again becomes permeable, or if suitable additions are made to the soil, deflocculation does not occur and the impermeable condition does not arise.

This matter has been investigated by Hibbard (38, 39), Kelley, and associates (43, 44, 45, 70) of the California Experiment Station, Burgess (9), and by others (10). Kelley (44) found that gypsum or sulphur is quite effective on black alkali soils. Sulphur was by far the most economical material used in Kelley's experiments. A ton to the acre was necessary on the land studied, but it was thought possible that an application of 1000 pounds would give good results if used in combination with barnyard manure or growing of an alkali-resistant legume. It is probable that black alkali soils of other types can be successfully treated with sulphur, but the amount of sulphur required would depend upon the quantities of sodium carbonate and replaceable sodium in the soil. Several months or even a year or more are required before the full effects of the sulphur are manifest. Sulphur is not needed if the soil contains considerable amounts of soluble calcium salts. To be effective, drainage conditions must be favorable, an abundance of irrigation water available, and the ground water kept continuously six or more feet below the surface of the soil (with insufficient drainage, sulphur or other applications may be ineffective).

Gypsum was recommended by Hilgard in 1906 or earlier (40) and Hibben (38), Burgess in 1925 (9), and others have found gypsum of advantage with certain alkali soils.

It is evident that sulphur or gypsum may be useful in connection with irrigation, either in the reclamation of alkali soils, or in the treatment of soils which have a tendency to run together under irrigation, or in the prevention of the accumulation of alkali, in connection with proper irrigation and drainage. The matter requires further study.

Probable Needs for Sulphur as Plant Food

Although at the present time there is practically no need for the use of sulphur on soils receiving commercial fertilizers, it is possible that a need for sulphur may develop if new synthetic fertilizers, which are low in sulphur, are used extensively. It is generally recognized that possible needs for sulphur are supplied by fertilizers used for other ingredients. Lint (46) states that part of the superior merit of superphosphate may be due to the sulphur it contains. Greaves and Gardner (33) believe that sulphur will become, in time, a limiting factor in plant growth on soils in Utah. C. B. Williams (85) in North Carolina believes that the superiority of potassium sulphate over potassium chloride on Norfolk and Durham sandy loams may be interpreted as a deficiency in sulphur which is brought out when other limiting elements are supplied. Sulphur is not likely to be needed as plant food in the following localities or under the following conditions:

(1) On soils which now supply sufficient sulphur for the crops. Practically all the Texas soils examined came in this group.
(2) On soils under irrigation. The irrigation water contains sufficient sulphur for the crops grown.
(3) On soils which receive ordinary commercial fertilizers since the commercial fertilizer carries sufficient sulphur.
(4) By crops such as corn, rice, oats, or wheat which require small amounts of sulphur.

There is a possibility for the use of sulphur as a plant food on:

(1) Soils sufficiently supplied with other plant foods but deficient in sulphur and which receive little or no sulphur in rain water or irrigation water. Soils of this kind are found in the States of Washington and Oregon, but so far none have been found in Texas.
(2) Soils low in plant food and sulphur on which highly concentrated commercial fertilizers containing little sulphur have been used for several years. There are no soils of this kind known to exist in Texas at the present time, but there is a possibility of their occurrence in the future.

There is a possibility for the use of sulphur or gypsum as a soil amendment under the following conditions:

(a) On soils which contain black alkali, the use of sulphur or gypsum may be advisable to prevent the soils from running together and to make them more easily penetrated by water. Very little soil of this kind is known in Texas at the present time.
(b) On soils which contain carbonate of lime and have such an alkaline condition that plants suffer from chlorosis, there is a possibility that sulphur or gypsum may correct the excess of alkalinity. This possibility needs investigation.
(c) Soils which, for any reason, require to be made acid, may be made acid by means of the bacterial oxidation of sulphur, but this condition of acidity is not advised, nor is the procedure recommended, at the present time.

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SUMMARY AND CONCLUSIONS

(1) Large deposits of sulphur and of gypsum occur in Texas.

(2) Sulphur is an essential plant food but is usually required in smaller amounts than nitrogen, phosphoric acid, or potash.

(3) Alfalfa, cabbage, cotton, onions, and turnips take up about 13 to 39 pounds of sulphur to the acre while corn, rice, oats, and wheat remove 3 to 7 pounds.

(4) On an average of 4 years, about 12 pounds per acre of sulphur was brought down yearly in rainfall at Beaumont, College Station, Nacogdoches, Denton, and Weslaco, about 8 pounds at Angleton, Beeville, Chillicothe, San Antonio, Spur, Temple, and Troup, and about 4 pounds at Balmorhea.

(5) Irrigation waters in western Texas supply 200 pounds or more of sulphur to the acre-foot of water, which is sufficient for all crops grown.

(6) Irrigation water in the rice-growing region of Texas supplies 12 to 33 pounds of sulphur per acre-foot of water. Rice removes about 3 pounds of sulphur to the acre.

(7) A large number of soils from various sections of the State were analyzed for sulphur. The sulphur content is usually lower than that of nitrogen or phosphoric acid. Individual samples are quite low in sulphur.

(8) Many soils in Texas are deficient in nitrogen, phosphoric acid or potash, or are likely to become deficient in one or more of these elements. The fertilizers which are used to supply these deficiencies usually carry sulphur. Deficiencies in nitrogen, phosphoric acid, or potash cannot be supplied by gypsum or sulphur, but sulphur is usually applied when these deficiencies are corrected.

(9) A survey shows that sulphur or gypsum gave good results in some parts of Washington, Oregon, and Montana in the Pacific Northwest. The use of sulphur or gypsum is generally not advised in the other states except under exceptional conditions, such as for the treatment of black alkali in California or Arizona.

(10) In pot experiments, sulphur alone did not give as good results as complete fertilizers.

(11) Pot experiments in which sulphur was used to supplement a complete fertilizer containing no sulphur, indicated that sulphur gave increases in yield of crops in some instances.

(12) Applications of sulphur increased the amount of sulphur taken up by plants in pot experiments. Additions of sulphur did not increase the nitrogen or potash taken up by crops in pot experiments. There was some tendency for sulphur to increase the amount of phosphoric acid removed by crops.

(13) Reciprocal relations of sulphur and nitrogen or sulphur and phosphoric acid show that increasing the applications of one material may increase the effect of the other. That is to say, the effect of the minimum amount of an element depends upon the supply of other essential elements.

(14) When the pot experiments are arranged in groups according to the sulphur content of the soils, the quantity of sulphur removed by the crops grown on the soils in the first three

groups low in sulphur was found to increase as the sulphur content of the soil increased but the quantity removed in the other five groups was lower and irregular. The amount of sulphur removed calculated to the cotton possibility of the sulphur was low on some of the soils.

(15) Oxidation of sulphur had practically no effect upon the active phosphoric acid or active potash in the soils tested.

(16) Oxidation of sulphur apparently increased the permeability of some of the soils to water.

(17) No practical gain in the solubility of phosphoric acid by composting sulphur and rock phosphate was found in a series of tests conducted by the Division of Agronomy of this Station.

(18) Sulphur or gypsum may increase the permeability of soils containing black alkali, thereby aiding the alkali to be washed out so that the soil can be cultivated.

(19) There is a limited possibility for the use of sulphur or gypsum as an amendment on soils containing black alkali or which run together under irrigation.

(20) It is possible that the continued use of concentrated commercial fertilizers containing little or no sulphur may result in deficiencies of sulphur as a plant food in some soils which will require correction. Practically all commercial fertilizers at the present time contain sulphur, but highly concentrated fertilizers which contain little or no sulphur are being manufactured. The continuous use of such fertilizers may result in a deficiency of sulphur in soils in some sections, especially for crops with high sulphur requirements, such as cotton, alfalfa, onions, cabbage. However, some sulphur is added to soils by rain and snow.

(21) Sulphur is not likely to be needed in Texas to supply plant food on soils under irrigation, or on soils which receive ordinary commercial fertilizer or on which crops such as corn, rice, oats, or wheat which require small amounts of sulphur are grown. In fact, sulphur at the present time cannot be recommended as a fertilizer in any part of Texas. This is also the conclusion drawn from the field experiments in Bulletin 408 of the Division of Agronomy of this Station.

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