PLANT RESPONSES TO SULFUR APPLICATIONS

by 632

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INTRODUCTION

Sulfur is an essential element for plant growth with a requirement nearly equal to that of phosphorus. The sulfur reservoir for plant requirements in most soils is the organic matter. Areas in south central Kansas with sandy soils are known to be low in organic matter and sulfur reserves. This low organic matter content, along with increased use of S-free fertilizers and increased crop yield requirement for all nutrients, makes this a potential area for sulfur deficiencies.

Calcareous soils in western Kansas contain an abundance of nutrient elements tied up in unavailable states. Sulfur studies from various locations indicate a possible release of these nutrients by the ability of sulfur to lower the soil pH and to reduce certain metallic ions.

This investigation was initiated to study the response of corn and wheat to sulfur on calcareous, low organic matter soils and to determine the effects of sulfur applications on the availability and plant absorption of other nutrients.

REVIEW OF LITERATURE

The average amount of S in the earth's crust is approximately 0.08 percent while the amounts in soil vary from less than 100 ppm to several tenths percent. The original source of most soil sulfur was the sulfides of metals contained in plutonic rocks (46). As these rocks were exposed to the weathering processes, the minerals were decomposed and sulfides were oxidized and released as sulfates. These sulfates were then either precipitated as soluble and insoluble sulfate salts in arid and semiarid climates, absorbed by living organisms or reduced by other organisms and thus with time the sulfur cycle was complete.

Sulfur in the Nutrition of Plants

Plants obtain sulfur from the soil and from the air. The available S in the air was shown by Thomas et al. (45) to be mainly SO_2 and its absorption by leaves was proven by Fried (15) using radioactive S.

Soil sulfur is taken up by the plant primarily as the sulfate ion and is then subsequently reduced. Reduction takes place by activation of sulfate by ATP and the enzyme sulfurylase to form adenosine-5'-phosphosulfate (APS) (38). APS is then reacted with a second molecule of ATP and a specific kinase to form 3'-phosphoadensine-5'-phosphosulfate (PAPS) or "active sulfur." Equations (1) and (1) show the activation process.

$$SO_4 + ATP \xrightarrow{\text{Sulfurylase}} APS + P\text{-}P \qquad (1)$$

$$APS + ATP \xrightarrow{\text{Kinase}} PAPS + ADP \qquad (2)$$

Activated sulfate is then reduced by enzymic pathways to eventually be incorporated in the amino acids methionine and cysteine (6).

The amino acids methionine, cysteine and cystine play a prominent role in protein structure (47). The disulfide (-S-S-) bonds of cystine provide for the covalent cross-linkage of two polypeptide chains or the formation of stable loops in a single chain. The sulfhydryl (-S-H) groups of methionine and cysteine provide sites for attachment of metallic cations, and may thus affect secondary structure due to the conformation of the polypeptide chain around the metal. The sulfhydryl bonds may also function as sites of hydrogen bonding, and as points of attachment of prothetic groups to enzymes.

Other S containing compounds of critical importance for plant growth include the vitamins biotin, thiamine, and coenzyme A. They primarily function as acyl carriers in the oxidation processes of plant metabolism.

Sulfur Deficiencies

Symptoms of sulfur deficiency are much like those caused by nitrogen deficiency. The stunted growth, chlorosis, and delayed maturity are characteristic of both (48). In contrast to nitrogen deficiency, sulfur deficiency symptoms are usually most striking on younger leaves and the leaf patterns of deficient plants do not develop characteristically (24). Hilder and Spencer (20) noted anthocyanin pigmentation in plants with severe sulfur deficiency. The purple to brown tints changed to the typical chlorosis when a small amount of sulfur was added.

According to Eaton (14), sulfur deficient plants are higher in nitrogen, soluble sulfur compounds and starch, and lower in sugars than plants with sufficient sulfur. The accumulation of nitrates and carbohydrates seemed to be due to low nitrate assimilation resulting from low reductase activity. Some plants have thick cell walls and a relatively high proportion of fibers and lignified tissue. The protoplasm appears much like that of plants lacking nitrogen in that it is limited in amount but not noticeably injured as it is when phosphorus, calcium, or potassium are deficient (17).

Sulfate Retention in Soil

Elemental sulfur and organic sulfur compounds are insoluble in water and are not subject to loss by leaching. When sulfates are formed by the oxidation of elemental and organic sulfur, leaching may occur.

Most soils have the capacity to retain sulfate, but with varying degrees. Neller (32), working with soils in Florida, reported little or no sulfate-S in the surface horizons of the soils but considerable amounts were present in many of the sub-surface layers. These deposits of sulfate were found generally where clay was present in the profile. Chao et al. (9) found the amounts of sulfate retained by reference clays decreased from kaolinite to illite to bentonite. Aluminum and iron hydrous oxides are considered to be related to sulfate retention. Chao and co-workers (10) demonstrated that the amount of SO_4 retained was proportional to the amount of hydrous Fe- and Al-oxides coated on the soils. Kamprath, Nelson, and Fitts (25) studied the relationship between pH and sulfate retention. They found the amounts of sulfate adsorbed decreased as the pH of the soils increased from 4 to 6. They also reported the amount of sulfate adsorbed was directly related to the concentration of sulfates in solution.

Marked differences in retention exist between different anions (19). Sulfate is generally considered to be weakly held with the strength of retention in the order phosphate $>$ sulfate $>$ nitrate = chloride.

Barrow (3) reported the amount of extractable sulfate present in soils was highly correlated with the ability to adsorb sulfate. On soils which could adsorb large amounts of sulfate, the sulfate present was taken up by plants more slowly than on non-adsorbing soils.

The mechanism of adsorbing sulfate is thought to involve OH groups in the hydrous oxide and silicate clays (7). Hydroxyl groups held by aluminum ions in the oxides or silicates are replaced by sulfate or acid sulfate ions. The following general equation illustrates how this may occur.

$$-Al{<}^{OH}_{OH}{>}Al- \quad + \quad KHSO_4 \rightleftharpoons \quad -Al{<}^{OH}_{\underset{K}{\overset{|}{SO_4}}}{>}Al- \quad + \quad H_2O \qquad (3)$$

The addition of OH ions (increasing pH) would tend to drive the preceding equation to the left, releasing the adsorbed sulfate.

<u>Oxidation of Sulfur in Soils</u>

The two processes by which sulfur is oxidized in the soil are inorganic chemical oxidation and biological oxidation. Evidence now indicates that biological oxidation is by far the more important (8). The substrates for these oxidation processes are the incompletely oxidized products of microbial decomposition such as sulfide, elemental S, thiosulfate, tetrathionate and pentathionate (42).

Biological oxidation of sulfur proceeds continuously in arable soils unless stopped by some unusual environmental condition. As a result, essentially all the inorganic sulfur in well-aerated soils is present in plant available sulfate form (8).

A wide variety of sulfur oxidizing autotrophic and heterotrophic organisms exist in arable soils and are active over a wide range of conditions. The autotrophic bacteria of the genus <u>Thiobacillus</u> are considered to be the most important in soils (43). <u>Thiobacillus thioparus</u> is a characteristic autotrophic bacteria and is widely distributed in soils with a neutral to slightly alkaline reaction. Thiosulfate, sulfide, elemental S, and tetrathionate provide the substrate for this bacteria. The following are typical reactions of Thiobacillus thioparus.

$$\underset{\text{elemental S}}{2S} + 3O_2 + H_2O \longrightarrow 2H_2SO_4 \qquad (4)$$

$$\underset{\text{thiosulfate}}{5Na_2S_2O_3} + 4O_2 + H_2O \longrightarrow 5Na_2SO_4 + H_2SO_4 + 4S \qquad (5)$$

Sulfur oxidizing heterotrophs may be bacteria, actinomycetes, or filamentous fungi growing dependently on organic substrates. They are capable of oxidizing elemental S and thiosulfate.

Environmental Factors Influencing Sulfur Oxidation

Temperature. The temperature range within which biological oxidation occurs in soils is from about 4 to 55 degrees centigrade (8). Only minimum oxidation occurs near the extremes of these temperatures with the optimum between 27 and 40 degrees, depending on the organisms involved.

Soil Moisture and Aeration. Microorganisms that oxidize sulfur require molecular oxygen and water. The degree of soil aeration is inversely related to soil moisture making oxygen the limiting factor at high moisture levels and the lack of metabolic water limiting at low moisture levels (30).

Soil pH. Sulfur oxidation by microorganisms is not critically dependent on soil pH. Different bacteria of the genus Thiobacillus are active in all arable soil pH ranges.

Soil Microflora. Most arable soils contain sulfur oxidizing organisms (43). Limited soil populations of organisms usually multiply rapidly with an addition of substrate (8).

Sulfur Oxidation and Acidity

Sulfur oxidation is an acidifying process as shown above in equations (4) and (5). Different buffering capacities of soils are variable making the actual prediction of pH change practically impossible (8). However, studies on different soils are quite helpful. Bertramson et al. (5), working with a Maumee loam, lowered the pH from 6.7 to 4.0 by mixing 0.5 gm of ground sulfur with 200 gm soil. The decrease in pH was gradual for the first four weeks then leveled off for the next 12 weeks. Vaura and Frederick (49) reported a decrease in soil pH to between 3.5 and 3.8 on a Brookston silt loam and Maumee fine sandy loam with initial pH's of 6.0 and 7.2 respectively. The treatment of .25 gm elemental sulfur per 50 grams of soil stabilized after 2 to 3 weeks until completion of the experiment after 45 days. Rudolfs (39) mixed elemental sulfur in amounts ranging from 100 to 3500 lbs/acre in a Hanford fine sandy loam with a pH of 7.2. During the first five weeks the soil pH decreased with increasing amounts of S to 7.0 for the 100 lb/acre treatment to 4.0 for the 3500 lb/acre treatment. After 8 weeks, tests showed the soil reaction moving back toward the neutral point.

In these experiments some application rates were considerably higher than would be required to supply adequate plant nutrient sulfur. However, the pH at or near the surface of a sulfur particle at lower rates is undoubtedly lower than that of the soil mass as a whole (8).

Soil pH and Nutrient Availability

Plant nutrition is directly affected by the change in soil reaction (7). Decreasing the soil pH lowers the reduction potential and increases the solubility of materials that contain plant nutrients.

Phosphorus. Available phosphate will precipitate with the calcium ion in calcareous soil in a form unavailable to plants. As the pH of the soil is lowered to a neutral to slightly acid reaction, the $HPO_4^{=}$ and $H_2PO_4^{-}$ ions become available to plants (7). Lipman and McLean (27) were the first to note an increase in citrate-soluble and water-soluble phosphorus when sulfur and mineral phosphate were added to three different soils. Aldrich and Turrell (1) carried out an acidification study on a Ramona sandy loam lowering the pH at one unit intervals from 7.0 to 3.0. Water soluble PO_4 increased from 1.62 ppm to 4.05 ppm through the given range while the percent P in the alfalfa tissue increased from .207 to .325. However, at the lower pH ranges yields were reduced. Neller (30), in a greenhouse experiment, using a Leon fine sand, reported that sulfur had a marked increasing effect on the availability of the phosphorus of rock phosphate. Increasing the sulfur treatment from 50 to 1600 lbs/acre increased the phosphorus content of oats from .125 to .845 percent. Working with rock phosphate-sulfur fusions on a neutral soil, Kittams and Attoe (26) showed that RP-S fusions gave significant increases in both yield and P uptake over the use of RP alone. Increases for a calcareous soil were less pronounced but still significant. Mitchell (29), in a greenhouse study, found by adding 5 percent sulfur to di-calcium phosphate the availability and uptake of phosphorus would equal that of the more available ammonium phosphate. However field tests failed to parallel the greenhouse work. Apparently oxidation of the added sulfur was much slower under field conditions.

Micronutrients Mn, Fe, Zn, and Cu. The micronutrient cations are most soluble and available under acid conditions. As the pH is increased, the ionic forms of the cations are changed to the hydroxides or oxides. The hydroxides of all trace element cations are insoluble (7). In the case of manganese, lowering the soil reaction to around 6.5 favors the release of available manganous manganese (40). Soils tie up copper most securely in the range from pH 7.0 to 8.0, appreciably less securely at pH 6.0, and progressively less as the soil becomes more acid (27). Reduced availability of zinc is generally associated with high soil pH (29). Most pH induced zinc deficiencies occur within the range of 6.0 to 8.0 (47).

Studies on lowering soil pH to increase the solubility of micronutrient cations have shown some favorable results. Peech (35) adjusted the pH on a Norfolk fine sand at ranges from 3 to 7 and found the amounts of extractable Zn and Cu increased rapidly with the decreases in soil pH. Wear (50) reported an increase from 60 to 300 ppm Zn in sorghum tissue as the pH decreased from 7.5 to 4.5. Hasson and Olson (18) found increases in available and total uptake of Fe when the soil pH was lowered from 8.1 to 7.3 by the addition of sulfur. Sulfur treatments were also beneficial to Cu and Zn availability in this study. Increases in Mn availability by sulfur applications have been reported by Hoeft and Sorensen (21) on a Thurman soil, by Tisdale and Bertramson (46) on a Maumee loam, and by Garey and Barber (16) on a Maumee fine sandy loam.

Sulfur Oxidation and Reducing Capacity

A second effect of sulfur oxidation in nutrient availability is the release of electrons during oxidation which may serve to reduce the oxidized forms of iron and manganese. Although an acid media favors reduction of these elements the controlling factor is the supply of electrons (19). The release of electrons when elemental sulfur is added to the soil is shown in equation (6).

$$S + 4H_2O \rightleftharpoons SO_4^{=} + 8H^+ + 6e \qquad (6)$$

According to Tisdale and Bertramson (45), the reduction of the insoluble manganese under favorable conditions is as follows.

$$MnO_2 + 4H^+ + 2e \rightleftharpoons Mn^{++} + 2H_2O \qquad (7)$$

If equations (6) and (7) are combined, an overall expression of the oxidation of sulfur and reduction of MnO_2 would be the following reaction.

$$3MnO_2 + 4H^+ + S \rightleftharpoons 3Mn^{++} + SO_4^= + 2H_2O \qquad (8)$$

This reaction has been used to explain the increases in available Mn above that due to pH in various studies (5, 16, 46).

METHODS AND MATERIALS

Field Experiments

Exp. I Effect of Rate and Method of Application of Sulfur-Phosphorus Solutions on Yield and Nutrient Concentration of Corn.

This study with irrigated corn was conducted on a fine sandy loam alluvial soil along the Kansas River in Pottawatomie County, Kansas. Five combinations of liquid ammonium thiosulfate (12-0-0-26S) and liquid ammonium polyphosphate (10-34-0) were applied by three methods. Application methods included knifing the liquids into the soil to a depth of about 18 cm, broadcasting (spraying on the soil surface), and banding near the seed at the time of planting. Nitrogen, to balance the N in the liquid S and P materials at 280 kg/ha, was supplied as a non-pressure urea-ammonium nitrate (32% N) solution.

'DeKalb XL 390' corn was planted in 89 cm rows with four rows per plot. Herbicides (Ramrod and Atrazine) and insecticide (Diasinon) were applied to the study and irrigation water was applied as needed.

The first full leaf at the 8 leaf stage and the ear leaf at tasseling were collected from 8 plants. The leaves were washed with distilled and deionized water and oven dried at 60^{o}C for three days. The samples were ground through a Wiley mill using stainless steel knives and screens (40 mesh) and then stored for analysis.

Grain was hand harvested from the two center rows, shelled, and weighed for yield. Moisture content was determined and yield was adjusted to that of no. 2 corn (15.5% moisture).

Exp. II Effect of Rate and Method of Application of Sulfur and Phosphorus on Yield and Nutrient Concentration of Winter Wheat.

Sulfur-Phosphorus dual application studies were initiated at five locations in the fall of 1969 on winter wheat. Sites in Greeley, Thomas, and Cheyenne counties were located on calcareous, silt loam soils while those in Pawnee and Stafford counties were on sandy loams. Liquid sulfur and phosphorus were supplied in the forms of ammonium thiosulfate and ammonium polyphosphate at all locations. Nitrogen was balanced at 56 kg/ha with 32% N solution.

At the Greeley, Thomas, Cheyenne, and Stafford County locations, the liquids were knifed into the soils at a depth of approximately 18 cm prior to planting. At the Pawnee County location, two methods of application were employed. A broadcast application consisted of spraying the liquid(s) on the soil surface while the band application placed the liquid near the seed at the time of planting.

Leaf tissue samples were collected during the first weeks in November and April. Preparation of wheat tissue for analysis was identical to that for corn tissue.

The wheat grain was harvested mechanically from a 2.2 X 15.2 meter strip and weighed for yield. The grain was tested for moisture and yield was adjusted to 12.5% moisture.

Growth Chamber Study

Exp. I Effect of Rate and Simulated Method of Application of Sulfur, Phosphorus, and Sulfur-Phosphorus Mixtures on Growth and Nutrient Concentration of Corn.

The soil for this study, a Ulysses silt loam, was taken from the top 20 cm of an irrigated field in Greeley County, Kansas. The field had been leveled and under irrigation for a number of years thereby offering a potential sulfur depleted soil.

Five combined nutrient rates and three methods of application were used in this experiment. The treatment rates in ppm consisted of 25 S, 50 S, 50 P, 25 S-50 P, and 50 S-50 P using ammonium thiosulfate and ammonium polyphosphorus as sources for S and P respectively. Simulated methods of application were termed knifed, broadcast, and band.

The containers for the soil were made of plywood and were constructed 15 cm wide, 15 cm deep, and 25 cm long. Urea to balance the nitrogen at 150 ppm was added to the air-dried soil at the time the containers were filled.

The knifed method (Fig. 1) of application consisted of removing the top 11 cm of soil, pipetting the liquid fertilizer the length of the container and refilling with the soil removed. The broadcast method (Fig. 2) was performed by removing the top half of the soil, spraying and mixing the solutions into the removed soil and refilling. The band application (Fig. 3) was identical to the knifed treatment with the exception of being applied at a shallower (4 cm) depth.

The soils were incubated at 28°C for a four-week period at a 30% moisture level. The broadcast and knifed treatments were applied prior to incubation to allow the sulfur to oxidize, simulating pre-plant treatments. The band treatment was applied after incubation at the time of planting.

'DeKalb XL 390' corn seed was planted in pairs at 5 cm intervals down the center of the container. The containers were then placed in the growth chamber at 30 C day-20 C night temperatures. Moisture level was held at 30% by regular additions of distilled water. Treatments were thinned to 5 plants per container after 6 days.

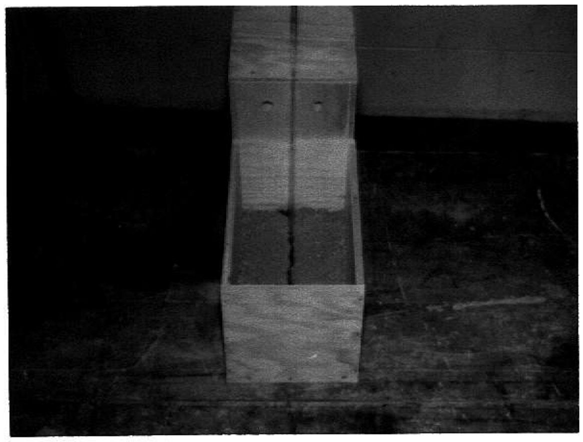

Fig. 1. Knifed method of application

Fig. 2. Broadcast method of application

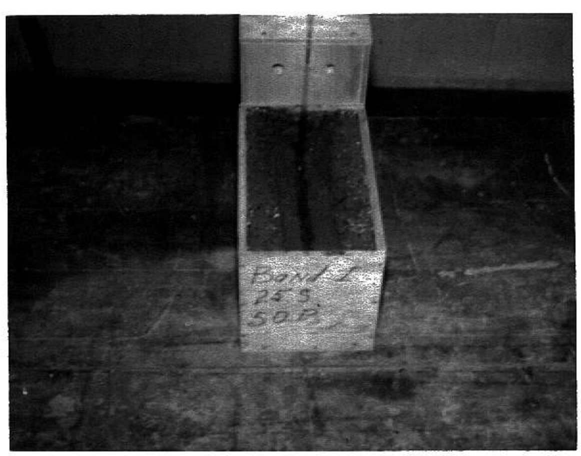

Fig. 3. Band method of application

The three center plants were harvested at the base after 25 days in the growth chamber. The plant material was oven dried for 3 days at 60 C and weighed for dry matter yield. The samples were then ground in a Wiley mill and stored in plastic containers for analysis.

Exp. II Effect of Sulfur on Soil Chemical Properties.

After harvesting in the experiment described above, soil samples were collected on 2.5 cm centers throughout the vertical profile of the knifed and band applications of the 50 S-50 P treatment. These samples were analyzed for pH. Samples from the band treatment were also analyzed for available SO_4-S, P, Mn, and Fe.

Soil Analysis

Organic matter, available P, and exchangeable K were determined by the Kansas State University Soil Testing Laboratory. Organic matter was determined by the colorimetric chromic acid wet-oxidation procedure. Bray's P-1 test (fluoride-extractable P) was used in the analysis of available P. Exchangeable K was extracted with ammonium acetate and concentration was determined with a Perkin-Elmer flamephotometer. The Beckman 180 single electrode pH meter was employed to evaluate soil reaction. Available soil sulfates were extracted with Morgan's solution (30 ml of 99.5% acetic acid and 100 g of Na Acetate per liter of solution) and determined turbidimetrically by the method of Chesnin and Yien (11). The centrifuge procedure according to Jackson (23) was used for determining cation exchange capacity. The method involved saturating exchange sites on the colloids with Ca and replacement of Ca with ammonium. Concentration of displaced Ca in solution was determined with a Perkin-Elmer Model 303 atomic absorption spectrophotometer.

Plant Analysis

The nitro-perchloric acid wet digestion procedure of Early and DeTurk (12) was used to prepare plant samples for analysis. The digestion mix of 0.25 g plant material, 5 ml 70% HNO_3, 5 ml 70% $HClO_4$, and 5 ml H_2O was evaporated to dryness and the salts were dissolved in approximately 20 ml of 0.1 N HCl. Silica was removed by filtering through Whatman No. 42 paper and the filtrate was diluted to 25 ml with 0.1 N HCl. From 10 ml aliquots of the filtrate, S was determined by the turbidimetric method of sulfate analysis by Chesnin and Yien (11) and P was determined colorimetrically by the vanadomolybdophosphoric yellow color method of Jackson (23). Cations were determined directly from the filtrate or from dilutions of the filtrate. Potassium was determined by flamephotometry, and Fe, Zn, Mn, and Cu were determined by atomic absorption spectrophotometry. The macro-Kjeldahl technique of Piper (36) was used to analyze for total nitrogen.

RESULTS AND DISCUSSION

Field Experiments

Exp. I Effect of Rate and Method of Application of Sulfur-Phosphorus Solutions on Yield and Nutrient Concentration of Corn.

Soil test data in Table I suggests the Cass fine sandy loam at the Pottawatomie County site could be responsive to sulfur and phosphorus applications. Organic matter and cation exchange capacity were also low, adding to fertility problems.

TABLE I

SOIL TEST DATA FOR SPRING OF 1969, POTTAWATOMIE COUNTY, KANSAS

pH	OM %	C.E.C. meq/100g	SO_4-S kg/ha	Avail. P kg/ha	Exch. K kg/ha
8.1	0.9	9.8	12.4	23.8	223

The objectives of this experiment were to determine plant responses to S applications on a potentially S-depleted soil and to study the effects of S on availability of P and micronutrients. The oxidation process that occurs when thiosulfate-S is converted to sulfate-S produces protons which serve to increase the acidity of the soil (8). The fact that the solubility of P increases as the pH is lowered (47) would indicate that applying oxidizable S might improve the availability of soil P. Sulfur, in combination with P fertilizers, might also be beneficial in preventing the formation of less available forms of the applied P.

The nutrient concentrations of corn leaf tissue are reported in Tables II and III. Manganese concentration at the first sampling date was significantly increased by sulfur additions of 22 and 45 kg/ha with the band method of application and by all methods at the 90 kg/ha level. The increased availability of Mn may have been due to a lowering of soil pH (41) or the reduction of MnO_2 made possible by release of electrons during sulfur oxidation (19).

Significant increases in the percent P were observed in all treatments at the June sampling. The response appeared to be due to applied phosphorus and was accompanied by marked visual responses. There were no apparent increases in P uptake which could be related to sulfur additions as suggested by Hassan and Olson (18).

Leaf tissue samples taken in August indicated an increase in percent S in the leaf tissue. Application of 45 and 90 kgS/ha by the band method significantly increased the plant S content at the 10% level.

The yield and nutrient concentration of corn grain, shown in Table IV, were influenced by the method of application. Banding the fertilizer solutions gave significantly higher yields at all rates with the best yield recorded at the 40 P-10 S rate. Yields for knifed applications of P and S were generally higher than the check but consistently lower than those achieved by the band method. Little response was shown by the broadcast treatment.

No significant trends in N, K, Fe, Zn, and Cu concentrations in the samples were observed in this study. The large variance in values obtained between replications due to land leveling was a factor attributing to this.

TABLE II

EFFECT OF RATE AND METHOD OF APPLICATION OF SULFUR-PHOSPHORUS SOLUTIONS ON COMPOSITION OF CORN TISSUE
Pottawatomie County, Kansas June 1969

Treatment P	Treatment S	Method of P-S Application	S	P	N	K	Fe	Zn	Mn	Cu
			Nutrient Element Concentration in Corn Tissue							
kg/ha			%				ppm			
0	0	------	.137	.150	2.64	2.59	190	38.9	59.1	10.9
40	0	Knifed	.127	.204	2.48	2.35	172	37.6	49.3	10.3
40	0	B'cast	.128	.191	2.46	2.73	222	56.4	65.9	10.9
40	0	Band	.126	.186	2.58	2.63	194	49.5	66.7	10.8
40	11	Knifed	.140	.176	2.74	2.53	235	57.0	63.7	11.2
40	11	B'cast	.137	.209	2.53	2.64	176	47.9	64.9	14.5
40	11	Band	.141	.181	2.72	2.22	170	57.5	55.7	11.2
40	22	Knifed	.136	.204	2.65	2.59	199	47.3	66.0	10.2
40	22	B'cast	.148	.187	2.80	2.39	193	50.2	64.1	11.4
40	22	Band	.154	.177	2.82	2.28	192	56.5	79.2	11.8
40	45	Knifed	.140	.196	2.58	2.61	216	60.8	55.9	10.8
40	45	B'cast	.148	.221	2.77	2.94	196	59.8	66.4	12.2
40	45	Band	.153	.178	2.95	2.16	173	46.9	77.1	11.5
40	90	Knifed	.137	.202	2.53	2.42	186	53.1	77.3	11.1
40	90	B'cast	.163	.189	2.34	2.52	185	50.6	67.2	11.5
40	90	Band	.153	.212	2.91	2.18	185	56.6	76.3	11.8
$LSD_{(0.10)}$			NS	.024	NS	NS	NS	NS	15.2	NS

TABLE III

EFFECT OF RATE AND METHOD OF APPLICATION OF SULFUR-PHOSPHORUS SOLUTIONS ON COMPOSITION OF CORN TISSUE
Pottawatomie County, Kansas August 1969

Treatment P	Treatment S	Method of P-S Application	S	P	N	K	Fe	Zn	Mn	Cu
			Nutrient Element Concentration in Corn Tissue							
kg/ha			%				ppm			
0	0	------	.127	.135	2.19	2.01	89.7	33.1	50.1	4.10
40	0	Knifed	.110	.143	1.82	1.96	92.1	28.7	48.9	4.22
40	0	B'cast	.110	.148	1.93	1.98	100.8	31.8	47.9	2.85
40	0	Band	.147	.166	2.51	1.80	98.4	38.8	61.0	6.42
40	11	Knifed	.120	.142	1.96	1.96	81.4	39.5	57.6	4.02
40	11	B'cast	.114	.159	2.12	1.82	89.1	25.5	53.6	4.02
40	11	Band	.132	.165	2.37	2.02	90.9	49.1	57.3	5.87
40	22	Knifed	.141	.181	2.47	2.01	96.3	54.5	61.4	4.45
40	22	B'cast	.135	.167	2.13	1.91	94.2	22.2	56.0	4.92
40	22	Band	.146	.183	2.36	1.84	100.6	34.9	67.3	5.27
40	45	Knifed	.131	.158	2.23	1.78	81.3	38.6	60.4	3.77
40	45	B'cast	.119	.173	2.14	1.95	89.6	38.5	61.2	4.62
40	45	Band	.158	.155	2.35	1.86	96.2	44.3	58.9	5.25
40	90	Knifed	.144	.165	2.49	2.03	112.7	48.1	67.3	5.50
40	90	B'cast	.142	.165	2.30	2.00	98.8	27.4	59.4	5.22
40	90	Band	.154	.174	2.23	1.79	110.7	38.2	66.9	5.87
$LSD_{(0.10)}$			.023	NS	0.37	NS	NS	NS	NS	NS

TABLE IV

EFFECTS OF RATE AND METHOD OF APPLICATION OF SULFUR-PHOSPHORUS SOLUTIONS ON YIELD AND COMPOSITION OF CORN GRAIN
Pottawatomie County, Kansas Fall 1969

Treatment		Method of P-S		Nutrient Element Concentration of Corn Grain							
P	S	Application	Yield	S	P	N	K	Fe	Zn	Mn	Cu
kg/ha			kg/ha	-------------%-------------				-------------ppm-------------			
0	0	------	4233	.092	.194	1.43	.297	13.3	28.2	6.15	4.35
40	0	Knifed	3897	.092	.220	1.33	.302	13.3	23.3	5.60-	3.75
40	0	B'cast	5577	.087	.196	1.32	.297	16.5	32.3	6.47	3.47
40	0	Band	7324	.091	.191	1.38	.360	13.4	21.3	6.40	3.20
40	11	Knifed	4704	.085	.206	1.30	.285	15.5	18.4	5.67	3.75
40	11	B'cast	4502	.089	.211	1.22	.335	13.3	25.1	6.72	3.75
40	11	Band	7795	.085	.187	1.39	.290	16.5	28.7	5.90	3.47
40	22	Knifed	5712	.092	.252	1.33	.325	19.7	26.5	5.90	4.35
40	22	B'cast	3897	.088	.192	1.32	.240	13.3	26.0	5.07	3.47
40	22	Band	7392	.091	.189	1.43	.292	14.8	23.7	6.15	3.47
40	45	Knifed	6182	.089	.233	1.39	.342	13.7	26.4	5.97	3.47
40	45	B'cast	3696	.090	.243	1.26	.350	17.0	21.7	5.90	3.20
40	45	Band	6451	.094	.173	1.45	.277	18.4	32.2	5.65	3.82
40	90	Knifed	5040	.092	.205	1.49	.297	14.3	22.3	6.40	3.47
40	90	B'cast	4099	.091	.221	1.31	.300	16.5	47.7	5.21	3.20
40	90	Band	6384	.092	.179	1.29	.305	16.5	21.9	4.85	3.82
$LSD_{(0.10)}$			1680	NS	.038	.013	.053	NS	NS	NS	NS

Exp. II Effect of Rate and Method of Application of Sulfur and Phosphorus on Yield and Nutrient Concentration of Winter Wheat.

Results of this field experiment were influenced by the favorable moisture conditions that existed during the fall and spring. Grain yields in Stafford and Pawnee Counties were 600 to 900 kg/ha (10-15 bu/A) above average while those in Greeley, Thomas, and Cheyenne Counties were 1200 to 1800 kg/ha (20-30 bu/A) higher.

Greeley County

Soil analysis data from Table V indicate the high fertility level of this Richfield silt loam. Available plant P and SO_4-S were determined to be sufficient for plant requirements. The site was chosen in hopes of showing increased P and micronutrient uptake due to S additions.

The nutrient concentration of wheat tissue and grain along with grain yields are reported in Table VI. Data from the leaves sampled in the spring showed treatments with S alone and P-S combinations produced significantly higher plant P concentrations than check and the P-only treatments. This agrees with the enhancing effect of S on P uptake reported by Kittams and Attoe (26) and by Hassan and Olson (18).

The nutrient concentrations of S, N, K, Fe, Mn, Zn, and Cu as well as the yield were not significantly affected by treatment in this study.

Thomas County

Soil analysis data of the Keith silt loam from the Thomas County site presented in Table V indicate only moderate amounts of available SO_4-S. Available P and exchangeable K were adequate to meet requirements of small grains.

TABLE V

SOIL DATA FOR SITES OF P-S STUDIES ON WHEAT
Fall 1969

Location	pH	OM %	C.E.C. meq/100g	SO_4-S kg/ha	Avail. P kg/ha	Exch. K kg/ha
Greeley County	7.8	1.4	21.8	47.8	95	1000+
Thomas County	8.0	1.3	24.0	22.8	53	1000+
Cheyenne County	7.6	1.2	22.3	43.4	47	1000+
Stafford County	7.0	.8	7.3	14.8	66	560
Pawnee County	7.1	.4	4.6	10.5	23	392

TABLE VI EFFECTS OF RATE OF SULFUR, PHOSPHORUS, AND SULFUR-PHOSPHORUS APPLICATIONS ON COMPOSITION OF WHEAT TISSUE AND WHEAT GRAIN YIELDS

GREELEY COUNTY, KANSAS

Treatment P	Treatment S	Nutrient Element Concentration in Wheat Tissue--Nov. 12, '69 S	P	N	K	Fe	Zn	Mn	Cu
kg/ha		%				ppm			
0	0	.326	.447	5.74	3.14	355	39.9	123	7.2
0	11	.313	.452	5.64	3.20	391	39.0	138	8.7
0	22	.303	.441	5.63	3.22	387	37.7	129	7.2
0	45	.331	.435	5.58	3.05	371	49.2	109	5.2
25	0	.306	.442	5.65	3.07	363	39.3	131	6.6
25	11	.323	.409	5.65	2.97	338	51.7	111	9.2
25	22	.323	.454	5.73	3.24	408	52.5	135	9.8
25	45	.309	.401	5.73	3.19	371	43.2	124	8.2
$LSD_{(0.10)}$		.012	NS	NS	NS	NS	NS	13	NS

Treatment P	Treatment S	Nutrient Element Concentration in Wheat Tissue--Apr. 11, '70 S	P	N	K	Fe	Zn	Mn	Cu
kg/ha		%				ppm			
0	0	.336	.332	5.26	3.16	198	20.2	160	8.2
0	11	.335	.342	5.29	3.15	172	22.0	155	8.3
0	22	.326	.349	5.30	3.22	159	20.3	147	9.4
0	45	.345	.383	5.22	3.25	188	25.9	148	8.8
25	0	.341	.334	5.34	3.13	185	16.6	161	8.7
25	11	.361	.369	5.38	3.25	151	22.5	140	8.8
25	22	.343	.365	5.34	3.25	164	18.3	143	8.5
25	45	.342	.321	5.35	3.16	155	17.9	153	8.0
$LSD_{(0.10)}$		NS	.032	NS	NS	NS	NS	NS	NS

Treatment P	Treatment S	Yield and Composition of Wheat Grain Yield	S	P	N
kg/ha		kg/ha	%		
0	0	3669	.128	.289	2.73
0	11	3844	.116	.263	2.69
0	22	4126	.121	.260	2.66
0	45	4395	.108	.259	2.54
25	0	4449	.115	.240	2.47
25	11	3904	.119	.271	2.65
25	22	3501	.122	.309	2.81
25	45	4025	.110	.274	2.78
$LSD_{(0.10)}$		NS	NS	NS	NS

Sulfur applications increased the N and K concentration in tissue sampled in the spring (Table VII). According to Eaton (14), S may be the limiting factor in protein formation and when added, the nitrogen content of plants will increase. The increase in concentration of K by S applications is in agreement with work reported by Nielsen et al. (34).

The P concentration in wheat grain was increased by S applications. All treatments receiving S alone were significantly higher in P than the check. This appeared to be a carry over of increased P concentration in tissue sampled in the spring. Grain yield and concentrations of S, Fe, Zn, Mn, and Cu in the leaf tissue and grain were not affected by sulfur treatments (Table VII).

Cheyenne County

The soil analysis data of the Keith silt loam from the Cheyenne County site are given in Table V. Available SO_4-S and exchangeable K were found to be high while available P was potentially limiting at high yields.

Table VIII contains data on the composition and yield of wheat grown in Cheyenne County. The concentrations of P and S in the tissue at the first sampling date were significantly affected by treatment. The increase in percent P in plant tissue appeared to be a response to fertilizer P rather than an enhancing effect caused by S. Sulfur treatments had a higher S concentration in the tissue than the check and P only treatments. There was some carry over of increased S in the second sampling but no response was noted in total yield. Micronutrients were not significantly affected by S applications at this location.

TABLE VII EFFECTS OF RATE OF SULFUR, PHOSPHORUS, AND SULFUR-PHOSPHORUS APPLICATIONS ON COMPOSITION OF WHEAT TISSUE AND WHEAT GRAIN YIELDS

THOMAS COUNTY, KANSAS

Treatment		Nutrient Element Concentration in Wheat Tissue--Nov. 12, '69							
P	S	S	P	N	K	Fe	Zn	Mn	Cu
kg/ha		%				ppm			
0	0	.299	.251	5.11	2.84	398	32.1	109	9.5
0	11	.290	.250	5.05	2.90	490	46.9	112	10.1
0	22	.296	.250	5.10	2.92	454	38.7	108	9.9
0	45	.291	.247	5.10	2.84	417	36.3	103	9.8
25	0	.295	.272	5.13	2.95	413	26.8	112	8.7
25	11	.301	.268	5.19	2.86	341	39.1	103	9.3
25	22	.294	.288	5.06	2.87	427	31.3	105	8.9
25	45	.296	.250	4.99	2.81	462	27.7	107	9.6
$LSD_{(0.10)}$		NS	NS	NS	NS	NS	NS	NS	NS

Treatment		Nutrient Element Concentration in Wheat Tissue--Apr. 11, '70							
P	S	S	P	N	K	Fe	Zn	Mn	Cu
kg/ha		%				ppm			
0	0	.269	.235	5.01	3.07	120	46.2	106	9.5
0	11	.291	.245	5.18	3.25	127	38.8	97	10.3
0	22	.304	.253	5.44	3.18	109	29.3	107	10.8
0	45	.295	.254	5.54	3.16	131	42.1	99	11.2
25	0	.287	.230	5.16	3.22	108	28.3	111	8.9
25	11	.311	.253	5.43	3.41	112	35.3	105	10.1
25	22	.298	.250	5.34	3.27	125	24.0	110	9.2
25	45	.329	.272	5.45	3.37	132	28.1	108	10.2
$LSD_{(0.10)}$		NS	.032	0.26	0.18	NS	20.8	NS	NS

Treatment		Yield and Composition of Wheat Grain			
P	S	Yield	S	P	N
kg/ha		kg/ha	%		
0	0	2728	.094	.293	2.11
0	11	2338	.110	.321	2.46
0	22	2298	.114	.334	2.33
0	45	2305	.106	.322	2.33
25	0	2251	.124	.342	2.52
25	11	2123	.115	.341	2.72
25	22	2782	.101	.320	2.39
25	45	2433	.095	.322	2.45
$LSD_{(0.10)}$		NS	.022	.023	NS

TABLE VIII EFFECTS OF RATE OF SULFUR, PHOSPHORUS, AND SULFUR-PHOSPHORUS APPLICATIONS ON COMPOSITION OF WHEAT TISSUE AND WHEAT GRAIN YIELDS

CHEYENNE COUNTY, KANSAS

Treatment		Nutrient Element Concentration in Wheat Tissue--Nov. 12, '69							
P	S	S	P	N	K	Fe	Zn	Mn	Cu
kg/ha		%				ppm			
0	0	.287	.326	5.24	3.34	275	33.7	94	7.2
0	11	.317	.320	5.31	3.37	295	46.4	92	7.4
0	22	.314	.322	5.25	3.43	258	35.5	92	7.4
0	45	.296	.306	5.15	3.22	286	46.1	103	6.8
25	0	.291	.353	5.26	3.58	306	42.8	109	8.3
25	11	.316	.352	5.25	3.29	285	36.1	105	6.8
25	22	.311	.335	5.28	3.15	271	37.9	93	6.6
25	45	.321	.357	5.45	3.39	271	41.1	87	6.6
$LSD_{(0.10)}$		.014	.024	NS	NS	NS	NS	NS	NS

Treatment		Nutrient Element Concentration in Wheat Tissue--Apr. 11, '70							
P	S	S	P	N	K	Fe	Zn	Mn	Cu
kg/ha		%				ppm			
0	0	.329	.299	5.55	3.34	146	39.1	108	14.2
0	11	.335	.301	5.50	3.39	127	52.9	101	14.1
0	22	.331	.295	5.46	3.31	129	90.8	103	14.5
0	45	.304	.304	5.45	3.36	140	68.7	124	14.6
25	0	.292	.322	5.47	3.30	126	33.4	134	15.2
25	11	.322	.308	5.52	3.36	127	79.8	127	14.5
25	22	.350	.339	5.44	3.37	118	37.0	114	13.4
25	45	.349	.322	5.63	3.42	134	67.5	115	13.5
$LSD_{(0.10)}$		.026	NS	NS	NS	NS	NS	NS	NS

Treatment		Yield and Composition of Wheat Grain			
P	S	Yield	S	P	N
kg/ha		kg/ha	%		
0	0	3205	.097	.268	2.10
0	11	3178	.096	.271	2.09
0	22	3105	.094	.281	2.03
0	45	3246	.091	.281	2.09
25	0	3353	.097	.263	1.97
25	11	3239	.091	.278	2.02
25	22	3199	.092	.280	2.09
25	45	3232	.097	.264	2.07
$LSD_{(0.10)}$		NS	NS	NS	NS

Stafford County

Analysis of soil from the Stafford County site reported in Table V indicated that the Pratt loamy sand was low in organic matter, C.E.C., and available SO_4-S. Available P and extractable K were determined to be high for wheat requirements.

Yield and tissue composition data obtained from the Stafford County site are presented in Table IX. The Fe concentration of the wheat tissue was significantly increased at the two high S fertilization levels at the first sampling date. This enhancing effect agrees with Tisdale and Bertramson (46) who reported the ability of S to reduce Fe and Mn to an available state while S is being oxidized.

Sulfur treatments were beneficial to P nutrition at the second sampling date. Sulfur-only treatments increased the P concentration of tissue over that of the check while S-P combinations were more beneficial than the P-only treatment. These increases were similar to results found at the Greeley County site and can be attributed to the enhancing effect of S.

Yield data surprisingly revealed the check plots to be significantly higher than those receiving S treatments. Observations of the study throughout the growing season indicated a positive response to P and S fertilization. The decreased size and density of plants on the check plots may have been advantageous to moisture conditions during the maturing stage.

Pawnee County

The organic matter, C. E. C., and SO_4-S levels, as shown in Table V, were very low for the Lincoln sandy loam at the Pawnee County site. The available P was determined to be low and exchangeable K adequate for plant requirements.

TABLE IX EFFECTS OF RATE OF SULFUR, PHOSPHORUS, AND SULFUR-PHOSPHORUS APPLICATIONS ON COMPOSITION OF WHEAT TISSUE AND WHEAT GRAIN YIELDS

STAFFORD COUNTY, KANSAS

Treatment		Nutrient Element Concentration in Wheat Tissue--Nov. 11, '69							
P	S	S	P	N	K	Fe	Zn	Mn	Cu
kg/ha		%				ppm			
0	0	.302	.284	5.22	3.75	209	25.9	55	4.2
0	11	.305	.277	4.95	3.69	224	28.2	43	5.7
0	22	.307	.290	5.08	3.61	223	23.5	42	3.8
0	45	.320	.294	4.96	3.68	251	27.6	44	4.4
25	0	.304	.318	5.14	3.67	222	24.6	43	4.5
25	11	.304	.339	5.14	3.54	218	23.3	50	4.2
25	22	.315	.358	5.28	3.61	211	23.3	46	4.0
25	45	.312	.310	5.13	3.75	269	24.4	44	3.8
$LSD_{(0.10)}$		NS	.034	NS	NS	36	3.1	6	NS

Treatment		Nutrient Element Concentration in Wheat Tissue--Apr. 7, '70							
P	S	S	P	N	K	Fe	Zn	Mn	Cu
kg/ha		%				ppm			
0	0	.243	.286	3.96	2.37	88	27.3	47	5.0
0	11	.220	.306	3.79	2.36	82	33.6	40	5.9
0	22	.228	.319	3.86	2.37	88	25.9	48	5.4
0	45	.227	.330	4.00	2.42	95	20.9	52	4.9
25	0	.218	.338	3.86	2.37	90	29.0	50	5.1
25	11	.214	.347	3.81	2.32	86	19.0	47	5.1
25	22	.215	.365	3.74	2.24	83	30.9	55	4.8
25	45	.207	.359	3.77	2.26	81	33.3	55	5.7
$LSD_{(0.10)}$		.017	.047	NS	.08	NS	NS	NS	NS

Treatment		Yield of Wheat Grain
P	S	
kg/ha		kg/ha
0	0	3192
0	11	2708
0	22	2547
0	45	2668
25	0	2869
25	11	2654
25	22	2802
25	45	2748
$LSD_{(0.10)}$		423

Sulfur applied at high rates with the seed by the band method had a damaging effect on germination (Fig. 4). Damage was only slight at low rates, however, and surviving plants appeared to be more vigorous (Fig. 5).

Tissue nutrient concentrations were strongly influenced by the method of application of S and P (Tables X and XI). In both the first and second samplings, concentrations of S, P, and N were considerably higher with band applications. This can be attributed to the placement of the solutions near the seed as well as the decreased plant population brought on by the S treatments.

Grain yields (Table XII) were generally higher on plots that received P. The combination of the band method of application and the 22 P-10 S rate provided the highest yield indicating a response to both P and S. Plots severely damaged during germination recovered to yield within 200 kg/ha of the check.

Growth Chamber Study

Exp. I Effect of Rate and Simulated Method of Application of Sulfur, Phosphorus, and Sulfur-Phosphorus Mixtures on Growth and Nutrient Concentration of Corn.

Soil analysis data from Table XIII indicated the Ulysses silt loam soil used in the growth chamber study was low in available P, SO_4-S, and organic matter. Exchangeable K was adequate for corn requirements.

This investigation on a potentially S depleted soil studied 3 simulated methods of application of S and P. Intentions were to determine plant responses to S and to investigate possible enhanced uptake of P and micronutrients that accompany the oxidation of S.

Fig. 4. Effect of banding sulfur at high rates on the germination of wheat.

Fig. 5. Comparison of the low S-P band treatment (right) and the check (left).

TABLE X

EFFECT OF RATE AND METHOD OF APPLICATION OF SULFUR, PHOSPHORUS, AND SULFUR-PHOSPHORUS SOLUTIONS ON COMPOSITION OF WHEAT TISSUE
Pawnee County, Kansas Fall 1969

Treatment		Method of P-S	Nutrient Element Concentration in Wheat Tissue							
P	S	Application	S	P	N	K	Fe	Zn	Mn	Cu
kg/ha			-------%			-------	------ppm			------
0	0	------	.285	.245	5.13	3.18	183	37.1	71.2	5.52
0	11	B'cast	.314	.270	4.96	3.31	184	37.5	67.1	8.07
0	11	Band	.320	.241	5.09	3.39	185	54.4	64.9	5.27
0	22	B'cast	.323	.238	4.98	3.92	192	29.2	62.3	5.70
0	22	Band	.386	.220	5.00	3.06	174	32.2	69.9	5.92
0	45	B'cast	.336	.227	4.90	3.21	180	33.9	72.3	5.70
0	45	Band	.409	.235	5.05	3.21	198	51.7	70.6	5.72
25	0	B'cast	.281	.288	5.30	3.42	144	26.5	66.9	5.72
25	0	Band	.316	.422	5.64	3.21	165	24.0	71.7	6.35
25	11	B'cast	.329	.288	5.29	3.19	146	45.0	64.2	5.47
25	11	Band	.373	.403	5.56	3.13	150	47.9	65.2	6.17
25	22	B'cast	.342	.280	5.34	3.22	140	27.2	64.1	5.07
25	22	Band	.361	.318	5.26	3.14	191	53.4	66.6	5.50
25	45	B'cast	.349	.285	5.29	3.23	170	42.1	64.2	5.95
25	45	Band	.360	.269	5.33	3.05	204	43.1	67.4	6.15
$LSD_{(0.10)}$			.030	.030	0.20	NS	NS	17.5	NS	NS

TABLE XI

EFFECT OF RATE AND METHOD OF APPLICATION OF SULFUR, PHOSPHORUS, AND SULFUR-PHOSPHORUS SOLUTIONS ON COMPOSITION OF WHEAT TISSUE
Pawnee County, Kansas Spring 1970

Treatment P	Treatment S	Method of P-S Application	S	P	N	K	Fe	Zn	Mn	Cu
kg/ha			%				ppm			
0	0	------	.277	.276	4.63	2.54	98	42.2	92	4.57
0	11	B'cast	.254	.201	4.33	2.32	113	49.6	101	4.38
0	11	Band	.301	.241	4.73	2.68	125	57.3	95	4.30
0	22	B'cast	.256	.211	4.13	2.28	108	26.8	103	4.01
0	22	Band	.285	.245	4.81	2.66	100	27.3	91	4.58
0	45	B'cast	.251	.216	4.20	2.31	93	41.1	93	5.34
0	45	Band	.293	.231	4.84	2.58	115	34.3	86	4.35
25	0	B'cast	.262	.265	4.27	2.38	104	23.4	106	4.51
25	0	Band	.275	.364	4.73	2.48	115	58.0	109	5.72
25	11	B'cast	.278	.258	4.37	2.34	98	36.3	111	5.23
25	11	Band	.307	.366	4.17	2.53	99	33.6	113	4.94
25	22	B'cast	.273	.279	4.24	2.25	114	23.5	112	5.00
25	22	Band	.327	.358	4.99	2.66	96	67.5	97	4.12
25	45	B'cast	.265	.264	4.29	2.13	94	60.0	109	4.35
25	45	Band	.315	.322	5.11	2.58	117	24.9	92	4.09
$LSD_{(0.10)}$			.022	.042	.28	.17	NS	NS	14	NS

TABLE XII

EFFECT OF RATE AND METHOD OF APPLICATION OF SULFUR, PHOSPHORUS, AND SULFUR-PHOSPHORUS SOLUTIONS ON YIELD AND COMPOSITION OF WHEAT GRAIN
Pawnee County, Kansas Summer 1970

Treatment P	Treatment S	Method of P-S Application	Yield	Nutrient Element Concentration in Wheat Grain S	P	N
kg/ha			kg/ha		%	
0	0	------	2191	.116	.259	2.67
0	11	B'cast	2043	.110	.258	2.41
0	11	Band	2117	.120	.280	2.61
0	22	B'cast	2251	.114	.295	2.40
0	22	Band	1949	.117	.257	2.63
0	45	B'cast	2137	.109	.272	2.45
0	45	Band	1949	.128	.283	2.66
25	0	B'cast	2291	.108	.289	2.54
25	0	Band	2547	.122	.324	2.41
25	11	B'cast	2506	.104	.292	2.41
25	11	Band	2621	.123	.313	2.57
25	22	B'cast	2406	.115	.274	2.40
25	22	Band	2197	.127	.316	2.70
25	45	B'cast	2332	.118	.298	2.38
25	45	Band	2016	.128	.288	2.73
$LSD_{(0.10)}$				NS	.043	.20

TABLE XIII

SOIL ANALYSIS DATA FOR GROWTH CHAMBER STUDY

pH	OM %	C.E.C. meq/100g	SO_4-S kg/ha	Avail. P kg/ha	Exch. K kg/ha
7.6	1.1	20.8	11.9	26.8	941

Nutrient concentrations and dry matter yield of the corn tissue are reported in Table XIV. Plant S content responded to additions of S as ammonium thiosulfate. All methods of application produced increases in percent S with the high (50 S) rate giving the greater concentration increase.

Nitrogen concentrations in the whole plants were generally significantly lower than the check when S and P were broadcast. This was presumably due to the dilution effect caused by higher yields because total N uptake (yield X %N) increased. Plants apparently grew better in the presence of adequate S and thus were able to utilize more N because of generally healthier conditions.

Dry matter yields were found to be significantly increased by both S and P treatments. The small variations in yield for the P-only treatment by all methods of application (4.10, 4.07, and 4.12 gms) would tend to suggest that differences in dry weight were due to S and its placement. Germination and early growth were retarded by banding S below the seed and little increase in dry weight was noted both with and without P by this method.

The knifed S applications increased plant growth considerably in the case of the S-only treatments, but dry weight decreased when P was added (Fig. 6). Since both S and P are taken up in the form of anions (47),

TABLE XIV

EFFECT OF RATE AND SIMULATED METHODS OF APPLICATION OF SULFUR, PHOSPHORUS, AND SULFUR-PHOSPHORUS SOLUTIONS ON TOTAL NUTRIENT UPTAKE OF CORN
Growth Chamber Study

Treatment P	Treatment S	Method of P-S Application	Yield	S	P	N	K	Fe	Zn	Mn	Cu
				Nutrient Element Concentration of Corn Grain							
ppm			gm	%				ppm			
0	0	------	2.72	.148	.172	3.50	5.55	41.3	70.9	138	11.2
0	25	Knifed	4.32	.171	.200	3.45	6.08	44.1	49.7	125	15.0
0	25	B'cast	4.56	.151-	.182	3.36	6.23	36.7	40.7	112	9.3
0	25	Band	3.57	.178	.204	3.44	6.06	42.4	40.8	122	8.7
0	50	Knifed	4.58	.174	.203	3.40	5.90	47.7	49.0	128	8.0
0	50	B'cast	3.82	.179	.202	3.54	6.04	40.1	45.7	127	8.9
0	50	Band	3.03	.172	.195	3.53	6.08	43.8	62.1	126	10.0
50	0	Knifed	4.10	.148	.193	3.42	6.08	41.9	49.6	127	7.5
50	0	B'cast	4.07	.154	.216	3.52	6.16	44.3	45.9	125	8.7
50	0	Band	4.12	.154	.176	3.06	5.88	36.7	42.8	114	6.2
50	25	Knifed	3.59	.158	.188	3.40	6.09	47.1	41.5	123	9.4
50	25	B'cast	4.90	.160	.192	3.25	6.01	51.2	41.9	125	11.2
50	25	Band	3.32	.164	.193	3.29	5.97	54.4	68.0	119	10.7
50	50	Knifed	3.53	.170	.209	3.39	5.90	55.5	59.8	128	10.7
50	50	B'cast	4.73	.184	.206	3.27	6.36	42.1	42.1	116	10.0
50	50	Band	3.28	.171	.177	3.31	6.09	38.5	46.4	123	8.2
$LSD_{(0.10)}$			1.00	.018	NS	0.18	NS	NS	16.7	NS	NS

Fig. 6. Comparison of effects of methods of S-P application on growth of corn.

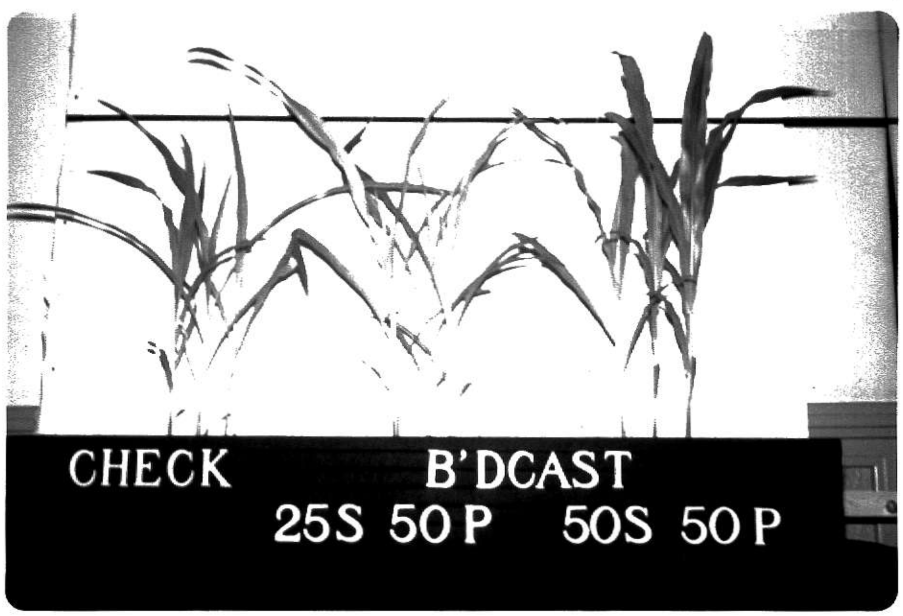

Fig. 7. Growth responses in corn from applications of S and P. Highest dry weight yields were produced by broadcasting the S-P combinations.

possible competition for absorbtion sites on roots may have prevented the plants from obtaining adequate S for maximum yield. Similar reductions in yield were reported by Miller and Ohlrogge (28) when nutrient anions were banded together.

Highest yields were recorded when both S and P were broadcast (Fig. 7) throughout the soil. This combination produced almost a two-fold increase in dry matter production as compared to the check.

Total nutrient uptake (dry weight X % nutrient) shown in Table XV was markedly influenced by increases in yield. Treatments significantly higher in total nutrients were generally higher in dry weight.

Exp. II Effect of Sulfur on Soil Chemical Properties.

Sulfur applications have been shown to lower the soil pH and increase availability of P and certain micronutrients (5, 38, 30). This experiment reports on the analysis of the soil after completion of the growth chamber study.

Figure 8 compares the pH of the vertical soil profiles as affected by the band and knifed methods of application. pH readings were taken at 2.5 cm intervals with a single electrode pH meter. Both methods of application produced a reduction in pH from 7.6 to 7.1.

Figure 9 presents the soil test data taken every 2.5 cm throughout the area of the 50 S-50 P band application. Available P and extractable SO_4-S remained concentrated around the area of application. The Mn and Fe extracted by Morgan's solution showed increases near the band application area. The release of electrons during S oxidation which serve to reduce oxidized forms of Fe and Mn (19) or the increased solubility of micronutrients at lower pH levels (46) were the probable causes for the increases in extractable Fe and Mn.

TABLE XV

EFFECTS OF RATE AND SIMULATED METHODS OF APPLICATION OF SULFUR, PHOSPHORUS, AND SULFUR-PHOSPHORUS SOLUTIONS ON NUTRIENT UPTAKE OF CORN TISSUE
Growth Chamber Study

Treatment P	Treatment S	Method of P-S Application	Total Nutrient Uptake S	P	N	K	Fe	Zn	Mn	Cu
ppm			mg/box							
0	0	------	4.04	4.68	95	151	114	209	377	30
0	25	Knifed	7.40	8.59	149	260	192	217	546	63
0	25	B'cast	6.99	8.32	153	282	167	184	513	41
0	25	Band	6.37	7.31	123	216	153	146	438	32
0	50	Knifed	8.04	9.29	155	270	206	227	587	36
0	50	B'cast	6.86	7.71	135	230	153	175	487	34
0	50	Band	5.26	5.86	107	184	131	181	384	30
50	0	Knifed	5.98	7.88	140	249	169	202	517	31
50	0	B'cast	6.11	8.70	141	248	181	179	511	37
50	0	Band	6.42	7.31	126	242	150	182	477	25
50	25	Knifed	5.76	6.91	122	219	170	165	443	33
50	25	B'cast	7.76	9.52	159	297	213	204	614	55
50	25	Band	5.43	6.40	109	198	114	226	376	35
50	50	Knifed	6.03	7.37	119	209	164	209	457	38
50	50	B'cast	9.03	10.04	160	316	211	208	574	43
50	50	Band	5.62	5.88	108	201	130	156	410	28
$LSD_{(0.10)}$			1.81	2.26	31	59	NS	NS	NS	15

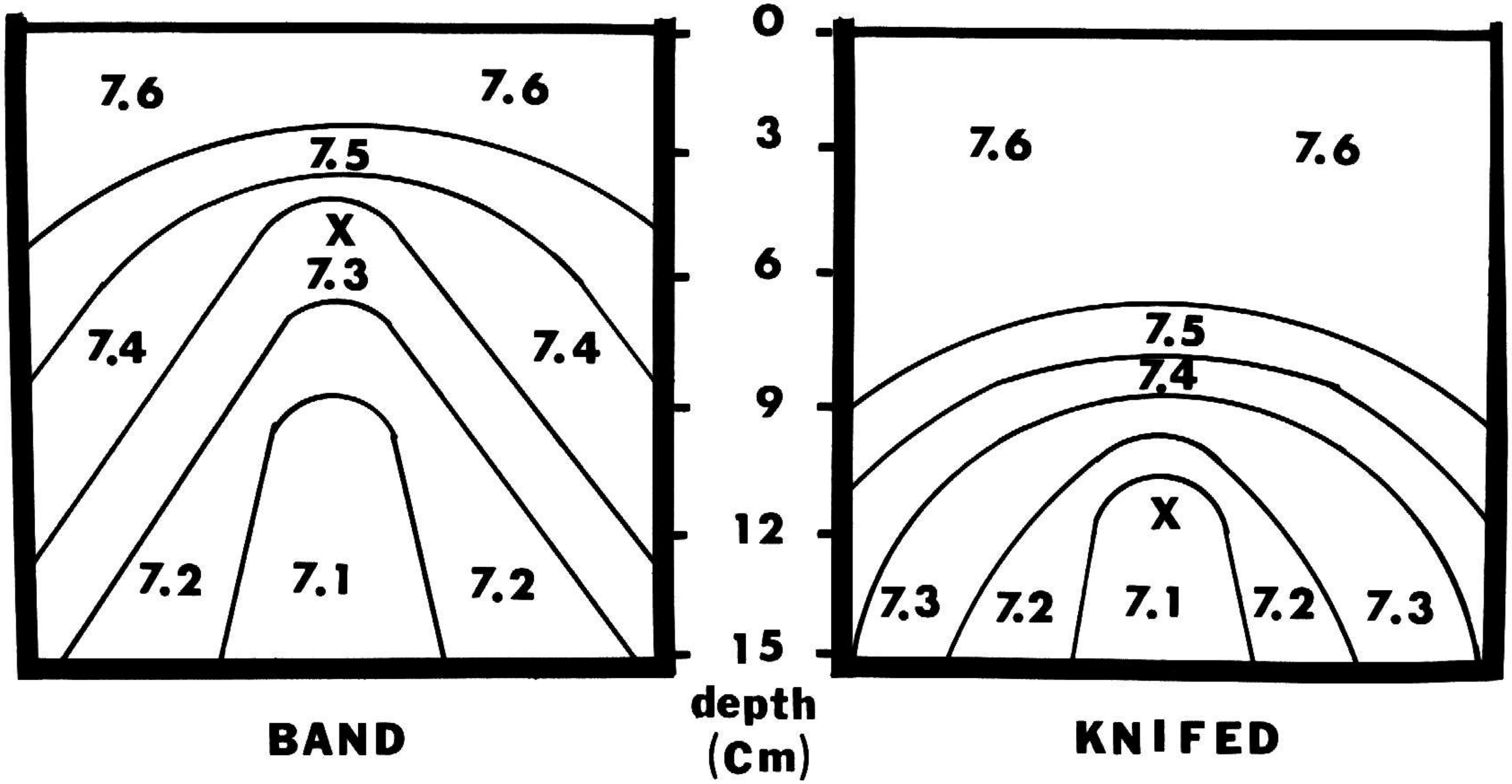

Fig. 8. Effects of method of application of P-S solutions on soil pH.
X -- denotes point of application.

Avail. P (pp2m)

					Depth (Cm)
41	33	88	26	20	1.0
27	25	1120	38	25	3.5
28	42	128	37	28	6.0
35	32	34	29	24	8.5
31	39	34	28	26	11.0
37	41	28	26	25	13.5

Extractable SO_4-S (ppm)

Depth (Cm)					
1.0	10	17	11	10	10
3.5	12	17	62	14	14
6.0	11	10	14	13	10
8.5	10	12	11	12	11
11.0	13	13	13	15	18
13.5	16	17	14	17	25

Extractable Mn (ppm)

					Depth (Cm)
50	51	52	46	48	1.0
53	48	83	49	46	3.5
45	47	55	48	46	6.0
45	47	43	43	44	8.5
44	44	44	43	43	11.0
43	44	43	44	43	13.5

Extractable Fe (ppm)

Depth (Cm)					
1.0	3.7	3.7	3.5	3.6	3.6
3.5	3.6	3.5	5.2	3.4	3.5
6.0	3.5	3.5	3.8	3.6	3.5
8.5	3.5	3.5	3.6	3.5	3.3
11.0	3.4	3.5	3.4	3.4	3.4
13.5	3.5	3.6	3.4	3.5	3.6

Fig. 9. Concentration of available and extractable plant nutrients as affected by the 50 S-50 P banded treatment. X -- denotes point of application.

SUMMARY AND CONCLUSIONS

Field Experiments

Responses to S in field studies with corn and wheat appeared only at low rates of S applications. High rates of S as ammonium thiosulfate banded with wheat at the time of seeding proved detrimental to germination and plant growth.

Banded applications of S and P-S solutions were superior to broadcast and knifed applications for irrigated corn. Wheat yields were equally affected by band and broadcast S and P-S applications; however, band applications produced higher nutrient concentrations in tissue sampled both in the fall and spring.

The ability of sulfur to enhance phosphorus and micronutrient uptake was observed under field conditions although responses were varied. The Mn content of corn tissue was significantly increased by S additions. Wheat tissue sampled in the spring revealed increases in P content at 3 of the 4 locations where S was knifed into the soil prior to planting. Increases in Fe content were also noted in wheat tissue at high S rates at one location.

Growth Chamber Study

The dry weight of corn grown in the growth chamber on a Ulysses silt loam was significantly increased by S and P additions. Band applications of high rates of S at the time of planting appeared to depress early growth. Mixing S-P solutions with the soil was most efficient in terms of dry matter production.

Plant P and micronutrient concentration were largely unaffected by S additions but total uptake of some elements was drastically increased. Soil test data revealed a decrease in soil pH from 7.6 to 7.1 with applications of 50 ppm S by the knifed and band methods. Soil extractions indicated increases in available Mn and Fe due to the band application of 50 ppm sulfur.

General

The fact that applications of S on Kansas soils showed both growth responses on S depleted soils and increased availability of P and micronutrients points to the need for continued investigation with sulfur fertilizers. The increased availability of P to wheat grown in western Kansas was not required for maximum yield; however, the higher total nutrient requirements of irrigated corn could benefit from these increases. Also, the increased P uptake was most prevalent in the spring tissue samplings of wheat indicating a possible need for earlier applications to get maximum responses on future corn studies. It would therefore be suggested that sulfur studies be continued on high pH soils in Kansas to further determine S deficiencies and nutrient availability with thought given to earlier applications.

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PLANT RESPONSES TO SULFUR APPLICATIONS

by

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

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MASTER OF SCIENCE

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Sulfur studies were conducted on corn and wheat to determine the extent of S deficiencies in Kansas and to study the possible increases in phosphorus and micronutrient availability from sulfur additions. Three methods of application and various S, P, and S-P rates were studied on high pH soils.

Band and knifed applications of S at low and medium rates produced some responses in irrigated corn. Band applications appeared to be superior to knifed and broadcast application methods for grain yields. Enhancement of P and micronutrient uptake due to S additions were minimal in this study with only Mn availability significantly affected in the early stages of maturity.

Data from wheat tissue sampled in the spring at three locations showed significant increases in P content when S was knifed into the soil prior to planting. Sulfur treatments were also beneficial to N, K, and Fe nutrition by this method in isolated instances.

Banding S in the form of ammonium thiosulfate near the seed proved detrimental to wheat germination at high rates of application. At lower rates of S, band treatments produced significant increases in N, S, and P content of tissue over broadcast treatments. Yield data indicated responses to P and to S at low rates for both methods of applications.

Corn grown in a growth chamber on a Ulysses silt loam responded to sulfur and phosphorus applications. Mixing S-P solutions with the soil provided the highest yields as compared to simulated knifed and banded treatments.

Soil analysis revealed a decrease in pH from 7.6 to 7.1 in the soil close to the points of band and knifed applications of 50 ppm S as ammonium thiosulfate.