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EFFECT OF SULFUR-CONTAINING AMENDMENTS ON MANGANESE AND  
PHOSPHORUS AVAILABILITY IN SOIL

THE UNIVERSITY OF ARIZONA

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ON MANGANESE AND PHOSPHORUS AVAILABILITY  
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by  
Mohamed M. Yacoub

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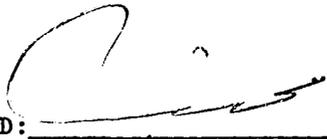
A Thesis Submitted to the Faculty of the  
DEPARTMENT OF SOILS, WATER AND ENGINEERING  
In Partial Fulfillment of Requirements  
For the Degree of  
MASTER OF SCIENCE  
WITH A MAJOR IN SOIL AND WATER SCIENCE  
In the Graduate College  
THE UNIVERSITY OF ARIZONA

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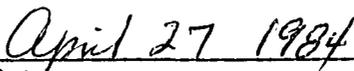
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## ABSTRACT

This study consisted of two greenhouse experiments to determine the effect of sulfur materials on phosphorus and manganese uptake, the dry matter weight, and the soil pH of three neutral-poorly buffered Arizona soils.

The sulfur materials significantly decreased the pH of the three soils by the end of the study.

The yields showed some significant increase. The uptake of P and Mn were in the satisfactory range in the first experiment, and in the second experiment the P, and Mn uptake were less and there was deficiency in P in Vinton soil.

Plants in the first study were planted from seeds and showed more uptake of P and Mn. In the second study, the plants were transplanted when seven weeks old, and had less P and Mn uptake. Actually the plants growing on Vinton soil were deficient in phosphorus.

In spite of two applications of sulfur materials, excess Mn uptake or toxicity was not shown in these three soils. The different sulfur materials did not produce consistent differences in yield and phosphorus and manganese uptake between the three soils and the two experiments.

## INTRODUCTION

A wide variety of materials is used as soil conditioners and fertilizers for alkaline calcareous soils. Many of these compounds are reduced-sulfur compounds. These include ammonium polysulfide (Nitrosul), calcium polysulfide (lime-sulfur), ammonium thiosulfate (Thiosul), ammonium bisulfite, and elemental sulfur. Generally speaking, oxidizing agents acquire electrons and become reduced, while reducing agents lose electrons and become oxidized (Brady and Humiston, 1978; Moeller, 1952). The reduced sulfur materials are oxidized in the soil and form sulfuric acid. In alkaline calcareous soils sulfuric acid may improve availability of phosphorus and metallic micronutrients. In sodic soils sulfur materials aid in the removal of exchangeable sodium. However, a few soils in Arizona are poorly buffered, and use of these amendments may result in excess soil acidity, resulting in toxic amounts of manganese and other heavy metals.

The purpose of this research was to study the effects of ammonium polysulfide, ammonium thiosulfate, and elemental sulfur on the availability of phosphorus and manganese in neutral to slightly alkaline, poorly buffered soils. Sulfuric acid was also used since it can be

regarded as a standard sulfur material and considerable research data are available on its use.

Availability of other elements including Fe, Cu, Zn, Ca, Mg, and K were also studied under these conditions.

## LITERATURE REVIEW

### Sulfur Oxidation

Oxidation of sulfur compounds takes place over a wide range of soil conditions. A wide variety of reduced sulfur compounds can exist as well as a wide range of environmental conditions and organisms which oxidize sulfur (Burn, 1967).

Kappen and Quensell (1915) reported that sulfur transformations were mainly chemical rather than biological. McGeorge and Greene (1935) and Dawood (1980) concluded that the conversion of sulfur or its oxidation to sulfuric acid in soils was either by chemical or biological agencies. Fuller (1952) has shown that sulfur is oxidized readily by certain microorganisms in the soil to form sulfuric acid.

Starkey (1964) reported that sulfide, thiosulfate, elemental sulfur, tetrathionate and pentathionate are generally oxidized to sulfuric acid. Nor and Tabatabai (1977) found that thiosulfate and tetrathionate are produced in soils during elemental sulfur oxidation. Shedd (1914) showed that regardless of the amount of sulfur added, when it was applied at 100 to 7,000 pounds per acre,

60 to 80% of the sulfur was oxidized after a period of four months.

Alexander (1977) reported that although the oxidation process may not be entirely microbiological, sulfides are readily oxidized in soils. Vitolins and Swaby (1969) have shown that some microorganism species of Arthrobacter, Bacillus, Flavobacterium, and Pseudomonas oxidize elemental sulfur or thiosulfate to sulfate.

Lipman et al. (1916a) reported that the sulfur oxidation in soil is a biological activity. They concluded that elemental sulfur is readily oxidized in soils containing sulfifying bacteria where conditions for the development of the organisms are favorable.

McGeorge et al. (1956) reported that all sulfur bearing materials such as calcium polysulfides, gypsum, and elemental sulfur oxidize in calcareous soils to sulfuric acid and form calcium sulfate. Soil microorganisms are instrumental in the oxidation of elemental sulfur and sulfide compounds in the soil.

According to the conclusions of Starkey (1950; 1966), Millar et al. (1965), and Li and Caldwell (1966), sulfur, thiosulfate and organic sulfur are oxidized to sulfate and sulfuric acid by many microorganisms, particularly certain autotrophic bacteria.

Thomas (1936) and Li and Caldwell (1966) showed that the amount of sulfur added was proportionally correlated to the rate of oxidation and decreased the soil pH. Joffe and McLean (1922) and Beaton et al. (1984) reported that elemental sulfur may be applied as a fertilizer to increase the soil acidity.

Starkey (1950) reported that the sulfur of thiosulfate and elemental sulfur oxidized to an equal quantity of sulfate by autotrophic bacteria, Thiobacillus thioparus. McGeorge et al. (1956) reported that the oxidation obtained from calcium, ammonium, potassium, and sodium polysulfides was remarkably uniform when applied to soil on the basis of equivalent amount of sulfur.

Lint (1914), Martin (1920), McGeorge and Greene (1935), Ryan and Stroehlein (1973), Cairns and Beaton (1976), and McCready and Krouce (1982) reported that sulfur oxidized in soil gradually to reduce the soil pH. By lowering the soil pH with sulfuric acid, Christensen and Lyerly (1954) and Ryan and Stroehlein (1973) reported that the availability of several micronutrients increased.

Tavassoli (1980) showed that when amendments such as ammonium thiosulfate, sulfur dioxide, ammonium polysulfide, and calcium polysulfide were added to soils, they were transformed to sulfuric acid. McGeorge and Greene (1935), Brady (1974), Pepper (1975), Alexander

(1977), and Pepper and Miller (1978) agreed that the sulfur oxidation lowered the soil pH; Hassan and Olsen (1966) found that the pH was reduced more in acidic soils than in alkaline soils.

Sulfuric acid is produced from calcium and ammonium polysulfide and  $\text{SO}_2$  oxidation (Mohammed et al., 1979), and elemental sulfur (Stromberg and Tisdale, 1979) by microorganisms (Tavassoli, 1980).

The oxidation of elemental sulfur or sodium thiosulfate applied to the soil lowered the soil pH and increased the manganese solubility (Vavra and Frederick, 1952). Cairns and Beaton (1976) reported that the sulfur products lowered the soil pH and increased the soil titrable acidity. Ryan and Stroehlein (1979) found that the sulfuric acid treatment reduced the soil pH and acid titrable basicity as well as increased the water solubility of phosphorus and the dry matter yield of tomato plants (Lycopersicum esculentum), and Stroehlein et al. (1978) reported that sulfuric acid reduced the soil pH and released more iron than elemental sulfur and gypsum.

Babiker (1979) showed that ammonium polysulfide oxidized faster than elemental sulfur in a period of 15 days and decreased the soil pH slightly and significantly.

Sulfur has been shown to be an effective acidifying soil amendment for the reclamation of alkali soils

(McGeorge and Greene, 1935). They found that during the sulfur oxidation, acid formed and neutralized the alkalinity of the soil by producing soluble calcium which replaces sodium, which is then leached away.

#### Sulfur Oxidation and Microorganisms

Lipman et al. (1916a) and Brady (1974) showed that elemental sulfur can be oxidized in soils to sulfuric acid by microorganisms, and McGeorge and Greene (1935), Overstreet et al. (1951), Clement (1978), and Babiker (1979) concluded that sulfuric acid will dissolve some important nutrients which are not otherwise available to plants.

Brady (1974) reported that elemental sulfur, thiosulfate, and polysulfides are subject to microbial oxidation. The autotrophic bacteria are responsible for oxidation of sulfur compounds in the soil such as elemental sulfur and sulfides oxidize to sulfuric acid.

Vitoline and Swaby (1969) showed that sulfur is oxidized primarily by heterotrophic organisms in neutral and alkaline soils until the soil pH is decreased when it is then suitable for the autotrophic organisms activity.

The rapid sulfur oxidation resulted in soils containing an abundance of sulfur bacteria as compared to soils lacking bacteria (Starkey, 1950). Then in 1966 he found that various types of soil microorganisms are capable

of oxidizing the different sulfur forms in soils but in this respect the bacteria are the most important organisms.

Burns (1967) and Babiker (1979) reported that the aerobic, obligate chemoautotrophic Thiobacilli are considered to be the most important group of oxidizing organisms in soils. McCready and Krouse (1982) showed that during sulfur oxidation by Thiobacilli, the sulfate content was enriched and the soil pH was lowered as the oxidation rate increased.

According to Babiker (1979), the aerobic and facultative aerobic heterotrophs are included as sulfur oxidizing organisms, and they include Bacillus, Aerobacter, Micrococcus, but they have not received much attention. Vishniac (1974), Alexander (1977), and Kuenen and Tuovinen (1981) have shown that Thiobacillus denitrificans and Thiobacillus thioparus are able to oxidize the sulfur compounds and can be found in soils. Vishniac (1974) and Kuenen and Tuovinen (1981) reported that there are nine species from the genus Thiobacilli that are considered to be responsible for sulfur oxidation, and they are T. thioparus, T. denitrificans, T. thiooxidans, T. ferrooxidans, T. noveler, T. neaplitanus, T. perometabolis, T. intermedius, and T. Az.

Autotrophic and heterotrophic bacteria include aerobic and anaerobic species which are responsible for

sulfur oxidation in soils, and by comparing Micrococcus (heterotrophs) and Thiobacillus thiooxidans (autotrophs), both were found to be effective in the oxidation of inorganic sulfur (Pepper, 1975).

Starkey (1966) showed that Thiobacillus thiooxidans oxidize sulfur, sulfides, thiosulfates, and tetrathionates rapidly and effectively, and Babiker (1979) explained that the bacteria used the sulfur compounds as electron donors and the carbon dioxide as a carbon source.

Happold et al. (1954) reported the oxidation of thiosulfate ( $S_2O_3^{2-}$ ) to sulfate ( $SO_4^{2-}$ ) by Thiobacillus thioparus, an organism which grows at neutral reaction, and is widely distributed in soils.

#### Factors Affecting Sulfur Oxidation in Soils

There are several factors by which sulfur can be affected, and the reaction can be rapid or slow. Joffe and McLean (1922) noticed that sulfur oxidation is variable from one soil to another due to differences in texture, composition, temperature, and reactions; therefore, these conditions for each soil determine a certain capacity to oxidize sulfur.

The presence of bacteria, aeration, optimum moisture content, organic matter, and manure are important

factors in increasing oxidation of elemental sulfur to produce sulfates (Brown and Kellogg, 1914).

Lipman et al. (1916a) have shown that the most essential factors in sulfur oxidation are oxygen, moisture content, and organic matter.

McLean (1918) and Pepper (1975) reported that aeration increases sulfur oxidation since an abundant supply of oxygen for aerobic microorganisms is needed, or as Starkey (1950) mentioned, that oxygen works as an electron acceptor in sulfur oxidation. Therefore, the most rapid sulfur oxidation was favored under aerobic conditions (Brown and Kellogg, 1914; Lipman et al., 1916a).

The soils to which the sulfur was added in varying amounts from 100 to 7,000 pounds per acre, 60 to 80% of the sulfur oxidized in a period of four months regardless of the amount added, and there was less oxidation in sandy soil compared to the other soil textures (Shedd, 1914). McGeorge and Greene (1935) and Babiker (1979) showed that in Arizona soils, sulfur oxidation was faster in fine textured soils than in coarse textured soils.

McLean (1918) concluded that in soils of fine texture and a high amount of organic matter, the oxidation of sulfur will be faster and greater in amounts than in soil with low organic matter and coarse texture.

Burns (1967) found that the oxidation of sulfur was enhanced by mixing it with the soil in the presence of a moisture condition above field capacity.

According to Burns (1967) and Tisdale (1968) the rate of elemental sulfur oxidation increases with the fineness of sulfur particles and its contact with the soil in the presence of sufficient moisture.

McGeorge and Greene (1935) and Thomas (1936) have shown that the rate of sulfur oxidation increased with the rate of sulfur applied, and Nor and Tabatabai (1977) found that with increasing temperature as well, it was accelerated more in alkali soils than in acid soils.

Rudolfs (1922), Waksman et al. (1923), and Vavra and Frederick (1952) reported that the oxidation of sulfur in soils is fairly rapid at pH values ranging from 4.0 to 9.6.

Temperatures between 27 to 40°C is the optimum range favorable for most of microorganisms (Rudolfs, 1922; Parker and Prisk, 1953). Pepper (1975) found that 35°C is the optimum temperature for oxidation of sulfur to sulfate in soils.

The solution form of sulfur-containing compounds such as ammonium thiosulfate and polysulfides can be oxidized without being affected by soil moisture (Maktari, 1983). Pepper (1975) showed that when the moisture content

of the soil is greater than field capacity, the sulfur oxidation rate is reduced due to the lower oxygen concentration which reduces aerobic microorganisms activity. The aeration and the moisture contents increase the sulfur oxidation rate (Lipman et al., 1916b), and they found that the oxidation of sulfur was retarded at low and high moisture contents with the optimum being 50% of the water holding capacity of the soil.

Lint (1914) found that soils with a low water content did not cause as rapid oxidation as those maintained at an optimum moisture content of the soils (50% of water holding capacity). At a moisture content near field capacity, sulfur oxidation was rapid, especially at optimum moisture content for the growth of crop plants (Burns, 1967).

#### Phosphorus and Oxidation of Sulfur

The oxidation of sulfur may be made to play an important role in the utilization of insoluble soil phosphorus by crops (Lipman, 1916).

McGeorge and Greene (1935), Overstreet et al. (1951), Hoeft and Sorenson (1969), Clement (1978), and Beaton et al. (1984) have shown that sulfur compounds can be used to correct the deficiency of some essential nutrients, such as phosphorus, manganese, and zinc in high pH soils.

Sulfur oxidizes to sulfuric acid which dissolves several compounds containing phosphorus, manganese, zinc, and iron, changing insoluble forms to available forms in deficient soils (Dawood, 1980). Stroehlein et al. (1978) showed the use of sulfuric acid in irrigation water increased the phosphorus and micronutrients availability slightly.

Hagen and Hopkins (1955), Sen Gupta and Cornfield (1964), Clement (1978), and Dawood (1980) reported that the soil pH has an important effect on the availability of phosphorus to plants. They concluded that phosphorus uptake increased as the soil pH decreased as a result of using elemental sulfur or sulfuric acid, and in addition Sen Gupta and Cornfield (1964) and Dawood (1980) reported an increase in the dry matter of plants. McGeorge and Greene (1935) concluded that the high application of sulfur reduced the soil pH, increased the amount of sulfate and availability of phosphorus.

The different phosphate ion species distribution are determined by soil pH with  $\text{H}_3\text{PO}_4$  being dominant at pH less than 2,  $\text{H}_2\text{PO}_4^-$  dominant at pH 3 to 6.8,  $\text{HPO}_4^{2-}$  at pH of 8 to 12, and above pH 12 the  $\text{PO}_4^{3-}$  will dominate (Tisdale and Nelson, 1975; McGeorge and Greene, 1935; Bohn et al., 1979). Tavassoli (1980) reported that at soil pH values below 7, the  $\text{H}_2\text{PO}_4^-$  will be available for plant uptake and

reported by McGeorge and Greene (1935) as the preferable ion to plants. Lipman et al. (1916a; 1916b), McLean (1918), and Clement (1978) have shown that the sulfur oxidation and sulfuric acid furnished available phosphorus and increased plant uptake of phosphorus. In 1966 Starky explained that the increase of plant phosphorus by the reaction of sulfuric acid with rock phosphate, or according to Ryan and Stroehlein (1979) that with calcium phosphate to produce soluble phosphates forms. McGeorge and Greene (1935), Burns (1967), Tisdale (1970), Stevens and Reuss (1975), Babiker (1979), Dawood (1980), and Tavassoli (1980) reported that there were increases in the solubility and availability of phosphorus, manganese, calcium, magnesium, iron, zinc, potassium, and copper by lowering the soil pH.

Alexander (1977) showed that elemental sulfur oxidation is an effective means of providing utilizable phosphorus to crops. Supplying sulfuric acid at a low rate to tomato plants growing in calcareous soil low in available phosphorus in the greenhouse, the growth, vegetation yield and phosphorus solubility and uptake by plants increased (Ryan and Stroehlein, 1973).

Clement (1978) and Babiker (1979) have reported that the phosphorus concentration increased as a result of increasing the application rate of elemental sulfur which oxidized to sulfuric acid. Pratt (1961) concluded that

oxidized to sulfuric acid. Pratt (1961) concluded that after acidification of calcareous soils, phosphorus solubility, uptake and growth increased. The amount of phosphorus available to plants and the capacity of soils to replenish phosphorus in solution can be increased significantly by using sulfuric acid (Ryan and Stroehlein, 1973; 1979). In 1973 they showed that sulfuric acid applied on the soil surface decreased the soil pH and calcium carbonate, and increased the availability of phosphorus and iron at the soil surface. Plant uptake of phosphate ions is greatest from the slightly acid to neutral soil pH range. A potential use of sulfuric acid is for increasing phosphorus availability and hence plant growth on phosphorus deficient soil.

McLean (1918) reported that in sand and soils, the amount of available phosphorus increased as a result of increasing sulfur oxidation and soil aeration.

Breazeale and McGeorge (1932) reported that phosphate ions are not absorbed by plants when the pH was 7.6 or higher around the soil-root contact film.

Beaton et al. (1968) concluded that the yield can be increased through improving soil structure, water penetration and availability of some elements such as phosphorus, zinc, iron, and manganese resulting from use of ammonium thiosulfate, sulfuric acid, sulfur dioxide,

elemental sulfur, and ammonium polysulfide. McGeorge and Greene (1935) showed that the addition of sulfur decreased the soil pH and helped the plants to meet their phosphate requirement.

#### Manganese and Sulfur Oxidation

The reduced forms of manganese and iron are much more soluble than the oxidized forms in soils. As the soil is acidified, the pH decreases and the availability of micronutrients increases except for molybdenum (Olson et al., 1971).

According to Bertramson et al. (1950), Garey and Barber (1952), and Maktari (1983), sulfur oxidation decreased the soil pH and lowered the oxidation-reduction potential as well as decreased concentration of the oxidized forms of manganese and iron, making them more soluble and available for plants.

Bohn (1967) showed that manganese availability is related to soil reaction, and increases when soil pH decreases below 5.5. Manganese deficiency can result when soil pH levels are 6.2 or more.

Garey and Barber (1952) and Vavra and Fredrick (1952) have shown that when sulfur was oxidized to sulfate ( $\text{SO}_4^{2-}$ ), electrons were released and reduced the insoluble  $\text{Mn}^{4+}$  or  $\text{Mn}^{3+}$  to more the soluble  $\text{Mn}^{2+}$  form. During oxidation of sulfur compounds by microorganisms, manganese

dioxide plays a role as an electron acceptor and becomes reduced (Vavra and Fredrick, 1952).

Quastal et al. (1948) concluded that manganese availability depends upon oxidation-reduction and not entirely on soil acidity. The release of mananese is due to chemical oxidation of soil organic matter and subsequent reduction of  $MnO_2$  (Hammes and Berger, 1960). Ryan et al. (1974) showed that manganese, zinc, and iron solubility and availability are pH dependent. Soil acidity controls manganese released to water-soluble, exchangeable, or acid soluble forms (Hammes and Berger, 1960). Water soluble manganese was increased by sulfuric acid application to calcareous soils (Ryan et al., 1974). They found that the use of sulfuric acid, in case of iron and manganese deficient soils, lowered the soil's pH, increased availability of those elements and corrected the plant deficiency of iron and manganese symptoms. Garey and Barber (1952) reported that the acidity is important for maintaining more available manganese in the soils.

Maktari (1983) concluded that when sulfur is applied with excess water at 1.5 times field capacity, the soil pH and redox potential decreases and manganese solubility in soil increases. He showed that the increased solubility of manganese and iron is enhanced by both the increased acidity and lowered in redox potential during

sulfur oxidation. Tisdale and Bertramson (1949) and Babiker (1979) have reported that the manganese concentration and availability increased as a result of oxidation of added sulfur in soils. According to Brady (1974), sulfur is used in arid regions to reduce the high pH of alkali soils to allow plants to grow and to eliminate manganese, iron, and zinc deficiencies.

Sherman and Hermer (1941), Quastal et al. (1948), Tisdale and Bertramson (1949), and Bertramson et al. (1950) showed that the application of elemental sulfur and thiosulfate reduced manganese deficiency symptoms as a result of releasing available manganese and increasing its availability in the soils. On the other hand, Quastal et al. (1948) reported that the soil pH did not change when elemental sulfur and thiosulfate were added, but manganese deficiency symptoms were reduced.

Bertramson et al. (1950) and Stevens and Reuser (1975) showed that increasing sulfur application and its resulting oxidation increased manganese solubility and plant uptake. According to Stevens and Reuss (1975), the manganese concentration in soils was significantly increased by increasing the application rate of ammonium sulfate.

Tisdale and Bertramson (1949) and Garey and Barber (1952) showed that sulfur and thiosulfate oxidation

decreased the soil pH, increased manganese uptake and yield of plants, as well as corrected the manganese deficiency as a result of releasing soluble forms of manganese. Sherman and Hermer (1941) found similar results after using elemental sulfur, acid, and/or a strong reducing agent.

Garey and Barber (1952) reported that sulfur oxidation by sulfur bacteria reduced the manganese and increased its availability to plants.

Vavra and Fredrick (1952) showed that by supplying elemental sulfur and sodium thiosulfate, the rate of sulfate formation and manganese release was greatly increased.

Alexander (1977) concluded that manganese deficiency can be corrected by the use of elemental sulfur or thiosulfate, which increases the divalent manganese (reduced form) concentration. Sulfur oxidation increases phosphorus and manganese solubility and uptake by plants.

#### Manganese Toxicity

Manganese toxicity to plants or excesses commonly occur in extremely acid soils or in waterlogged soils (Mortvedt et al., 1972; Tisdale and Nelson, 1975). They agreed that toxic concentrations of manganese are found at pH value of less than 6.5 as a result of maximum availability or abundant amount of manganese in soils. Mortvedt et al. (1972) showed manganese toxicity symptoms

in high pH soils as a result of over-fertilization of manganese. Manganese toxicity symptoms can result from using acid forming compounds (Stroehlein, 1984). Tisdale and Nelson (1975) reported that manganese is required by plants in only small quantities while large amounts can be toxic.

Bohn et al. (1979) reported that poor root penetration in acid subsoils may be due to high concentrations of soluble aluminum or manganese.

Adams and Wear (1957) and Tisdale and Nelson (1975) reported that as a result of manganese toxicity, crinkle leaf of cotton occurred due to high acidity which caused a high potential supply powering of soluble manganese in soils. Adams and Wear (1957) reported that as a result of toxic manganese conditions, cotton plants showed dwarfing of stems and cotyledons.

Draycott (1972) reported that sometimes high soil acidity causes the uptake of excess metal ions, particularly manganese, which results in a chlorosis and stunting of affected sugarbeet plants. The laminae and petales are uniformly pale yellowish green, and the plants have an upright appearance with leaf margins rolling inward.

Lohnis (1951) reported that chlorosis all over beans leaves was induced as a result of manganese excess in soils.

#### Objectives of the Study

During recent years sulfur compounds have been used extensively in Arizona for reducing exchangeable soil sodium, improving infiltration rates, and increasing the availability of phosphorus and certain micronutrients. A few soils in Arizona are poorly buffered with respect to acidity and have been reported to have problems related to crop growth after sulfur treatment. One hypothesis is that this problem is manganese toxicity. The objective of this study was to determine if the use of several sulfur compounds may be responsible for manganese toxicity with poorly buffered soils. The influence on other elements such as phosphorus was also studied.

## MATERIALS AND METHODS

This study was conducted in the greenhouse of the University of Arizona near the Agricultural Science Building. Three soils, Table 1, were used in the study. They were selected because of the low range in calcium carbonate or buffering capacity. Hayhook and Vinton soils do not contain calcium carbonate, and Arizo soil contains 6.64% calcium carbonate.

A Hayhook soil (NCSS, 1982) was used with a pH value of 6.9. It is a Typic Torriothent, coarse-loamy, mixed, non-acidic, thermic. The Hayhook series consists of deep well drained, moderately rapid permeable soils formed in alluvium located on fan Terraces, predominantly from granite. These soils have a yellowish brown sandy loam surface. Uncultivated topsoil was collected from Range 11E, Township 15S, near Sandario Road from the vicinity of Three Points for the study. Elevation is about 2500 ft. Average annual precipitation is about 10 to 20 in. Frost-free season is 220 to 270 days. Slopes range from 1 to 2%.

A Vinton soil (Gelderman, 1972) of pH 7.6 was used. The Vinton series is a member of the sandy, mixed, thermic family of Typic Torrifuvents. Typically, Vinton soils are

Table 1. Physical and chemical characteristics of the three soils used in the study.\*

Soil Parameter	Soils		
	Arizo	Hayhook	Vinton
Sand (%)	51	73	77
Silt (%)	38	12	19
Clay (%)	11	15	4
Texture	loam	sandy loam	loamy sand
pH <sup>+</sup>	7.1	6.9	7.6
EC <sub>e</sub> x 10 <sup>3</sup> (mmhos/cm)	10.27	2.37	0.87
Soluble salts (mg/kg)	7189	1659	609
Na (mol/l) in sat. ext.	7.18	8.57	0.77
K (mol/l) in sat. ext.	3.38	1.71	0.41
P (mg/kg)	19.8	27.6	3.5
N-NO <sub>3</sub> (mg/kg)	308	63	38.2
CaCO <sub>3</sub> (%)	6.64	0	0
ESP	0.29	3.48	0
Fe (ppm)	5.31	4.07	2.78
Mn (ppm)	21.12	15.78	8.20
Cu (ppm)	2.04	1.18	0.72
Zn (ppm)	2.73	10.75	0.42

\* Analysis made by Soil, Water and Plant Testing Laboratory, University of Arizona.

+ Paste with distilled H<sub>2</sub>O.

more than 150 cm deep, contain less than 1% organic matter, and are calcareous. They have brown loamy sand A-horizons and loamy sand and sand C-horizons that contain thin strata of silt loam, very fine sand loam or sandy loam. Uncultivated A-horizon from the Buckelew farm at Three Points was selected for this study. The Vinton soil is well-drained; runoff is slow; permeability is moderately rapid. Elevation and climatic conditions are very similar to the Hayhook soil. The soil from this site was noncalcareous.

An Arizo soil (Gelderman, 1972) was used, which had a pH value of 7.1. The Arizo series is a member of the sandy skeletal, mixed, thermic family of Typic Torriorthents. Typically, Arizo soils are light brownish-gray gravelly sandy loam on the surface and calcareous throughout, and subsoils are very gravelly and cobbly sand to depths of 100 cm or more. An Ap horizon from the east side of the University of Arizona Campbell Avenue farm was collected for the study.

The Arizo soil is excessively drained. Surface runoff is very slow, except during convection storm periods and when the runoff from higher-lying soils may collect on these soils. Soil permeability is very rapid.

### First Experiment

A number of 60 plastic pots were used (20 pots for each soil). Each pot contained an average weight of 1583 g of soil. The treatments, Table 2, were added on the basis of the same amount of sulfur in each of the following compounds: elemental sulfur, Nitrosul (ammonium polysulfide or APS), Thiosul (ammonium thiosulfate or ATS), and sulfuric acid. These were compared with an untreated control. The elemental sulfur was mixed with the soils one week before planting the seeds, and the moisture was kept at field capacity. The other treatments were solutions and were added to the soils one day before planting. Ten tomato seeds (Lycopersicum esculentum) were planted per pot. Tap water, Table 3, of the greenhouse was used for irrigation. A fungicide powder (Captan) was applied as a seed coating before planting.

The addition of amendments was based on 100 kg of sulfur per hectare/15 cm. There were four applications of each treatment. Planting was on 28 February 1983, and harvesting was on 19 April 1983.

The positions of the pots on the bench were rotated every four days in order to give an average exposure to microclimatic differences in the greenhouse and create a completely random statistical design.

Table 2. Treatments based on amount per pot (1583 g) of first and second experiment.

Amendment	% S	Addition of Amendment Per Pot*	
		First Rate 100 kg S/ha	Second Rate 200 kg S/ha
Control	0	0	0
S	100	0.0754 (g)	0.1508 (g)
H <sub>2</sub> SO <sub>4</sub>	32.65	0.1255 ml	0.2510 ml
APS	45	0.0947 ml	0.1894 ml
ATS	26	0.1727 ml	0.3454 ml

\* Average weight of each pot = 1583 (g)

+ The soil depth of hectare is 15 cm.

Table 3. Water analysis which was used for irrigating the plants in the GH.

Tap Water Parameter	Values
EC x 10 <sup>3</sup> (mmhos/cm)	0.44
Soluble Salts (mg/kg)	328.7
pH	6.9
Ca (mg/l)	47.0
Mg (mg/l)	2.7
Na (mg/l)	48.2
Cl (mg/l)	42.0
SO <sub>4</sub> (mg/l)	37.5
HCO <sub>3</sub> (mg/l)	151.3
CO <sub>3</sub> (mg/l)	0
F (mg/l)	.22
NO <sub>3</sub> (mg/l)	1.21
Pb (mg/l)	.004
SAR	1.85

\* The water of pH 6.9 is considered to have little or no effect on the soil pH.

Five weeks after planting, nitrogen as  $\text{NH}_4\text{NO}_3$  was added at a rate of 100 ppm.

Plants were harvested seven weeks after planting and subjected to the treatments found under the section on Yields, Soil and Tissue Analysis.

### Second Experiment

This experiment was continued using the soils from the same pots. The treatments were added again but at twice the rate as the first addition, i.e., the rate was 200 kg of sulfur per ha/15 cm. Tomato plants were transplanted on 26 April 1983, instead of seeding as in the first experiment and harvested on 14 June 1983. Transplanting was done in order to complete the experiment before temperatures became extreme in the greenhouse.

Nitrogen fertilizer ( $\text{NH}_4\text{NO}_3$ ) was added, four weeks after transplanting and the amount was the same as the first addition in the first experiment. Harvesting was carried out seven weeks after transplanting. Dry matter yields and sample preparation were as in the first experiment.

### Yields, Soil and Tissue Analysis

After harvesting, the plants were dried in an oven for 48 hours at 60°C with ventilation and weighed. The tissue was ground in a Wiley mill to pass a 40 mesh screen.

One gram was placed into a 50 ml beaker and placed into a cool muffle furnace and dry ashed according to the method of Greweling (1976). The temperature was raised to 500°C and held there until the ash was white (5 hours). Then the samples were removed from the furnace after cooling for 12 hours and moistened with deionized water. A 2-ml portion of concentrated HCl was added and evaporated to dryness on a steam plate at 400°C and then baked for one hour to dehydrate silica. Then 10 ml of 1N HCl were added, stirred after 15 minutes, and washed with deionized water into a centrifuge tube by using a plastic policeman, allowed to stand 30 minutes, and then centrifuged to produce a clear solution. A 50 ml volume was prepared in 50 ml volumetric flasks for elemental analysis. This method was selected in order to maintain the solubility of manganese as well as the other elements of interest.

Phosphorus was determined by the ammonium metavanadate method (Jackson, 1958).

Atomic absorption was used to determine manganese, copper, zinc, calcium, and manganese, while potassium was determined by flame emission.

Soil from each pot was well mixed and a 50-g subsample was taken for analysis. Saturated paste soil pH was determined with a glass electrode pH meter. The pH data were transformed to antilogs for statistical analysis

and calculation of the means. After analysis the data were transformed back to logs.

#### Statistical Analysis

Experimental data were analyzed according to Little (1960). Analysis of variance for the completely randomized design by a factorial arrangement of treatments (elemental sulfur and sulfur compounds, soils, and soil treatments interaction) individually for each soil and each treatment, was used. Because of large variances among the treatments in all the study (except for dry matter weight), log transformation was used to homogenize the variances. The Least Significant Difference (LSD) Test was used for comparing means at the 0.05 level.

## RESULTS AND DISCUSSION

### First Experiment

#### Dry Matter Weight of Tomato Plants

The dry matter weight was the highest from Hayhook soil and the lowest from Vinton soil. All three soils (Table 4) were significantly different. Considering Vinton soil as control (lowest), Arizo soil produced 4.5 times as much as Vinton soil, and Hayhook soil produced 5.6 times as much as Vinton soil and 1.2 times as much as Arizo soil in dry matter weight. Using sulfur and sulfur compounds increased the dry matter weight in Hayhook and Arizo soils (Figure 1).

Treatments with Amendments. The sulfur compounds (treatments) showed an overall increase in dry matter weight. Thiosul resulted in 60% increases of dry matter weight compared to the control. Elemental sulfur and polysulfide produced 37% increases in dry matter weight followed by sulfuric acid, which gave 27% increases of dry matter weight. The increases of dry matter weights were significantly different among each other and against the control, except for polysulfide and elemental sulfur, which were the same.

Table 4. The dry matter yield of tomato plants of the first and second study of the three soils.

Amendment	Arizo		Hayhook		Vinton	
	1st	2nd	1st	2nd	1st	2nd
	----- g -----					
Control	2.42	0.51	2.88	3.02	0.73	4.43
S	3.33	1.36	4.43	1.76	0.50	2.38
H <sub>2</sub> SO <sub>4</sub>	2.37	1.79	4.00	3.77	1.30	3.91
APS	3.47	1.73	4.28	6.20	0.52	4.94
ATS	4.62	2.66	4.47	4.77	0.52	5.48

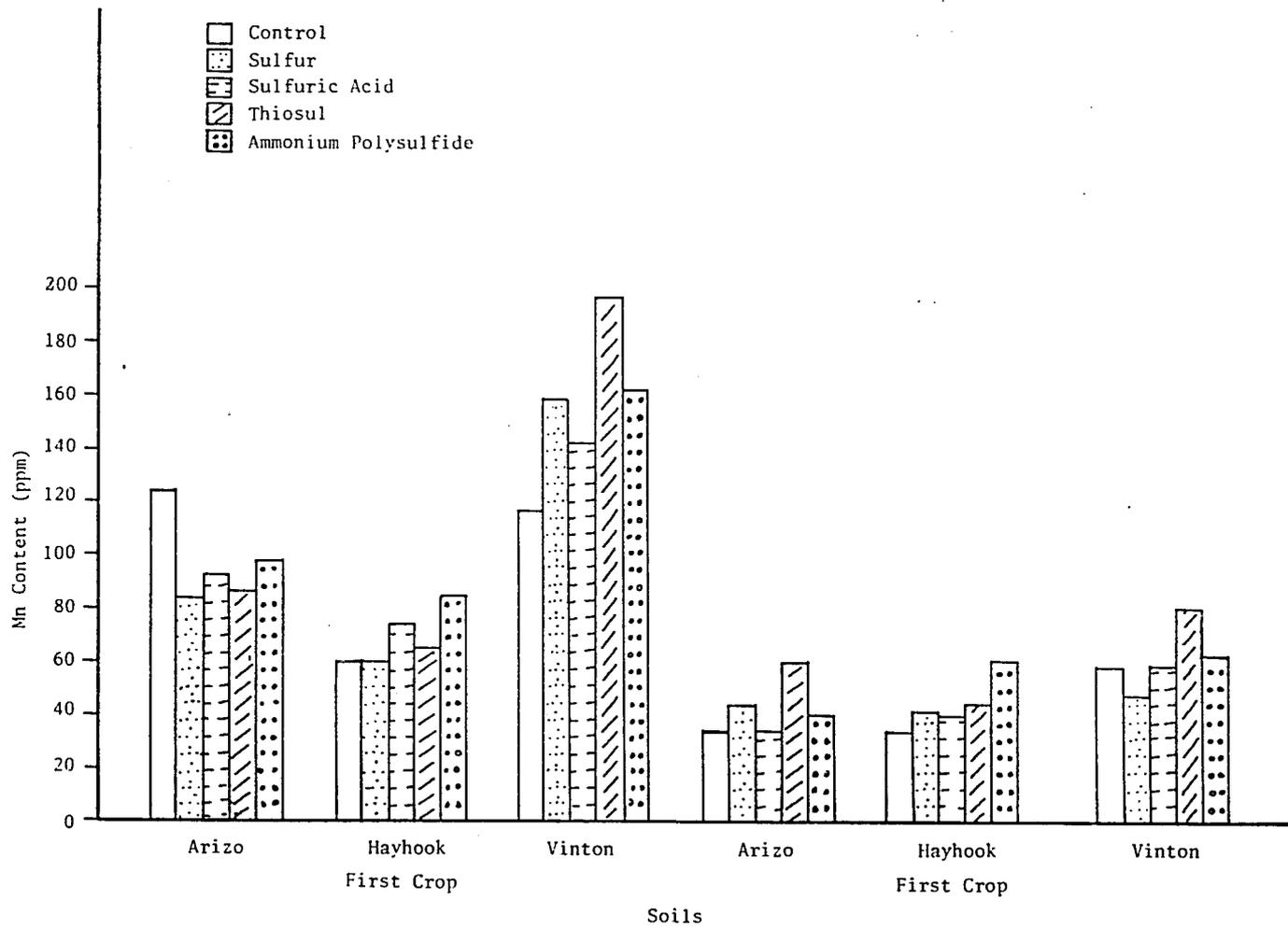


Figure 1. Effect of amendments on tomato plants dry weight grown on the three soils. -- Means of four replications.

Soil-Treatments Interaction. For Arizo soil all the treatments and the control were significantly different, with the response to Thiosul the highest. Elemental sulfur and polysulfide produced considerable increases in the dry matter weight, but sulfuric acid showed a significant decrease in the dry matter weight.

For Hayhook soil, elemental sulfur and sulfur compounds were significantly different against the control and showed a considerable increase in the dry matter weights (Table 4). Thiosul increased dry matter weight by 56%, elemental sulfur showed 53.8% increase, polysulfide produced 48.6% increase, and sulfuric acid showed 39% increase against the control. The increases in the dry matter weight were significantly different among all the sulfur compounds and elemental sulfur (Figure 1).

For Vinton soil, sulfuric acid showed a considerable dry matter increase of 78.6% from the control (Table 4). Thiosul, polysulfide, and elemental sulfur showed a significant decrease in the dry matter weight.

Overall, Vinton soil produced the lowest dry matter weight (Figure 1). Hayhook soil produced the highest dry matter weight.

The root growth in Hayhook soil was the greatest in terms of size and distribution, followed by Arizo and Vinton soils.

## Manganese

Manganese uptake was significantly different for for the three soils (Figure 2). The tomato plants showed considerably higher manganese uptake from Vinton soil than from Hayhook soil, while Arizo soil was intermediate in manganese uptake. The elemental sulfur and sulfur compounds noticeably increased manganese uptake from Vinton soil more than Hayhook soil and tended to decrease manganese uptake from Arizo soil. Hayhook soil was least affected by the sulfur amendments of the three soils studied (Table 5).

Treatments with Amendments. The polysulfide showed a highly significant difference at the 0.05 level in manganese uptake against the control. Elemental sulfur, sulfuric acid, and Thiosul showed slight increase in manganese uptake, but those increases were not significantly different against the control.

Soil-Treatments Interaction. For Arizo soil, the manganese uptake from amendment-treated plants was significantly lower than the control. The elemental sulfur and sulfur compounds did not increase the manganese uptake.

For Hayhook soil polysulfide increased the manganese uptake the most, and sulfuric acid also showed a significant increase. Thiosul showed a slight but insignificant increase against the control. Uptake of

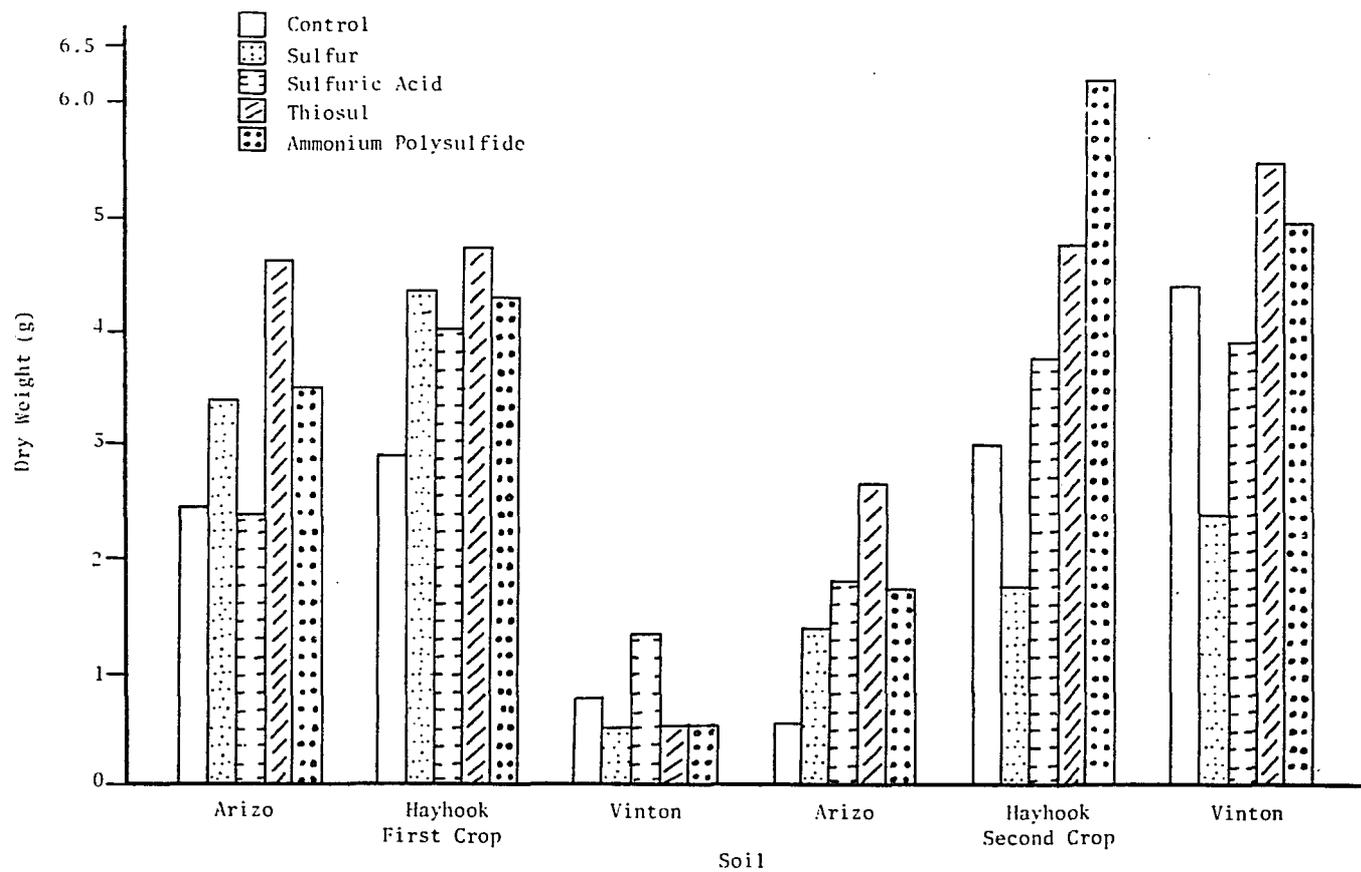


Figure 2. Effect of amendments on manganese content of tomato plants grown on the three soils. -- Means of four replications.

Table 5. The manganese uptake of tomato plants of the first and second study of the three soils.

Amendment	Arizo		Hayhook		Vinton	
	1st	2nd	1st	2nd	1st	2nd
	mg/kg*					
C	125	34	60	33	117	58
S	84	44	61	42	159	47
H <sub>2</sub> SO <sub>4</sub>	93	35	74	41	143	59
APS	98	41	85	61	162	62
Thiosul	88	60	65	45	197	80

\* mg/kg = ppm.

manganese by using elemental sulfur and the control was the same.

For Vinton soil, the elemental sulfur and sulfur compounds increased the manganese uptake. Thiosul and polysulfide were equal in their effect on manganese uptake and significantly higher than the sulfuric acid, elemental sulfur, and the control (Figure 2). The elemental sulfur was significantly different in increasing the manganese uptake but was less than the Thiosul and polysulfide. The increase with sulfuric acid was not significant.

#### Phosphorus

The phosphorus uptake (Table 6 and Figure 3) was highest in Hayhook soil, followed by Arizo and Vinton soils, and all were significantly different. The elemental sulfur and sulfur compounds released more available phosphorus in Hayhook and Arizo soils than Vinton soil.

Treatments with Amendments. The elemental sulfur and control showed no difference in phosphorus uptake. Polysulfide showed a greater increase than thiosul and sulfuric acid, but they were not significantly different than the control. Polysulfide, thiosul, and sulfuric acid tended to increase the availability of phosphorus, but this trend was not significant against the control. Elemental sulfur produced the same phosphorus uptake as the control.

Table 6. The phosphorus uptake of tomato plants of the first and second study of the three soils.

Amendment	Arizo		Hayhook		Vinton	
	1st	2nd	1st	2nd	1st	2nd
	mg/kg*					
C	0.288	0.132	0.432	0.181	0.147	0.062
S	0.182	0.119	0.461	0.224	0.195	0.056
H <sub>2</sub> SO <sub>4</sub>	0.210	0.193	0.536	0.263	0.145	0.084
APS	0.228	0.167	0.493	0.182	0.205	0.052
Thiosul	0.218	0.137	0.446	0.190	0.199	0.076

\* mg/kg = ppm

1000 ppm = 0.1%

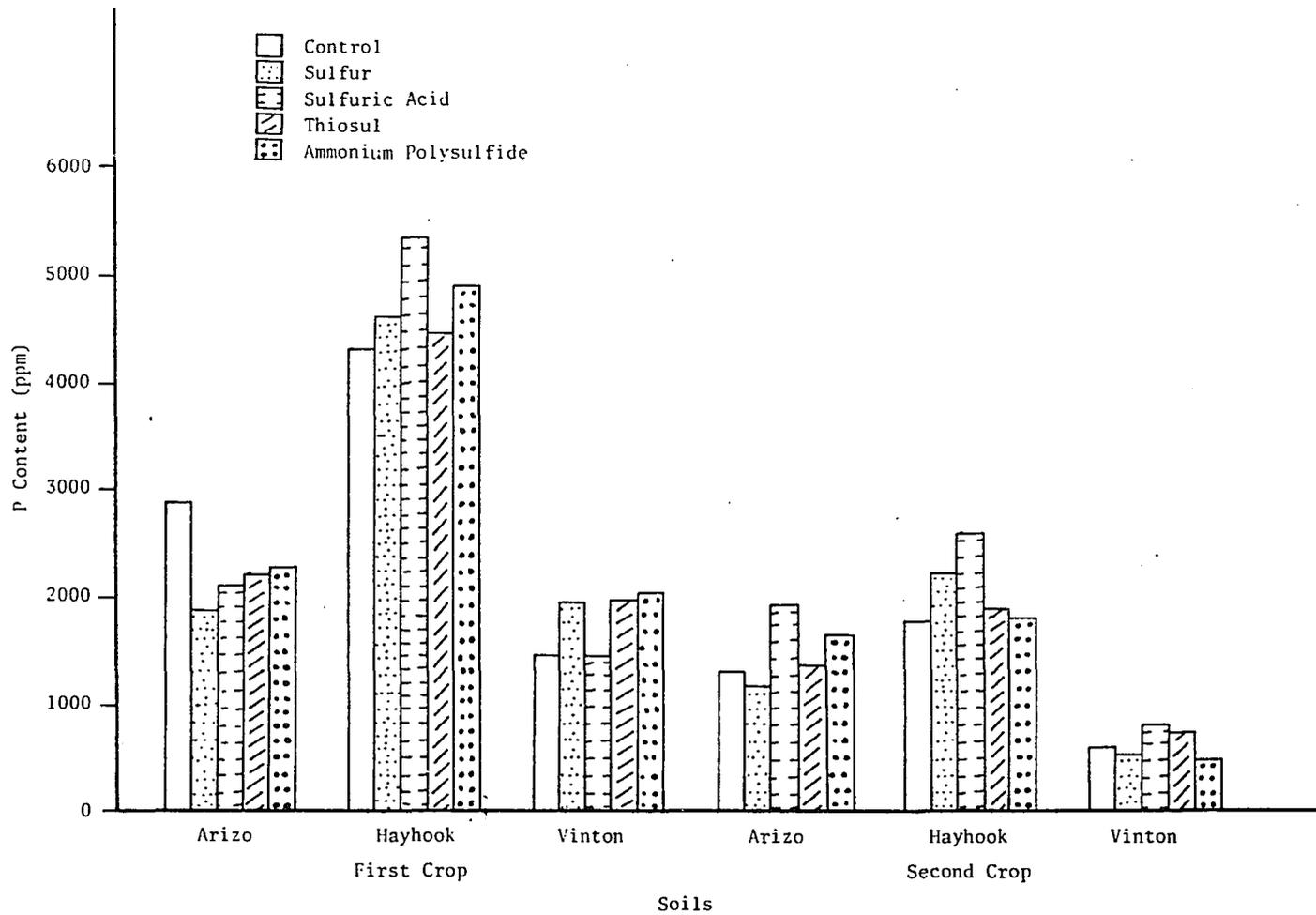


Figure 3. Effect of different treatments on P content of tomato plants grown on the three soils. -- Means of four replications.

Soil-Treatments Interaction. For Arizo soil, elemental sulfur was significantly lower than the control in phosphorus uptake. Thiosul, polysulfide, and sulfuric acid showed no significant difference from the control. All treatments failed to increase the phosphorus availability in Arizo soil.

For Hayhook soil, elemental sulfur, thiosul, polysulfide, and sulfuric acid increased the phosphorus availability and uptake in Hayhook soil. The increases in phosphorus availability and uptake were not significantly different except with sulfuric acid against the control. Elemental sulfur, thiosul, and polysulfide tended to increase the phosphorus availability, but the trends were not significant.

For Vinton soil, the phosphorus uptake increased as a result of using elemental sulfur, sulfuric acid, thiosul, and polysulfide. The polysulfide increase was significant, but the other trends were not significant. Elemental sulfur and thiosul appeared to increase the phosphorus uptake considerably, but they were not significant. Sulfuric acid showed a slight nonsignificant increase. Polysulfide was the most effective in releasing phosphorus and in increasing the phosphorus uptake than thiosul and elemental sulfur.

## Second Experiment

### Dry Matter Weight

Vinton soil produced the highest dry matter weight, which was 2.58 times the amount produced from Arizo soil and 1.10 times the dry matter weight from Hayhook (Table 4 and Figure 1). The elemental sulfur, polysulfide, thiosul, and sulfuric acid increased the dry matter weight of Vinton and Hayhook soils more than Arizo soil. All of these dry matter weight differences were significant. Considering Arizo soil as a control, Hayhook soil increased the dry matter weight by 2.35 times.

Treatments with Amendments. Polysulfide, thiosul, and sulfuric acid increased the dry matter weight significantly. Elemental sulfur decreased the dry matter weight significantly against the control. Polysulfide increased the dry matter weight more than thiosul, which was higher than sulfuric acid.

Soil-Treatments Interaction. For Arizo soil, all the treatments showed highly significant increases in the dry matter weight. Thiosul, sulfuric acid, polysulfide, and elemental sulfur increased the dry matter weight by 7.0, 4.5, 4.0, and 3.0 times as much as the control, respectively. These increases in dry matter weight were significantly different against the control. As a result

of using elemental sulfur and sulfur compounds, the dry matter weight increased in Arizo soil.

For Hayhook soil, elemental sulfur reduced the dry matter weight significantly. Polysulfide, thiosul, and sulfuric acid increased the weight by 2.05, 1.47, and 1.25 times, respectively, against the control. These increases in dry matter weight were significantly different. In Hayhook soil, using sulfur compounds increased the dry matter weight significantly.

For Vinton soil, thiosul and polysulfide increased the dry matter weight of the tomato plants. Thiosul increased the dry matter weight more than polysulfide, and both were significantly different against the control and each other. Elemental sulfur and sulfuric acid showed a significant decrease in the dry matter weight in Vinton soil. However, thiosul and polysulfide were the most effective in increasing the dry matter weight (yield) in Vinton soil.

#### Manganese

Uptake of manganese was significantly different between Arizo and Vinton soils. Vinton soil provided more available manganese than Hayhook and Arizo soils. Arizo soil was not significantly different than Hayhook soil, and Hayhook soil was not significantly different than Vinton soil in availability of manganese, while Arizo soil

released the least available manganese. Sulfur compounds were effective in increasing the manganese availability in Vinton and Hayhook soils than in Arizo soil.

Treatments with Amendments. All the treatments tended to increase manganese availability, but the increases were not high enough to be significantly different against the control except for thiosul. Polysulfide tended to increase the availability of manganese less than thiosul, but this increase was not enough to be significant against the control. Sulfuric acid and elemental sulfur did not increase the manganese availability significantly against the control.

Soil-treatments Interaction. For Arizo soil, thiosul and elemental sulfur increased the manganese availability significantly by 41 and 31%, respectively, against the control. Polysulfide and sulfuric acid tended to increase the manganese availability by 26 and 21%, respectively, but those increases were not significant. Thiosul and elemental sulfur were the best in increasing the availability of manganese in Arizo soil.

For Hayhook soil, all the treatments did not show a significant increase against the control of available manganese. Polysulfide increased the manganese availability more than thiosul, which was more than sulfuric acid and elemental sulfur, which were almost the same in increasing

the manganese availability. Elemental sulfur and sulfur compounds tended to increase the manganese availability in Hayhook soil.

For Vinton soil, thiosul increased the manganese uptake more than polysulfide and sulfuric acid, respectively. Elemental sulfur reduced the manganese availability. In Vinton soil, the apparent changes in manganese uptake were not significantly different than the control.

#### Phosphorus

Applying elemental sulfur and sulfur compounds, Arizo and Hayhook soils released more available phosphorus than Vinton soil. Hayhook soil had higher available phosphorus than Arizo soil. The increase of available phosphorus in Arizo and Hayhook soils was significantly different against Vinton soil, and the increase in phosphorus in Hayhook soil was significantly greater than in Arizo soil.

Treatments with Amendments. For Arizo soil, elemental sulfur and thiosul did not increase the phosphorus availability compared to the control, and they were not significantly different. Sulfuric acid increased availability of phosphorus more than polysulfide, and both were significantly higher than the control, thiosul, and elemental sulfur treatments. Using sulfuric acid or

polysulfide, phosphorus uptake significantly increased in Arizo soil.

For Hayhook soil, polysulfide severely reduced the phosphorus availability. Elemental sulfur and thiosul increased phosphorus availability, but that increase was not significantly different from the control. Sulfuric acid increased the phosphorus availability in Hayhook soil significantly from the control and the other treatments. In Hayhook soil, sulfuric acid was effective in increasing the availability of phosphorus significantly.

For Vinton soil, treatments with all the sulfur materials showed a negative response by lowering the phosphorus availability.

#### pH

Elemental sulfur and sulfur compounds lowered pH of the three soils compared to their initial (control) pH value (Figure 4 and Table 7). The three soils were significantly different. The pH dropped in Vinton soil by 0.51, Arizo soil by 0.30 and Hayhook soil by 0.22. The final pH value of Hayhook soil was the lowest and Vinton soil gave the greatest reduction.

Treatments with Amendments. Sulfuric acid reduced the soil pH of the three soils more than elemental sulfur, polysulfide, and thiosul, respectively. The reduction in the pH value was significantly different against each other

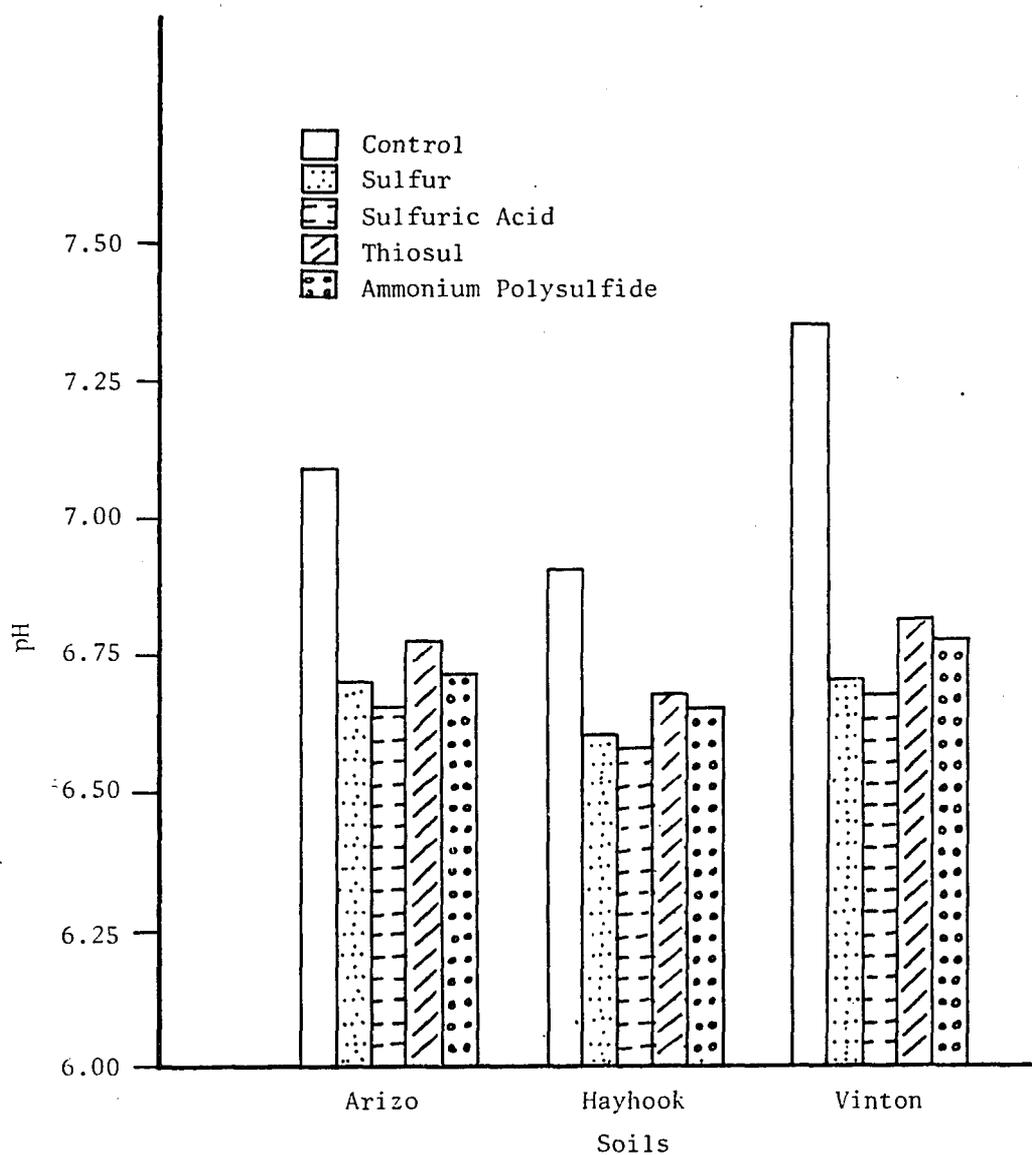


Figure 4. Soil pH values after amendment applications and two cropping periods.

Table 7. pH values of the soils after using the amendments for the two experiments.

pH Values of Amendments*	Soils		
	Arizo	Hayhook	Vinton
Control	7.09	6.90	7.38
Sulfur	6.70	6.60	6.70
Sulfuric acid	6.65	6.58	6.68
APS	6.71	6.65	6.78
Thiosul	6.78	6.68	6.81

\* Measured on saturation paste with deionized H<sub>2</sub>O.

and the control. Sulfuric acid, elemental sulfur, and polysulfide were the most effective in reducing the pH values, followed by thiosul.

Soil-treatments Interaction. For Arizo soil, sulfuric acid reduced the soil pH more than elemental sulfur, polysulfide, and thiosul, respectively. Elemental sulfur and polysulfide significantly decreased the soil pH against the control but not against each other. Thiosul significantly decreased the Arizo soil pH, and this decrease was the least. Using sulfuric acid, sulfur materials reduced the pH value significantly.

For Hayhook soil, sulfuric acid reduced the soil pH value more than elemental sulfur; and both were not significantly different from each other, but they were significantly different against the control. Polysulfide reduced the pH more than thiosul; and both were not significantly different from each other, but they were against the control. Sulfuric acid and elemental sulfur were significantly different from polysulfide and thiosul in reducing the Hayhook pH. Using sulfuric acid and elemental sulfur, the Hayhook soil pH decreased more than by using polysulfide and thiosul, respectively.

For Vinton soil, sulfuric acid and elemental sulfur reduced the pH by 0.7 and 0.675, respectively, and they were not significantly different from each other. Polysulfide

and thiosul decreased the pH value by 0.60 and 0.563, respectively, and they were not significantly different from each other. All the amendments of sulfur were significantly different from the control, and they reduced the Vinton soil pH considerably. Sulfuric acid and elemental sulfur were significantly different from polysulfide and thiosul in reducing the pH in Vinton soil.

## SUMMARY AND CONCLUSION

Two experiments were conducted to study the effect of elemental sulfur and sulfur compounds on dry matter weight, phosphorus and manganese uptake of tomato plants, and soil pH. Three soils were treated with elemental sulfur, sulfuric acid, ammonium polysulfide, and thiosul. The experiments were carried out in the greenhouse. The soils were planted with tomato seeds in the first experiment, and tomatoes were transplanted in the second experiment. The soil pH and plants were analyzed, and data were evaluated by analysis of variance.

### Effects of the Amendments

A comparison of the dry matter weights between the first and second experiment were irrelevant because in the first experiment tomato seeds were planted and seven-week-old tomato plants were transplanted in the second study. Moreover, the plants of the second experiment were irregular in size at the time of transplanting. Also temperature was higher, and the day length was increased in the second study. Therefore, the dry matter weights in the second experiment cannot be compared with the first experiment.

The second experiment showed decreases in manganese and phosphorus uptake compared to the first experiment in the three soils generally. The manganese uptake in the second study was 27 to 70% lower than the first study in the three soils. The phosphorus uptake decreased 8 to 75% in the second study lower than the first study in the three soils.

According to Stroehlein and Tucker (personal communication, 1984), the limit of phosphorus deficiency is below 0.1% (1000 ppm) in the dry matter weight tissues, and the sufficient uptake is 0.12% (1200 ppm) in the tissue dry weight of the plants. The phosphorus uptake from Vinton soil was less than 0.1% (Table 4) in the dry matter, which was in the deficient range. Moreover, the phosphorus uptake from the other soils and first harvest of Vinton soil was above the sufficient level.

The deficiency of phosphorus in the second study of the Vinton soil was not related to the temperature, which was high, especially in the second study. Black (1957) reported that phosphorus deficiency is more pronounced at low temperature than at high temperature. Gardner and Jones (1973) reported that nutrient uptake by plants from the soil depends on the size and activity of its root system. This is particularly true for the immobile nutrients such as P. Unless nutrients are very abundant,

soil temperatures that restrict root growth will restrict nutrient uptake. Therefore, the uptake of the phosphorus was low in the Vinton soil, due to the roots which were not active and a good size as in Hayhook soil, which had good sized roots which resulted in high uptake rate of phosphorus (Table 6). The soil conditions did not have deficiencies in the two studies, which may be related to the soils' pH, which was below 7.0, at which the  $\text{H}_2\text{PO}_4^-$  will be available and preferable to plants. That has been reported by McGeorge and Green (1935), excluding Vinton soil of the second study due to phosphorus deficiency.

A comparison of the phosphorus uptake between the first and second study, the amount that had been taken from the soils was more in the first study than in the second study. Since the temperature was high and the pH was favorable for phosphorus to be available, therefore, plants in the first study were at an earlier stage of growth compared with the second study where seven-week-old plants were transplanted. Phosphorus uptake in the early growth is greater than in the latter stages of the plants (Black, 1957). Therefore, the early stage of the plants is more important than temperature in phosphorus uptake when the pH value is favorable.

According to Mortvedt et al. (1972), the uptake of manganese at 20 to 500 ppm in the plant tissues dry weight

is the sufficient range and less than that is deficient while more is toxic. Therefore, the manganese uptake was at the range of sufficient in the three soils and both studies. Thus, the pH values of less than 7 of the three soils (Table 7) did not cause the manganese uptake to be toxic or deficient.

For all three soils, all the treatments were effective in reducing the soil pH. The calcium carbonate content of Arizo soil was 6.64% and Hayhook and Vinton soils did not contain calcium carbonate. The low calcium carbonate content allowed the sulfur treatments to reduce the soil pH, acidifying the soil, as has been found by Ryan and Stroehlein (1973) and Tavassoli (1980). Sulfuric acid was the most effective in reducing the soil pH values.

The pH of Vinton soil was lowered more than Arizo soil, followed by Hayhook soil in all the treatments. The pH of the three soils decreased significantly as a result of using sulfur amendments.

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