

THE CORRECTION OF IRON CHLOROSIS
IN SORGHUM AND WHEAT

By

RICHARD BRUCE HEIZER

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Tarleton State University

Stephenville, Texas

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Thesis Approved:

Billy B. Tucker

Thesis Adviser

Lavoy I. Crox

Robert D. Morrison

N. N. Durbin

Dean of the Graduate College

891329

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CHAPTER I

INTRODUCTION

Chlorosis in plants as result of Fe deficiency is a rather common occurrence on some soils. A voluminous amount of research has been reported in the literature concerning the possible cause of the deficiency. Efforts at finding an inexpensive soil treatment for correcting Fe deficiency has been discouraging. Ironically enough, Fe is one of the most common of the metallic elements in the earth's crust, it is needed by the plant in very small amounts, and it is generally found in adequate amounts in most agricultural soils; however, certain plants growing on many soils in Oklahoma and throughout the Great Plains region are showing Fe deficiency symptoms.

Iron deficiency is the major micronutrient deficiency existing in the state of Oklahoma. Probable causes are numerous but in general high pH soils, low organic matter, and low available Fe are considered the most likely. Shown in Figure 1 are the counties in Oklahoma in which Fe deficiencies on sorghum (Sorghum bicolor (L.) Moench) and wheat (Triticum aestivum L.) have been observed on significant acreages. The West Central counties of Roger Mills, Beckham, Custer, Washita, and Dewey have been the most severely chlorotic areas as far as wheat is concerned. This has been particularly noted since the early fifties and since this time, the problem has been observed in several other counties.

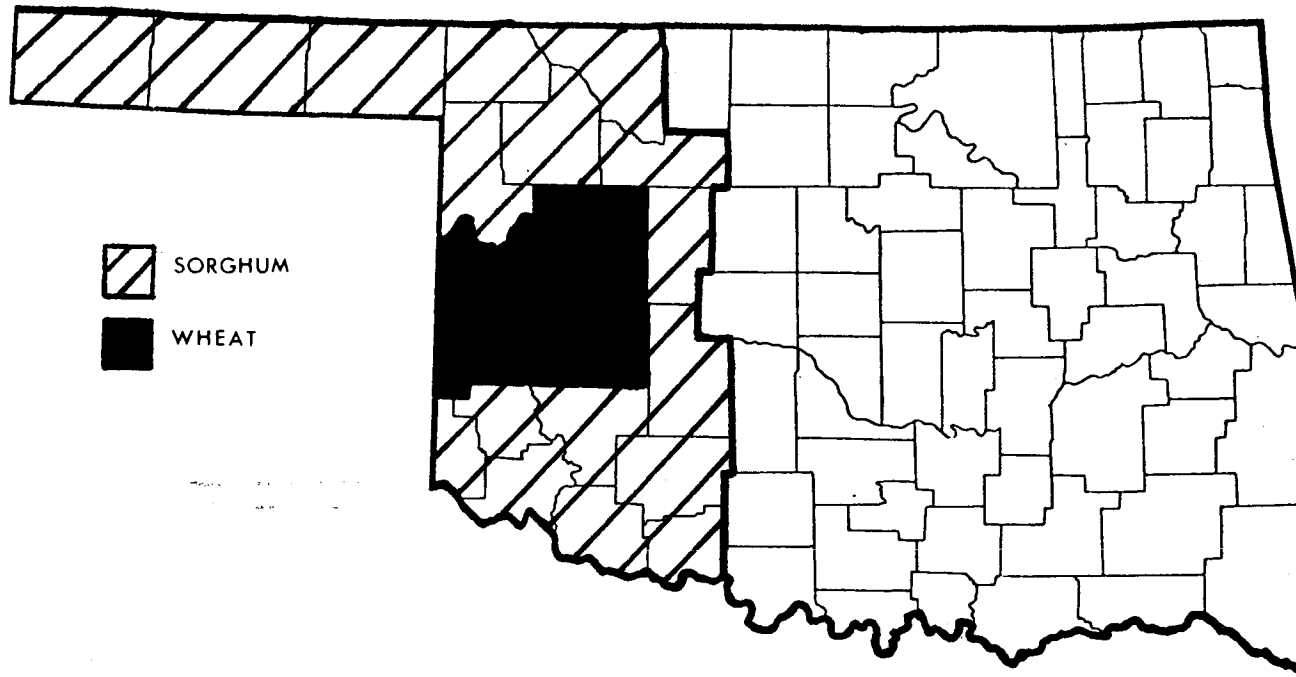


Figure 1. Counties in Oklahoma in Which Fe Deficiencies on Sorghum and Wheat Have Been Observed on Significant Acreages

Millions of dollars could be lost annually to farmers having the problem if corrective measures are not found. Chelated Fe materials have proved to be effective but not economically feasible in the case of grain crops. Research with the less expensive inorganic sources must be made to find good corrective measures.

The objectives of this thesis were three-fold: 1) screen promising Fe materials for the correction of Fe deficiencies by soil applications utilizing developed greenhouse pot techniques, 2) further evaluate the effectiveness of row applied fluid polyphosphates fortified with ferrous sulfates with emphasis on determining proper rates of Fe and carrier, and 3) compare solid sources of Fe fortified ammonium polyphosphate (APP) with fluid sources.

CHAPTER II

LITERATURE REVIEW

Iron is one of the most common of the metallic elements in the earth's crust, ranging from a low of 200 ppm to more than 10 percent (14). Chlorosis, caused by an Fe deficiency, is potentially a problem on most calcareous soils. Brown (2) estimates a third of the world's land is calcareous at the surface horizon. Iron deficiency in sorghum has been widespread in the Central and Southern Great Plains on calcareous soils for many years but Fe deficiencies on wheat has been noted only recently. Today Oklahoma alone has an estimated 50,000 acres of wheat which are Fe deficient (26).

Iron functions in the plant in several mechanisms, specifically in the activation of several enzyme systems—fumaric hydrogenase, catalase, oxidase, and in the cytochromes (14, 28, 31, 34). A shortage of Fe impairs the chlorophyll-producing mechanism because Fe is believed to be associated with the synthesis of chloroplastic protein (34). This reduction in the concentration of chlorophyll is a condition known as "chlorosis". More specifically, the reduction due to an Fe malfunction is generally referred to as "iron chlorosis".

Possible Causes of Iron Chlorosis

The cause of the impairment of chlorophyll production in a plant has been covered extensively in the literature. Possible causes of Fe

chlorosis will be discussed here in a general fashion and the correction of chlorosis will be covered in more detail, especially that occurring on alkaline and calcareous soils.

There are two possible localities of malfunctioning of iron leading to a chlorosis—one being the soil and the second being within the plant itself. Since it has been virtually impossible to pinpoint the exact location in all cases, I will treat the possible causes as one—the inavailability of the iron for the proper metabolism, and consequently the growth of the plant.

Much information has accumulated as to possible causes of Fe chlorosis in plants. A significant point is the differentiation of being a causitive factor or being an effect of the chlorosis (33). Several observations have been made from chlorotic plants and its immediate environment as to possible causitive factors. Since these have been thoroughly reviewed in the literature, a list of possible causes and/or effects follows with appropriate citations:

1. Low total Fe in the soil (2, 4, 14, 33, 34)
2. High pH soils (2, 25, 42)
3. Fine texture, high moisture content, poor soil aeration, cool temperatures (2, 4, 33, 42)
4. High soluble phosphate in soils and plants (2, 4, 8, 18, 25, 33, 41)
5. High K:Ca ratios in leaves (2, 33)
6. Antagonistic effects of other metals such as Mn, Zn or Cu (2, 6, 17, 24, 26, 29, 35)
7. Low organic matter—whether caused by management practices, erosion, or land leveling (2, 22, 26, 28)
8. Presence of a bicarbonate ion (2, 4, 39)
9. Soil compaction associated with heavy land grading equipment, tractors, or other farm equipment (22, 33).

These causes along with others mentioned by Wallace and Lunt (39) (including high light intensities, high levels of nitrate nitrogen, viruses, and root damage by nematodes and/or other organisms) are all factors involved with upsetting Fe metabolism in the plant. No one author agrees with all of the above; however, Fe chlorosis is generally agreed to be caused by a malfunction somewhere in its metabolic usage stage (5, 32).

Absorption of Fe seems to be related to the ability of the root to reduce Fe^{+3} to Fe^{+2} (5, 32) and several researchers feel this reduction is obligatory before Fe can be absorbed (5, 12, 31, 32). Brown et al. (5) state the reductive capacity of the roots is also greatly increased by Fe stress on plants and that this region of greatest reductive capacity is between the region of elongation and maturation which coincides with the region of greatest absorption and translocation.

Antagonism by other elements at absorption sites play an important role in the absorption and uptake of Fe. Lingle et al. (17) reported that Mn, Zn, Cu, Ca, Mg, and K reduced the Fe in the stem exudate of decapitated soybean plants. These ions, with the exception of Zn, stimulated Fe uptake and transport at low concentrations but at higher concentrations were inhibitory. Zinc was found to inhibit Fe accumulation in the exudate at all concentrations. Zinc has also been shown to inhibit the reduction of Fe^{+3} to Fe^{+2} . Other interactions, including P:Fe, Zn:Fe, Fe:Mn, Cu:Fe, and Fe:Mo are discussed at length by Olsen (24), all indicating the inactivation of Fe at certain metabolic stages causing a chlorosis. These interactions suggest that Fe absorption is extremely sensitive to the influence of other cations and help to explain the wide variation encountered in Fe deficiency of plants.

Plant species and varieties differ in their capacity to absorb Fe from a given growth medium after the Fe supply in the seed is exhausted. Soybean variety Hawkeye (HA) and PI-54619-5-1 (PI) are excellent examples. HA is an efficient plant in its capacity to absorb and translocate Fe from a nutrient media and is not susceptible to Fe chlorosis. The PI variety, on the other hand, is inefficient in this capacity of absorption and susceptible to Fe chlorosis. Brown (2) showed by grafting one onto the other that changes in capabilities of Fe uptake came about, depending on which root stock was used. Hodgson (12) noted that soybean varieties resistant to Fe deficiency were capable of reducing Fe^{+3} in solution while susceptible varieties were not able to induce the transformation. A fundamental difference between the two soybean varieties was that HA roots greatly exceed those of the PI variety in absorptive capacity for Fe from a relatively low Fe supply (2).

Earlier work by Brown et al. (4) showed that, depending upon two soil measurements, two types of chlorosis can be found in plants at high pH values. One type, dependent upon the soil's micronutrient balance status, can result in a competition at the absorption site for Fe externally. The second, dependent upon excess levels of available P or Ca, as is possible at higher pH values, tends to inactivate Fe internally because of an accumulation of P. A study in 1945 by Bennett (1) on the other hand, found P in pear leaves to be as high in green leaves as in the chlorotic ones. His conclusion was that the excess P found in the plant does not, at least directly, cause chlorosis by precipitating Fe. DeKock (8) feels this P:Fe ratio is an accurate assessment of the Fe status of the plant leaves because of the metabolic imbalance in the cell due to a deficiency of Fe. Others (18, 25,

41) have found P to play an important role in the deficiency of Fe in calcareous soils.

With both internal and external factors competing for Fe in plant growth, it is possible to realize a great variability of Fe concentration in the plant material dependent upon the competitive factors involved and the plant species grown (4).

Two interesting but complicating facts have been found with chlorotic plants. One, as reported by several researchers, is that chlorotic leaves often contain more total Fe than do normal green leaves (5, 26, 29, 38). This suggests that much of the Fe present in chlorotic plants is in a form that is not effective in the metabolic process. This is interesting because the cause of Fe chlorosis, then, must be on a basis other than that of the concentration of Fe in the plant.

The second complication of the overall problem is that Fe deficiency conditions in the field tend to diminish as the season progresses (26, 28). This makes a study of the problem very difficult but is explained physically by Schneider et al. (28) in that the warming of the soils, the reduction of soil moisture, and increased soil pore space improves aeration and encourages a greater microbial activity.

Iron deficiencies in plants, especially that found on calcareous soils and commonly called "lime-induced", does not appear to have a causitive factor common to other chlorosis forms. The problem is complex and occurrence of chlorosis is dependent upon the Fe requirement of the plant species and variable factors in the growth media which affect this requirement and the available Fe supply in the soil (7).

Visual Symptoms of Deficiency

After a general discussion on possible causes of Fe chlorosis, the plant can be studied as to the visual effect of improper Fe metabolism. In cases of slight chlorosis, the generally pale leaf color may not be distinguishable from a deficiency of nitrogen or other elements (42). As the plant is deprived of more Fe, the young leaves become affected first with a very slight striping parallel to the veins of the leaf in grasses and a faint interveinous yellowing in other plant types. The chlorosis of the younger leaves first is the result of the nonmobility of Fe in both soil and plants.

An intermediate degree of Fe chlorosis shows the typical interveinal discoloration that is diagnostic for such a deficiency, a yellowing of the interveinal areas of younger leaves with the veins remaining green. In more severely chlorotic conditions, green color will be absent in the leaf with the leaf being essentially devoid of chlorophyll and white in appearance. Growth of the plant is usually retarded, and in severe cases, the plants will die (28, 42).

At the interveinal chlorosis stage, there is a sharp distinction between green veins and less green (or yellow) tissue between the veins. This is in contrast with chlorosis resulting from Zn or Mn deficiencies in which there is a gradual variation in green color within the interveinal tissues with a darker color occurring adjacent to the veins (42).

Sources of Iron

Once an Fe deficiency has been diagnosed, corrective measures must

be undertaken if acceptable yields are to be obtained. Over the years, several inorganic forms have been used to supplement Fe to the plant.

Sauchelli (27) listed several of the more common:

1. Ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ at 20 percent Fe)
2. Ferric sulphate ($\text{Fe}_2(\text{SO}_4)_3 \cdot 4\text{H}_2\text{O}$ at 23 percent Fe)
3. Ferrous oxide (FeO at 77 percent Fe)
4. Ferric oxide (Fe_2O_3 at 69 percent Fe)
5. Ferrous ammonium phosphate ($\text{Fe}[\text{NH}_4]\text{PO}_4 \cdot \text{H}_2\text{O}$ at 29 percent Fe)
6. Ferrous ammonium sulphate ($[\text{NH}_4]_2\text{SO}_4 \cdot \text{FeSO}_4 \cdot 6\text{H}_2\text{O}$ at 14 percent Fe)
7. Iron Frits which vary in formula and Fe percentage.

Another important source with the advent of polyphosphates is iron ammonium polyphosphates containing approximately 22 percent Fe (21).

Because of poor response of many of the inorganic Fe sources as soil applicants, organic sources have been extensively researched (22, 28, 37, 38). A number of chelates as well as various polyflavonoid and ligninsulfonate compounds have proven to be effective but they are costly for low value crops (20, 21, 26, 37, 38). A few of the more important chelates include Mono sodium ferric ethylenediamine tetraacetate (Na Fe EDTA) at 5-14 percent Fe, Mono sodium ferric hydroxyethylene diaminetriacetate (Na Fe HEDTA) at 5-9 percent Fe, Mono sodium ferric ethylenediamine (di(o-hydroxyphenyl-) acetic acid) (Na Fe EDDHA) at 6 percent Fe, and Mono sodium ferric diethylenetriamine pentaacetate (Na Fe DTPA) at 10 percent Fe (21).

Rogers (26) evaluated two lignosulphates or lignin by-products of paper pulp, FeKeMin from Georgia Pacific Inc. at 11 percent Fe and

Rayplex Fe from Rayonier Inc. at 6.5 percent Fe. Other organic materials include polyflavonoids at 9-10 percent Fe and iron methoxyphenyl propane (Fe MPP) at 5 percent Fe (21).

The Correction of Iron Chlorosis

Soil amendments with either inorganic or synthetic organic sources have been extremely variable in their effectiveness due to the reactions that occur between the applied Fe and the soil components (21).

The application of the inorganic sources directly to the soil has had discouraging results. Higher rates do tend to be effective but the higher rates made in multiple applications tend to make the costs prohibitive (18, 23, 25, 43). Olsen (23), working with organic and inorganic Fe oxides and other soil amendments, found that the oxides at any rates had no effect on sorghum growth—either in decreasing the severity of chlorosis or increasing the amount of Fe uptake into the leaves. Ferrous sulphate at the rate of 1120 kg/ha increased chlorophyll production in the plant, and the use of sulphuric acid increased yields and decreased chlorosis. He later demonstrated the influence of lowered pH on availability of indigenous Fe (21).

Acidification of calcareous soils has been attempted by several researchers (18, 23). The amounts necessary are prohibitive under broadcast conditions; e.g. ten tons of sulphuric acid per acre-foot for each percent of CaCO_3 . The products of this reaction greatly increase soil salinity and these, if not removed by leaching, may injure crop performance (42). Mathers (18) studied the residual effects of heavy applications of FeSO_4 and H_2SO_4 on calcareous soils in the High Plains of Texas. He concluded that 250 ppm or more Fe with 250 ppm or more

H_2SO_4 significantly increased yields after three crop harvest intervals from time of application in the greenhouse. Banding with the seed in the field, 560 kg/ha Fe as $FeSO_4$ or 560 kg/ha H_2SO_4 produced essentially the same yield response. Increasing the amount of H_2SO_4 showed a decrease in yield agreeing with Wallihan (42). His results also agreed with Watanabe (41) and Onken and Walker (25) in which he found by adding P to Fe deficient soils, the deficiency became more severe.

A greenhouse investigation by Onken and Walker (25), also on soils of the Texas High Plains region, showed a distinct relationship between P and Fe. Soil applications of a low and high rate of ferrous sulfate and EDDHA along with foliar applications of the same materials were studied. The high rates, 600 kg/ha of $FeSO_4$ or 200.4 kg/ha of the chelate, significantly increased the yields, while the foliar applications at both high and low rates (5 percent and 2 percent) of $FeSO_4$ and high and low rates (1.5 percent and 0.5 percent) of EDDHA did not significantly increase yields. Rates of the Fe materials high enough to significantly increase the yield contained a P:Fe ratio of 0.4 while those that did not increase yields had a much higher ratio of 0.7 to 1.2. A possible interaction between P and Fe causing inactivation of the absorbed Fe was the probable cause of chlorosis in this area.

Much effort has been devoted to methods for supplying Fe directly to the plant. Spray solutions of iron sulphate or other salts differ widely in their effectiveness according to the species of the plant (42). Research by others (9, 42, 43) with foliar sprays have proven more satisfactory than that shown by Onken and Walker. Withee and Carlson (43) indicate that spraying chlorotic grain sorghum with three

sprays of 4 percent ferrous sulphate was an effective method of improving the yield of the grain. Soil application (broadcasting ferrous sulphate) to effectively overcome the chlorosis, required up to 720 kg/ha, an amount that is economically prohibitive. Fisher and Reyes (9) also found foliar sprays of Fe compounds to be much better and economical than soil treatments.

Those plants that do not respond well to sprays exhibit two principle difficulties: first, it was suggested the Fe enters the leaves only at localized spots, and second, the Fe that enters is quickly immobilized and therefore does not benefit leaves developed subsequent to the spray (42).

For these reasons, the problem of erratic results and common failures in Oklahoma, and the added disadvantage of having to spray more than one time is generally discouraging to this type of application.

In view of the lack of success with inorganic sources, a considerable amount of attention has been given to soil application of synthetic chelates. Research by Holmes and Brown (13) showed that of five chelates studied—EDTA, HEDTA, CDTA, DTPA, AND EDDHA—only DTPA and EDDHA were effective in eliminating Fe chlorosis in soybeans grown on 17 calcareous soils of western USA. Rogers (26) in his work with the lignosulphates FeKeMin and Rayplex Fe on calcareous soils of western Oklahoma demonstrated that the Fe sources were effective but impractical because of the necessity of high rates at high costs. Also, Rogers found manures to hold some promise in correction of Fe deficiency in wheat; however large rates were necessary and resulted in high treatment costs.

Organics, then, are effective but presently impractical for low

value crops use. Continued research in this area may someday lower this restriction of economics.

Banding Fe sources instead of broadcasting is another possibility to lower the amount of material needed and also lower the reaction of the soil with the Fe source. Murphy (22) using a 12-40-0 suspension studied fluid forms of FeSO_4 , $\text{Fe}_2(\text{SO}_4)_3$, and FeHEDTA. None of these forms significantly yielded higher than the check on grain sorghum in western Kansas. No information has been found on the possible banding of ferrous sulphate with the seed at time of planting—a source and type of application to be examined with the results of this thesis.

As stated earlier, soil application of the less expensive inorganic Fe sources must be effective for low value crops at low application rates to be economical. For this reason, research at Tennessee Valley Authority (TVA) has shown that the mixing of the Fe source with a fluid polyphosphate at low rates was effective, feasible, and economical. Mortvedt and Giordano (20) predicted this possibility in the greenhouse. Results of their experiments suggested several important points:

1. Both FeSO_4 and $\text{Fe}_2(\text{SO}_4)_3$ may be effective for crops at reasonably low rates if applied with fluid polyphosphate fertilizers.
2. Maximum level of Fe which can be dissolved in 11-16-0 (11-37-0 oxide form) solution is about 1 percent without dilution, an amount which might not be enough for early growth of a crop. Therefore a suspension may be required to supply more Fe. (The Fe level in these fertilizers can be increased to about 3 percent if the fertilizer is first diluted with an equal volume of water.)
3. Commercial grade 10-15-0 (10-34-0 oxide form) was about as effective as 11-16-0 but orthophosphate, 8-11-0 (8-24-0 oxide form) was ineffective as a carrier.

Because of the sequestering properties of polyphosphates, metals are significantly more soluble in ammonium polyphosphate solutions (Poly-N) 10-34-0 and 11-37-0 than in 8-24-0 (orthophosphate) solutions.

Iron, Cu, Mn, and Co sulphates are incompatible with 8-24-0 (19, 36). The incompatibility exists because of the formation of metallic ammonium orthophosphates (11, 15).

Frazier (11) reported that the chemical behavior of ferrous Fe in ammonium polyphosphate solutions is similar to that of zinc and divalent Mn. Ferrous Fe precipitates in two forms. The more common form is $\text{Fe}(\text{NH}_4)_2\text{P}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$, a grey-green precipitate that oxidizes and turns brown on exposure to the atmosphere. This salt is formed rapidly when metallic Fe is attacked by the fertilizer solution. The other form, $\text{Fe}(\text{NH}_4)_6(\text{P}_2\text{O}_7)_2 \cdot 6\text{H}_2\text{O}$, is less common but increases as the concentration of the solution increases and the pyro- to orthophosphate is increased much above 1. Lehr (15) adds that this precipitation is the product of the reaction with the ammonium pyrophosphate component of APP.

In a later publication, Mortvedt (19) reports that gelling generally occurs when a greater percentage of Fe in the P source is combined, but that the Fe in the resulting product is available to plants. He also adds that water must be used to reduce the viscosity of the product before it can be applied through conventional equipment and warns that it is not advisable to store the product overnight.

Forbes (10) outlined several important points in the use of fluid polyphosphates as carriers of an Fe source. Polyphosphates will sequester micronutrient metals, but in order to do this successfully, it is essential that there be a high ratio of polyphosphates to the metal being sequestered. As pointed out above, if one exceeds these ratios, a precipitate will form from the stock solutions being added so rapidly because of getting a high local concentration of the metal. As found by Rogers (26) dilution of both the metal source and the fluid

polyphosphate lowers this local concentration of the metal somewhat.

This type of application is not without its disadvantages, however. Dilution of the fertilizers is generally objectionable to dealers and applicaters. Also, the problem of storage and the necessity of banding with the seed is objectionable since the trend is toward broadcasting of fertilizers. Also a shortage of liquid polyphosphate exists and makes its use on a wide scale virtually impossible today.

Another potential type of addition of Fe sources with ammonium polyphosphates is a physical mixing in powdered form. Mortvedt (20) noted that soil applications of Fe sulphate in several granular fertilizers, NH_4NO_3 , $\text{NH}_4\text{H}_2\text{PO}_4$, or $(\text{NH}_4)_3\text{HP}_2\text{O}_7$ (a major component of APP products), were not effective as sources of Fe for grain sorghum. Lehr (15) reported reactions with solid fertilizers are much like those in liquids since the soil moisture breaks the fertilizers down into the same components. If this is correct, Fe added to the slurry in the making of a solid APP could be feasible in making a granule that is more acceptable to dealers and applicaters alike.

Other methods of application such as coating fertilizer granules and coating seeds have been tried at TVA in greenhouse tests (20). Neither method has been successful because the rate of Fe applied had to be limited to very small amounts.

CHAPTER III

METHODS AND MATERIALS

Greenhouse Experiments

Soil Collection for Greenhouse

Soil samples were collected from a Cordell loam soil near Foss, Oklahoma on which several crops had exhibited an iron deficiency. The soil was brought to the greenhouse, screened through a 0.5 cm sieve to remove roots and debris, and stored in 15 gallon stainless steel barrels. The soil was not dried since previous research by Rogers (26) showed that drying prevented the characteristic symptoms from developing. The complete analysis and classification of this soil is shown in Table I.

Pot Culture Technique for Screening

Fertilizer Materials

Plastic pots with six inch diameter tops were used to which 1200 grams of soil (applied on an oven-dried basis) were added. Ten sorghum seeds (Sorghum bicolor (L.) Moench, Wheatland Variety) were planted in each pot. Each pot was brought to 13 percent water content by weight every other day. The plants were grown for 21 days before they were clipped to a five inch height and thinned to six plants per pot. Fourteen more days of growth were allowed before the plants were

clipped to ground level, weighed, and taken to the laboratory for analysis.

TABLE I
CLASSIFICATION AND ANALYSIS OF SOIL USED IN
GREENHOUSE EXPERIMENTS

Classification		Analysis										
Series:	Cordell loam				lbs/A				ppm			
Family:	Loamy, mixed, thermic	pH	%OM	NO ₃ -N	P	K	Ca	Fe	Zn	Mn	Cu	
Subgroup:	Lithic Ustochrepts	7.9	0.8	26	41	370	5800	1.5	1.33	6.6	.78	

Experiment 1

The effect of a constant N-P level, several Fe sources, high P, and an acidifying agent were compared in a completely randomized design with three pots per treatment. Potassium was not included since the soil analysis showed it to be adequate. The treatments and sources are outlined in Table II. Each treatment included a "with" and "without" N-P constant except for the fluid APP, the solid APP, and the CSP.

Experiment 2

Iron, manganese, and zinc treatments were compared in a 2³ factorial arrangement with four pots per treatment. A N-P constant was used

TABLE II
TREATMENTS, SOURCES, AND RATES OF MATERIALS
USED IN GREENHOUSE EXPERIMENTS

Experiment	Treatment	Source	Rate
1	N-P Constant	NH_4NO_3 , $(\text{NH}_4)_3\text{PO}_4$	55 ppm N, 10 ppm P
	Fe	Sequestrene 330 Chelate	4 ppm Fe
	Fe	FeSO_4	10 ppm Fe
	Fe	FeKeMin	10 ppm Fe
	Fe	Fe_2O_3 (from hydrolysis of cable ilmenite leach liquor)	70 ppm Fe
	Acidifying Agent	Texas Sulfur Soil (pH 2.5)	2000 ppm material
	Fe & P	11-37-0 (Fluid APP) chemically fortified with FeSO_4	10 ppm Fe
	Fe, N, P	Solid Fe-coated APP (12-51-0; .9 Fe)	2 ppm Fe, 102 ppm P, 24 ppm N
	P	0-46-0 (CSP)	185 ppm P_2O_5
2	Fe	FeSO_4 (20% Fe)	10 ppm Fe
	Mn	MnSO_4 (20% Mn)	10 ppm Mn
	Zn	ZnSO_4 (36% Zn)	10 ppm Zn
3	Ammonium Polyphosphates	11-37-0 (Fluid APP) 10-57-0 (Solid APP)	40 ppm P_2O_5
	Fe	FeSO_4	5, 10 and 20 ppm Fe
	Fe	Sequestrene 138 (6% Fe) (with Fluid APP only)	4 ppm Fe

as in Experiment 1. The treatments and sources are shown in Table II.

Experiment 3

A comparison of the effectiveness between a solid (10-57-0) and a fluid (11-37-0) ammonium polyphosphate was made applying each alone and in combination with different rates of ferrous sulphate and one rate of Sequestrene 138 chelate in a completely randomized design with four pots per treatment. The treatments, sources, and rates are shown in Table II.

Field Experiments

Seven field sites were located in areas with a history of developing iron deficient plants.

Experiment 4

Two sites were initiated in the summer of 1973 in Beaver County, Oklahoma using non-irrigated sorghum-sudangrass hybrid (Sorghum bicolor (L.) Moench x Sorghum sudanense (Piper) Stapf) as a test crop. The two sites, soils information, location, and complete soil analysis and classification are located in Table III. Comparisons were made of various P fertilizers, Fe sources, and an acidifying agent set in a randomized block design with four replications.

The Fe sources included APP (11-37-0) fortified with ferrous sulfate (FeSO_4) banded at 45 kg/ha P_2O_5 and 11 kg/ha Fe; Fe-Ke-Min broadcast at 11 kg/ha Fe; Sequestrene 330 Fe chelate at 4.5 kg/ha Fe and TVA's solid coated APP (12-51-0, .9 Fe) banded at 114 kg/ha P_2O_5 and 2 kg/ha Fe, respectively. The acidifying source was Texas Sulfur Soil

TABLE III
 CLASSIFICATION AND ANALYSIS OF SOILS USED IN EXPERIMENT 4
 BEAVER COUNTY, OKLAHOMA

Site	Classification	Sample	pH	%OM	lbs/A			ppm			
					NO ₃ -N	P	K	Fe	Zn	Mn	Cu
1.	Canadian fine sandy loam [Udic Haplustoll; coarse loamy, mixed, thermic]	0-6"	7.9	0.7	<10	8.5	406	3.3	2.9	7.7	1.7
		6-12"	8.0	0.6	<10	3.0	329	4.2	1.7	7.7	2.5
Troy Hoover											
2.	Canadian fine sandy loam [Udic Haplustoll; coarse loamy, mixed, thermic]	0-6"	7.9	1.0	<10	8.5	606	4.1	1.5	9.3	2.9
		6-12"	7.9	0.8	<10	3.3	424	4.9	2.9	9.6	5.8
Jerry Howard											

(pH 2.5) broadcast at 2240 kg/ha material and the high phosphate source being concentrated superphosphate (CSP, 0-46-0) broadcast at 206 kg/ha P_2O_5 .

All Fe sources were applied mixed with water except the solid APP. When mixing the ferrous sulfate with the fluid APP, each were mixed with water first, then combined in a tank with constant agitation. Forage yields were made in two harvests in the field and plant samples were brought into the laboratory for analysis.

Experiment 5

Five sites were initiated in the fall of 1973 using wheat (Triticum aestivum L. Var. "Nicoma") as the test crop. The five sites, soils information, location, and complete soil analysis are located in Table IV.

The basic treatments included fluid APP alone and in combination with two rates of ferrous sulfate and one rate of an iron chelate. The fluid APP (11-37-0) was applied at 45 kg/ha P_2O_5 and the rates of ferrous sulfate were 5.6 kg/ha and 11.2 kg/ha Fe banded in all cases. The chelate was Sequestrene 330 Fe chelate combined with fluid APP banded at 4.5 kg/ha Fe.

Two of the sites were used for the comparison of a solid APP (10-57-0) with the fluid APP alone and in combination with the above rates of ferrous sulfate. Solid APP and the ferrous sulfate were mixed mechanically and applied in a band as a dry material.

Nitrogen was applied topdressed to bring all the plots to 67.2 kg/ha. Four replications in a randomized block design were established. Degree of chlorosis, soil physical and chemical properties were

TABLE IV
 CLASSIFICATION AND ANALYSIS OF SOILS USED IN EXPERIMENT 5
 WEST-CENTRAL, OKLAHOMA

Site	Classification	Sample	pH	%OM	lbs/A				ppm						
					NO ₃ -N	P	K	Ca	Fe		Zn		Mn		Cu
									M*	D*	M	D	M	D	
3.	Yahola fine sandy loam [Typic Ustifluent: coarse loamy, mixed (calcareous), thermic]	0-6"	8.1	0.8	<10	29	380	4200	1.0	3.8	0.5	1.9	1.1	7.5	1.2
		6-12"	8.1	0.5	<10	9	264	4750	0.8	4.7	0.4	2.5	0.7	4.6	1.3
Horace Smith Custer County															
4.	Yahola fine sandy loam [Typic Ustifluent: coarse loamy, mixed (calcareous), thermic]	0-6"	8.0	0.9	23	33	531	4513	1.3	7.0	0.4	4.1	1.0	7.0	3.8
		6-12"	8.0	0.7	65	29	481	4963	3.0	13.1	0.4	2.0	1.8	13.1	2.3
Sam Dobson Roger Mills County															
5.	Spur silt loam [Fluventic Haplustoll: fine loamy, mixed, thermic]	0-6"	8.0	1.3	36	85	685	5063	0.6	2.4	0.5	1.5	1.1	12.3	1.6
		6-12"	8.1	1.2	29	32	590	6238	0.4	2.9	0.4	2.7	1.6	11.2	1.9
Dale Tracy Roger Mills County															

TABLE IV (Continued)

Site	Classification	Sample	pH	%OM	lbs/A				ppm						
					NO ₃ -N	P	K	Ca	Fe		Zn		Mn		Cu
									M	D	M	D	M	D	
6.	Yahola fine sandy loam [Typic Ustifluent: coarse loamy, mixed (calcareous), thermic]	0-6"	8.1	1.4	23	66	1129	4925	0.6	2.6	0.7	1.7	1.3	12.4	1.7
		6-12"	8.1	0.9	17	28	691	5400	0.5	3.1	0.5	1.1	1.2	8.5	1.8
	Glenn Tracy Roger Mills County														
7.	Quinlan fine sandy loam [Typic Usto- chrepts: loamy, mixed, thermic, shallow]	0-6"	7.5	0.9	14	43	222	4133	1.8	3.2	0.4	0.9	1.9	9.5	0.9
		6-12"	8.0	0.4	12	15	136	4600	1.1	2.0	0.3	0.6	0.6	4.5	0.7
	Herb Weil Beckham County														

*M: moist; D: dry

characterized at the experimental sites, including periodic measurements of available Fe, Zn, and Mn and soil moisture contents. Plant samples were taken to the laboratory for analysis.

Laboratory Analysis

Sample Preparation of Plant Material

All plant samples brought into the lab were weighed for green weight and dried in a force draft oven at 70° C for 48 hours. A dry weight was taken, plants washed for possible contamination, and redried for 48 hours. The dried plant materials were then ground in a micro-wiley mill equipped with a 20 mesh stainless steel sieve and cutting blades.

Chemical Analysis of Plant and Soil Samples

The analysis of the micronutrients Fe, Zn, Mn, and Cu were made using the atomic absorption technique (DTPA extractant) for the soil samples and colorometric spectrophotometry (nitroperchloric acid digestion) for the plant samples. The analysis included N, P, K, Fe, Zn, Mn, Cu, and Ca for the plant samples and the same plus organic matter percentage and pH for the soil samples. Analysis procedures for all nutrients measured are shown in Table V.

TABLE V
ANALYTICAL PROCEDURES USED FOR CHEMICAL ANALYSIS
OF PLANT AND SOIL SAMPLES

Type Sample	Element	Procedure
Soil	NO ₃ -N	CaSO ₄ extractant, measured by Orion specific Ion Electrode
	P	Bray I (1:20 soil solution)
	K	1N ammonium acetate extractant measured by Flame Emission
	Ca	1N ammonium acetate extractant measured by Atomic Absorption
	Fe, Zn, Mn, Cu	DTPA extractant measured by Atomic Absorption
Plant	N	Micro-Kjeldahl analysis
	P	Nitroperchloric acid digestion measured by sodium molybdate color development
	K, Ca	Nitroperchloric acid digestion measured colorimetrically
	Fe, Zn, Mn, Cu	Nitroperchloric acid digestion measured colorimetrically

CHAPTER IV

RESULTS AND DISCUSSION

Several organic and inorganic Fe sources were tested for their ability to eliminate Fe chlorosis or to at least curtail the problem. For ease of reporting and comprehension, the data will be presented under two main headings—greenhouse pot experimentation and field plot experimentation.

Greenhouse Pot Experimentation

Several objectives were studied in the first greenhouse experiment. The major objective was that of screening several Fe sources as to their effectiveness in correcting Fe chlorosis in grain sorghum. Included in this experiment, however, were several other materials besides the Fe sources that have been under examination for their effects on Fe uptake and yields in Fe deficient soils. Each Fe source was tested with and without a N-P fertilizer. Table VI shows the rates of N, P, and Fe added to the soils, the consequent yield of the plant material by treatments and a visual rating of extent of chlorosis of the plants.

As can be seen from the data in Table VI, several materials, such as FeSO_4 , FeKeMin, Sequestrene 330 (Fe Chelate), fluid APP+ FeSO_4 and a solid Fe coated APP, did show promise under pot culture to carry available Fe to the plant. Further evaluation is shown in Figure 2

TABLE VI
 BASIC TREATMENTS, AMOUNTS OF NUTRIENTS ADDED, YIELDS,
 AND VISUAL RATINGS OF GRAIN SORGHUM FORAGE

Factor	Treatment	Amount Nutrients Added (ppm)			Forage Yield (mg)	Visual Rating*
		N	P	Fe		
Level 2 With N-P	1. Control	55	10	0	350	4
	2. FeKeMin	55	10	10	2373	2
	3. Sequestrene 330	55	10	4	1610	3
	4. FeSO ₄	55	10	10	2786	2
	5. Tx. Sulfur Soil	55	10	0	313	4
	6. Fe Oxide	55	10	70	313	4
Level 1 Without N-P	1. Control	0	0	0	633	4
	2. FeKeMin	0	0	10	906	1.5
	3. Sequestrene 330	0	0	4	840	2
	4. FeSO ₄	0	0	10	996	1.5
	5. Tx. Sulfur Soil	0	0	0	403	4
	6. Fe Oxide	0	0	70	483	4
Other	Fluid APP (11-37-0)+Fe	12	17	10	1407	1.5
	Solid-Fe coated APP (12-51-0)	24	44	2	1393	3
	CSP	0	79	0	683	4

*Visual rating average of 3rd and 5th week observation

1. No visual chlorosis
2. Slight chlorosis
3. Moderate chlorosis
4. Severe chlorosis

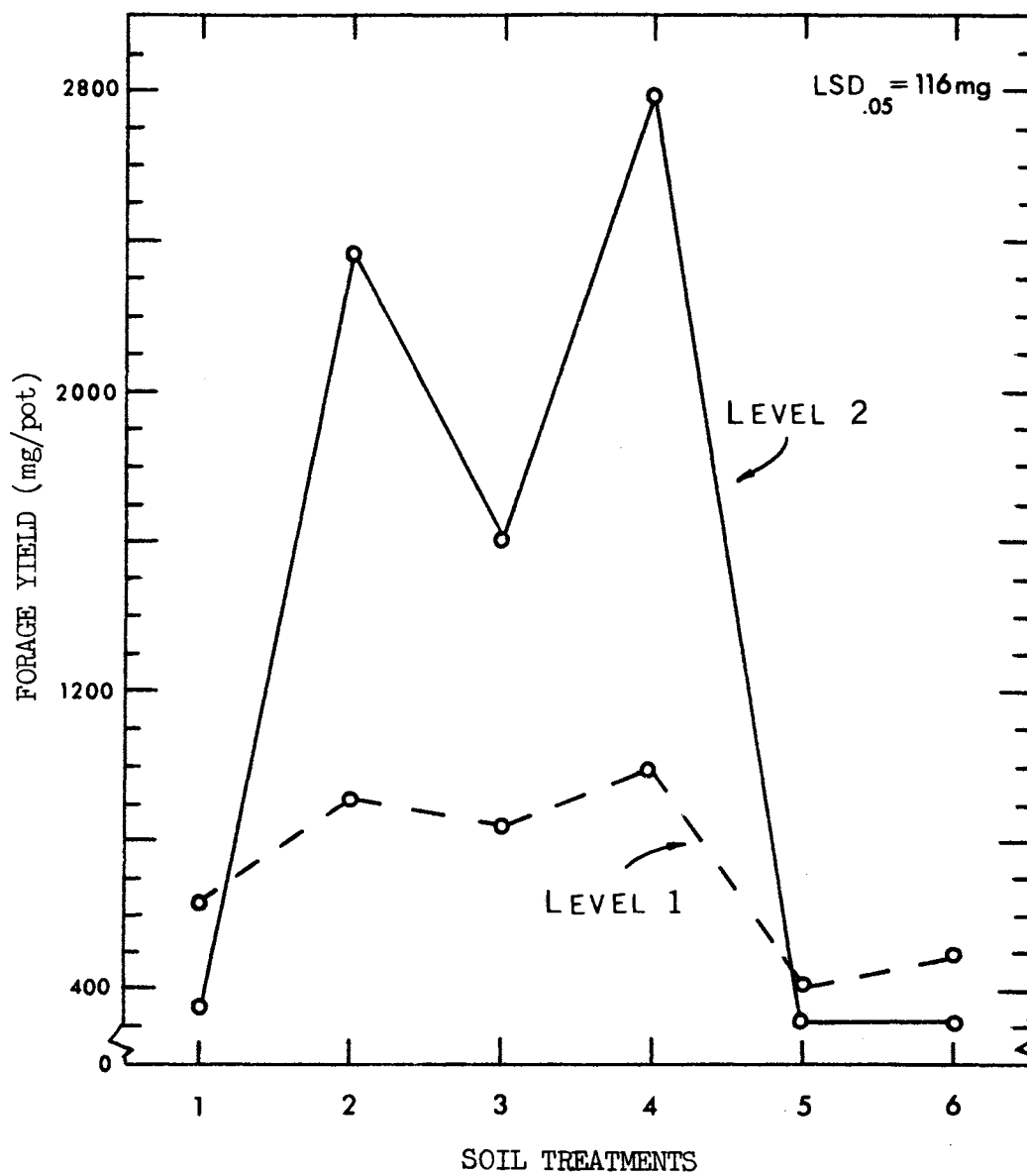


Figure 2. Interaction of the N-P Levels and Soil Treatments as Compared by Forage Yields of Sorghum

in which the N-P constant and the materials not containing N or P were analyzed as a 6^x2 factorial. Significant interaction did exist between the N-P level ("with" or "without") and the soil treatment. As can be seen from the graphical analysis in Figure 2, the treatments were affected to different extents by the addition of N-P. Yields from the control and FeO treatments were significantly lower than those obtained when a soluble iron source was added. Texas Sulfur Soil was ineffective in increasing yields. The other treatments, FeSO₄, FeKeMin, and Sequestrene 330 chelate, increased yields with the addition of N-P much more than without N-P. This interaction suggests the Fe sources ability to efficiently provide available Fe to the plant. Available Fe seemed to be the important factor in response from added Fe because when added to the soil (Table VI) FeO at 70 ppm Fe was greatly out yielded by FeSO₄ at 10 ppm Fe or Sequestrene 330 at 4 ppm Fe when N-P additions were made. The same was true, yet to a lesser degree, in the "without" N-P addition. Sequestrene 330 at 4 ppm Fe would be the most efficient of the Fe sources tested in this analysis but because of its high costs, was kept at this Fe concentration for more reasonable comparisons. Normal rates of synthetic chelates are less than 1 pound per acre. As also suggested from the analysis of the data, Fe is truly the limiting element in this soil and once supplied in available forms, can render normal plants that respond greatly to the primary nutrients N and P.

The addition of N and P resulted in an increase in visual chlorosis to some extent as noted from Table VI. This suggests possible increases in Fe rates are needed because of the plants increase in growth in these treatments. Also, the three treatments not included in the above

analysis but included in this experiment are presented in Table VI. Yields of forage proved not to be significantly different mainly because of a high coefficient of variability. This variation between treatments in pot experimentation has long been a problem with greenhouse pot experimentation and was a variation that was not satisfactorily controlled in this study. It is suggested from the yield data that both the fluid APP+FeSO₄ and the solid Fe-coated APP did carry available Fe for increased plant growth. The CSP at the high rate of P did not decrease yields as has been suggested by several authors (4, 8, 18, 41).

Total Fe and Mn uptakes are graphically shown in Figure 3. Again, significant interaction exists between the total uptakes of the metals and the N-P level. The greatest difference in uptakes occurred with FeSO₄ between no addition of N-P and the addition of N-P. The uptakes of Fe followed quite the same pattern as did the forage yields indicating a real soil deficiency in available Fe on the Cordell soil. Mn uptake followed the same general pattern but not to the extent as Fe uptake. This particular data suggests again the efficiency of several of the Fe-containing materials and their ability to carry available Fe to the plant. Once available Fe is supplied, this results in more normal plants with an increase in the uptake of other essential nutrients.

A possible antagonism has been reported by Watanabe et al. (41), Twyman (35) and Lingle et al. (17) between other metallic elements, especially Zn, and Fe. A second experiment was designed in a 2³ factorial to examine this possibility of antagonism in the Cordell loam soil and to compare the effects of Fe, Zn, and Mn upon the relationship

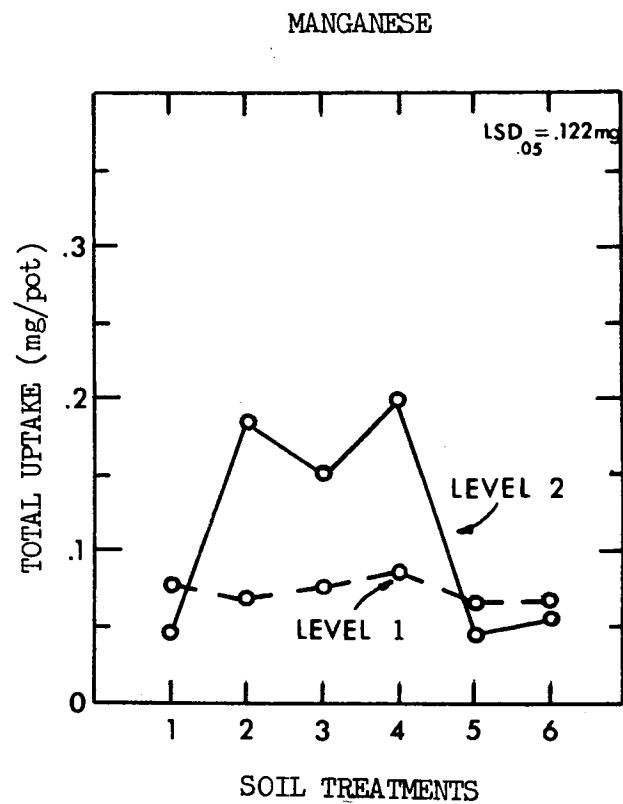
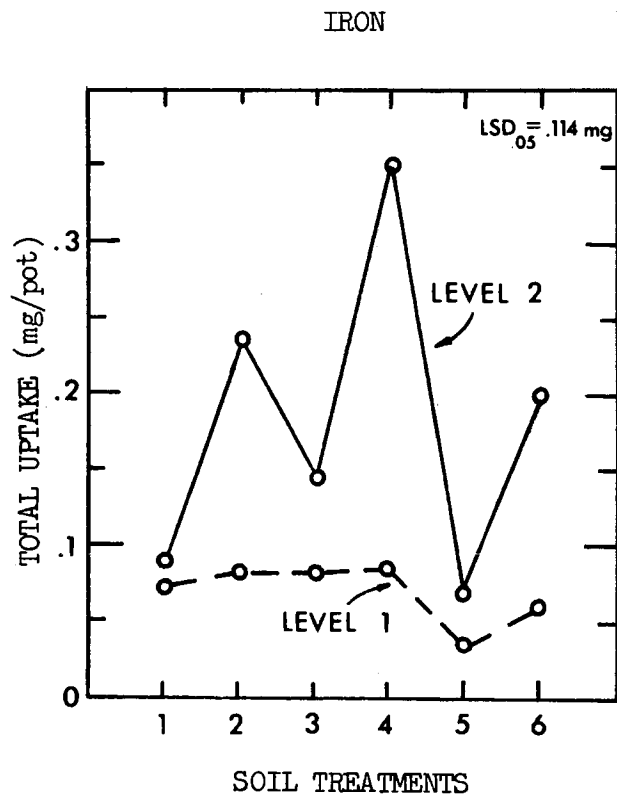
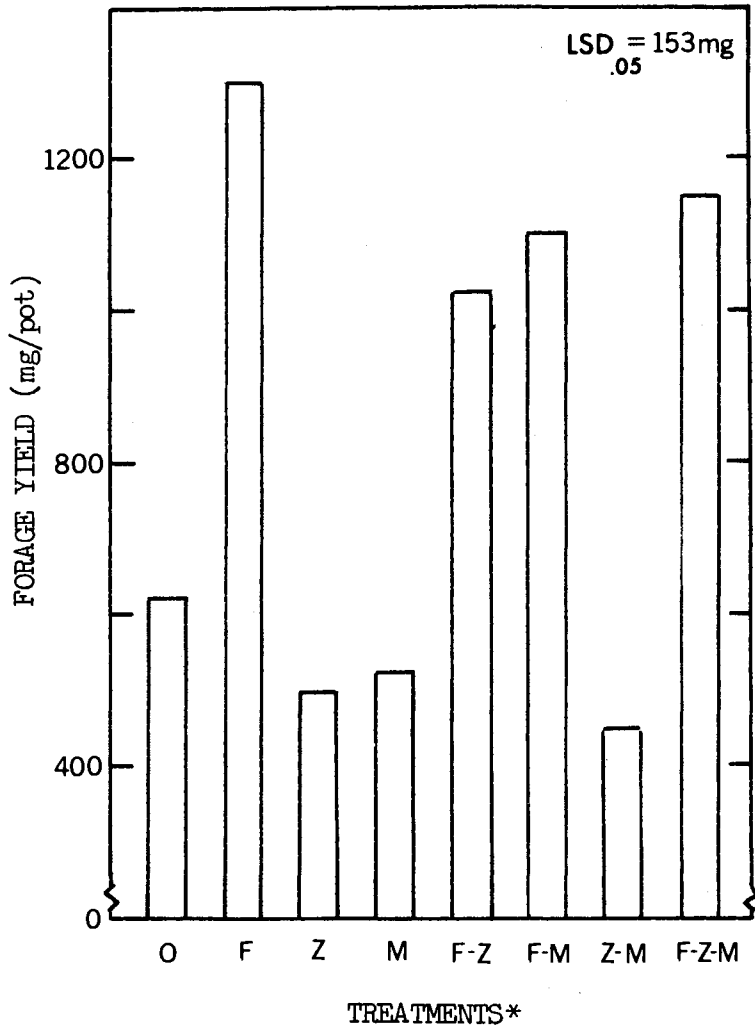


Figure 3. Interaction of the N-P Levels and Soil Treatments as Compared by the Total Uptake of Fe and Mn

of each other. The N-P was added to all treatments to bring all nutrients to the same level and to fully express the Fe chlorosis if it appeared. The resulting forage yields are shown in Figure 4. A true antagonism did exist between the metal elements especially in the treatments that included Zn and to lesser extent Mn. As indicated in Figure 5, the application of Zn significantly decreased the forage yields of grain sorghum both with and without Fe but the decrease was greatest in the presence of Fe. This suggests a definite antagonism exists between Zn and Fe agreeing with Lingle et al. (17) for they found antagonism by Zn at all rates of Fe. Somewhat of an additive effect occurred when all three metals were added at identical rates suggesting a lowered competition between the metals more than that with Zn, or Mn alone with no Fe. An equilibrium point is suggested here with the addition of all three metals compared to just one or two. Iron is shown to be the limiting micronutrient in the Cordell loam soil because of the significantly higher yield levels when Fe was added.

The sorghum plants were analyzed to find the concentrations and consequent total uptake levels of several of the primary, secondary, and micronutrient elements (Table VII). It is of interest that the plants showed no significant increase in Zn or Mn when only these metals were added to the soil but significantly increased in both when Fe was added. This implies the soil is sufficient in Mn and Zn and with low available Fe could possibly enter into an antagonism for Fe uptake sites. Zn probably plays the major role and even Mn at high concentrations. This theory agrees with Lingle et al. (17).

A second point shown by the analysis is the uptake of both Fe and Mn are nearly the same for each treatment. This supports the



*F-Fe; Z-Zn; M-Mn

Figure 4. Forage Yields of Grain Sorghum as Affected by Additions of Fe, Zn, and Mn

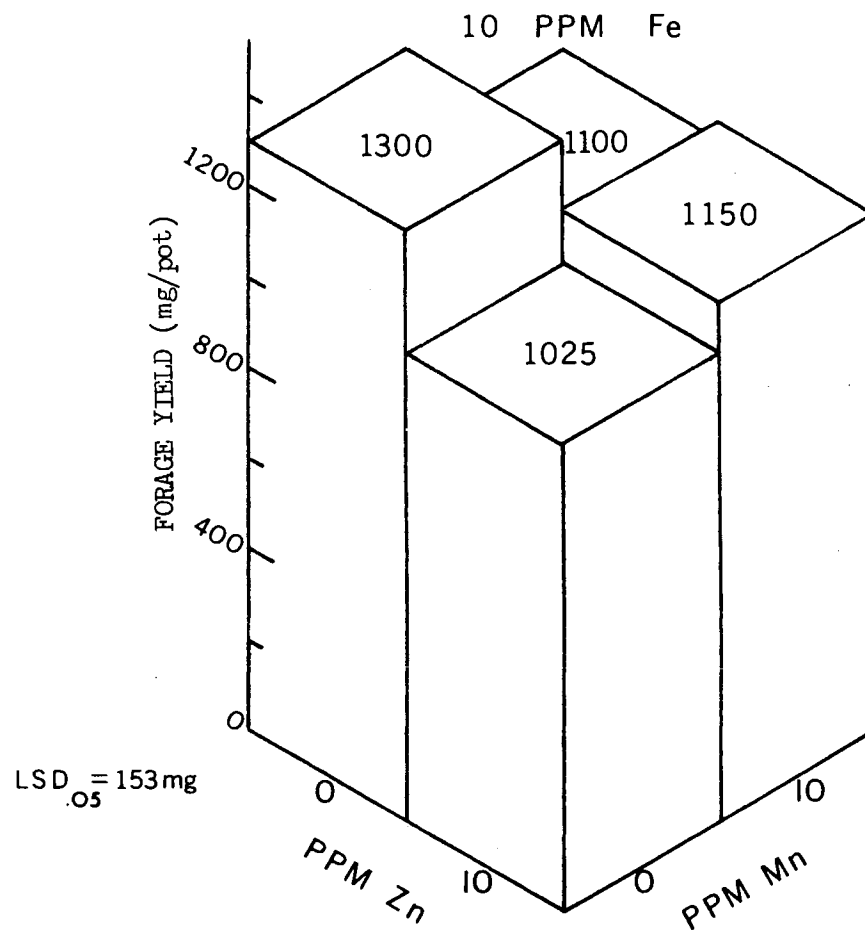
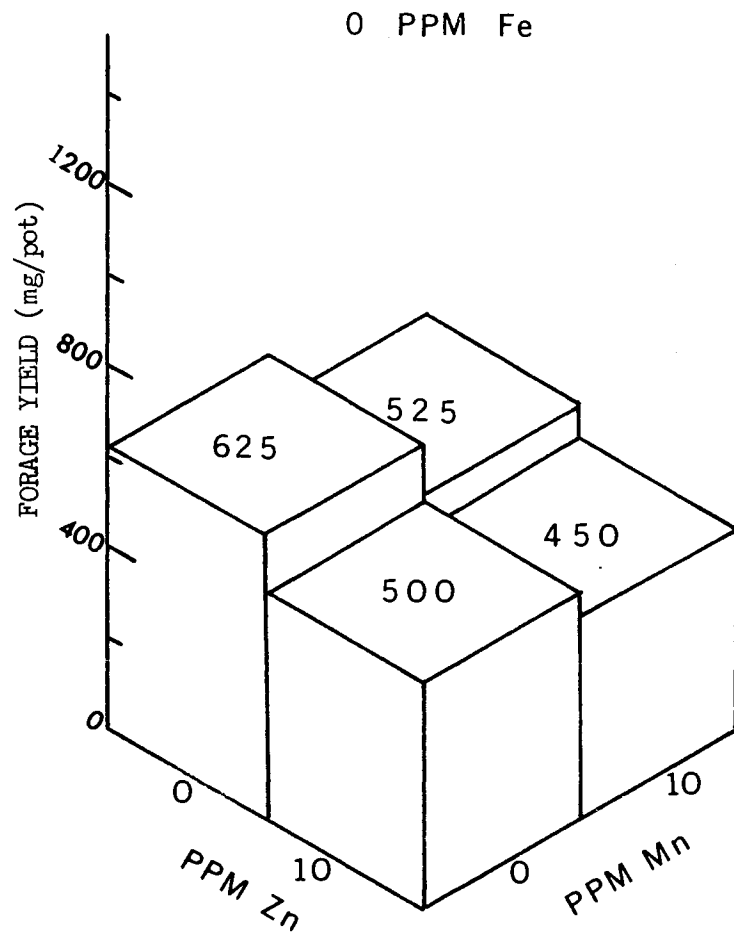


Figure 5. Forage Yields as Affected by the Fe-Zn-Mn Interaction

TABLE VII

TOTAL UPTAKE OF P, K, Ca, Fe, Zn, Mn, AND Cu BY SORGHUM
PLANTS AS RELATED TO ADDITIONS OF Fe-Zn-Mn FACTORIAL
AND CONSEQUENT VISUAL CHLOROSIS

Treatment	Total Uptake (mg)							Visual Rating*
	P	K	Ca	Fe	Zn	Mn	Cu	
O-O-O	2.04	30.4	3.74	.067	.149	.051	.009	4
Fe-O-O	2.23	47.1	6.33	.129	.092	.133	.015	2.5
O-Zn-O	1.83	26.4	2.80	.051	.066	.038	.006	4
O-O-Mn	1.79	28.5	3.24	.054	.064	.055	.007	4
Fe-Zn-O	2.12	46.9	6.04	.106	.146	.111	.013	3
Fe-O-Mn	2.19	52.3	6.17	.122	.223	.116	.013	3
O-Zn-Mn	1.44	20.4	2.92	.053	.071	.039	.006	4
Fe-Zn-Mn	1.41	46.6	6.09	.109	.215	.101	.012	3
LSD _{.05}	.99	13.3	1.31	.022	.129	.022	.004	

*Rating based on average observations taken 3rd and 5th week

1. No chlorosis
2. Slight chlorosis
3. Moderate chlorosis
4. Severe chlorosis

possibility that Mn can be tolerated at greater amounts than can Zn, depending, of course, on the Fe status.

As discussed earlier, additions of Fe to this deficient soil increased the uptake of all other elements which is also evident from the analysis and is to be expected of a more normal growing plant. From the analysis of the yields and the total uptakes of the several nutrients, it was found that Zn was not only antagonistic to Fe and consequently forage yield but it also significantly reduced the uptake of Mn as is graphically presented in Figure 6. Also shown graphically is the interaction of Fe and Mn to Zn uptake. High Mn and low Fe decreases the uptake of Zn. Fe in available forms, on the other hand, significantly increases Zn uptake with increases of other elements, also. These interactions of Zn and Mn with each other and their effect on Fe signifies the importance of a balance that these metallic elements must ultimately reach or the uptake of all three could be significantly changed.

The final greenhouse experiments were initiated with several objectives in mind. Fluid APP plus Fe has shown promise in previous work by Rogers (26) and Mortvedt and Giordano (20). From an economical standpoint, polyphosphate carriers of Fe have fared reasonably well. For this reason, tests were initiated using polyphosphate as a carrier for Fe. The first objective was to again test the effectiveness of the fluid APP and hopefully find optimum rates of ferrous sulphate that could be added as a chemical mixture to the fluid APP for the ultimate correction of chlorosis in grain sorghum forage. The results of rates of Fe chemically mixed with 11-37-0 (fluid APP) on forage yields of grain sorghum plants and the consequent ratings of chlorosis before

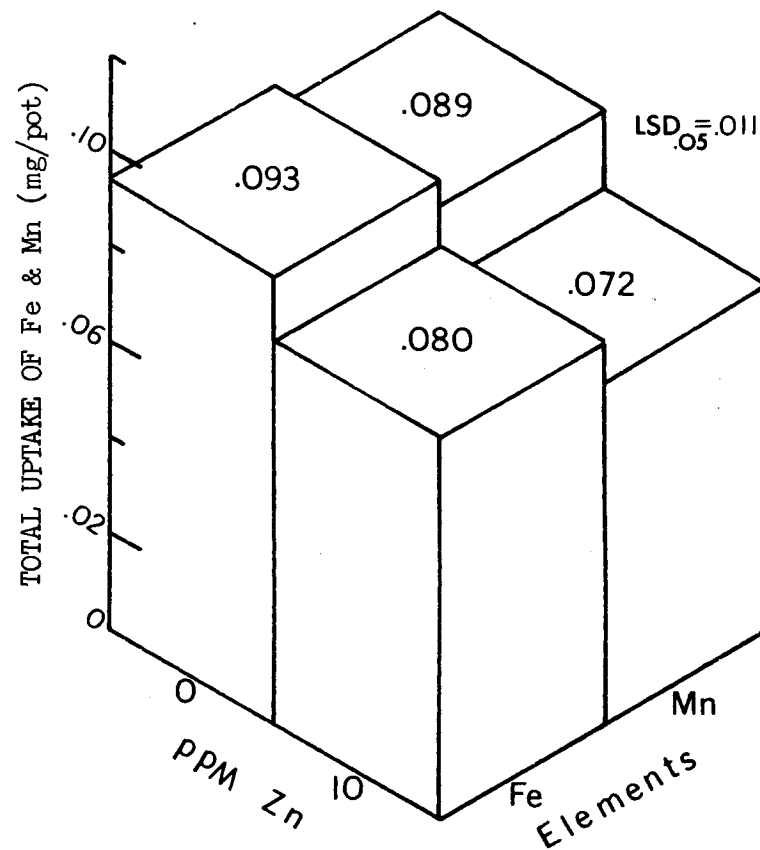
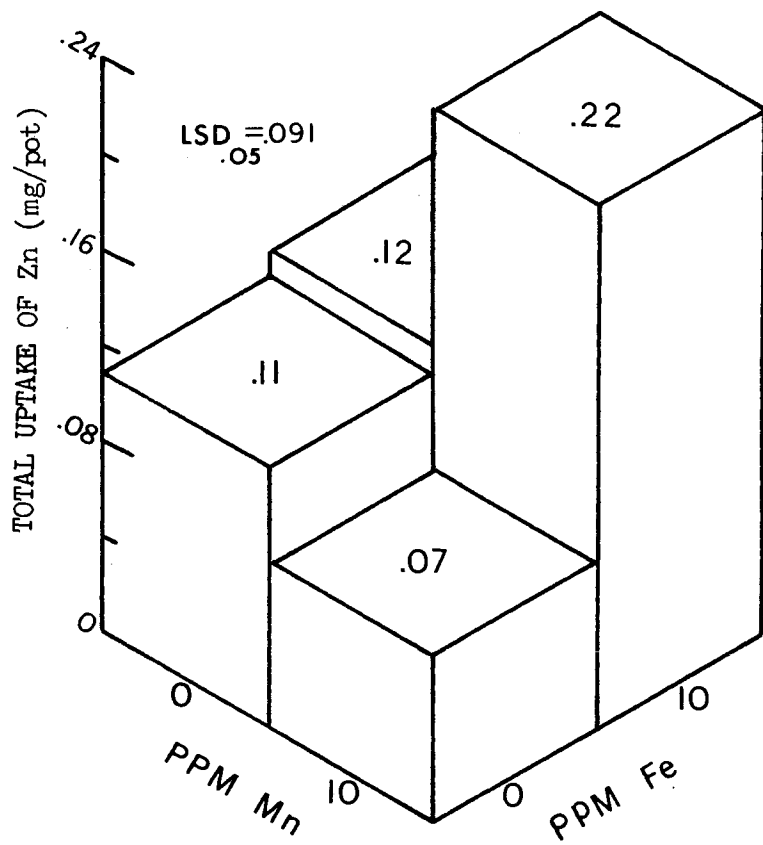


Figure 6. Total Uptake of Zn as Affected by Fe and Mn Additions and Total Uptakes of Fe and Mn as Affected by Zn Levels

and after clipping are presented in Table VIII. Increasing rates of Fe did tend to increase forage yields. Fluid APP with Sequestrene 330 (the synthetic organic Fe chelate) was used as a standard to evaluate the effectiveness of the rates of ferrous sulfate.

A second objective of this greenhouse experiment was to test the length or duration of effectiveness of the Fe carrier by clipping the sorghum plants the third week of growth. As can be noted from Table VIII, visual chlorosis was intensified by clipping suggesting that grazing of potential Fe deficient plants could worsen the problem. Also, judging by visual effects, chlorosis was least in the highest rate of included Fe (11-37-0+20 ppm Fe), again supporting the idea of the Fe deficiency problem in the Cordell loam soil.

Lehr (15) discussed the breakdown of a solid APP in the soil to act much the same as the fluid APP. This indicated possibilities of physically mixing ferrous sulfate with a solid APP and testing its effectiveness in the correction of Fe chlorosis with that of the fluid forms at the same rates.

Results of the comparison are graphically outlined in Figure 7. The same trends in yield responses were obtained from both carriers but the fluid APP+20 ppm Fe gave the highest forage yield response. Both the solid and the fluid APP responded the same when added alone so no advantages or disadvantages are shown by the polyphosphate source for supplying available P. The results of the experiment were statistically analyzed for possible interaction between the P source and the Fe rates. As can be noted from results presented in Figure 7, forage yields increased in the fluid treatments but no such significance of increase was found with the solid physical mix. A significance was found within

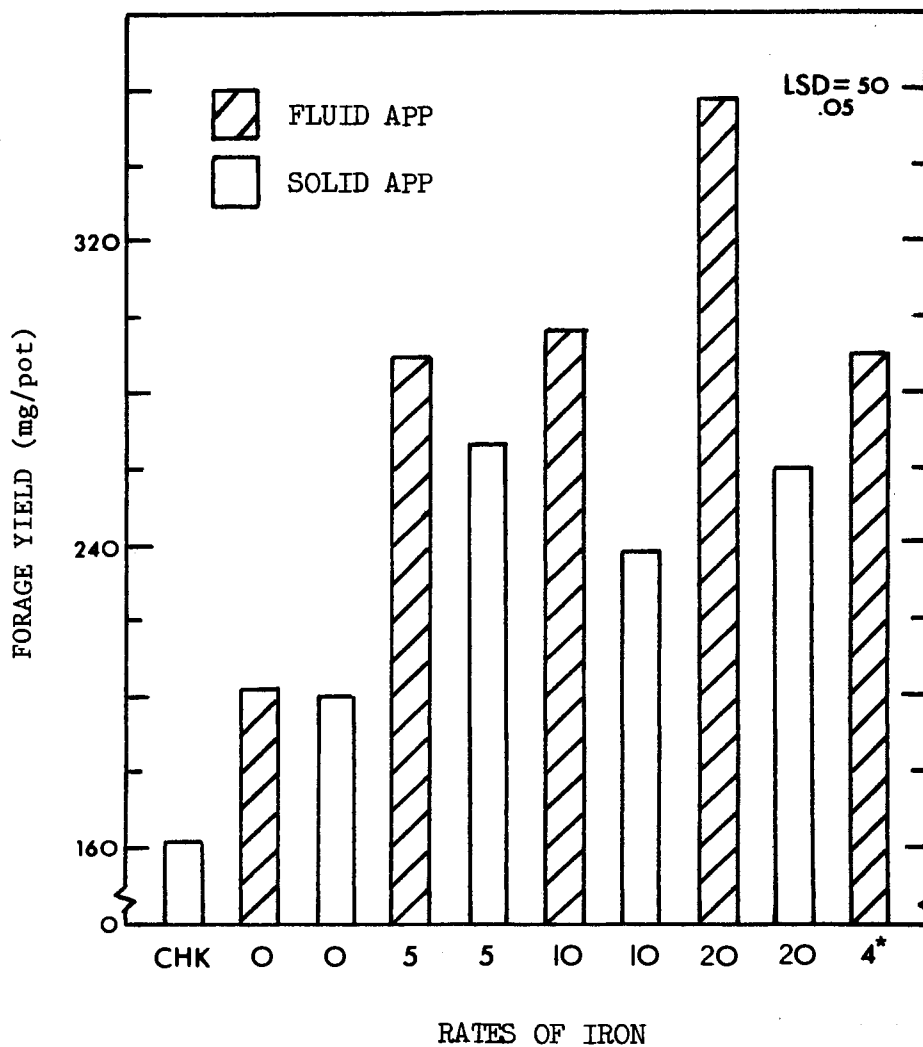
TABLE VIII
 FORAGE YIELDS AND VISUAL CHLOROSIS RATINGS
 OF FLUID AMMONIUM POLYPHOSPHATE FORTIFIED
 WITH DIFFERENT RATES OF IRON

Treatment	Yield mg/pot	Rating-Visually**	
		Before Clipping (3rd week)	Before Harvesting (5th week)
Control	430	4	4
11-37-0*	450	4	4
11-37-0+5 ppm Fe	960	2.5	3
11-37-0+10 ppm Fe	1098	2	2.5
11-37-0+20 ppm Fe	1145	1	2
11-37-0+4 ppm Fe (Chelate)	1068	2	2.5

*All fluid APP applied at rate of 40 ppm P_2O_5

**Visual rating

1. No chlorosis observed
2. Slight chlorosis
3. Moderate chlorosis
4. Severe chlorosis



*Sequestrene 138 Fe Chelate

Figure 7. Forage Yields of Grain Sorghum as Affected by Fe Rates and Phosphate Carrier

the rates of Fe used and between the P sources but no significant interaction occurred between the P and Fe source. This suggests an added availability of Fe in the chemically mixed form over that of the physically mixed Fe. The Fe carriers (APP's) were significantly different in these capacities thus the liquids carried the Fe more efficiently than did the solid physical mix over all levels of Fe.

Visual ratings of chlorosis between the two fertilizers were essentially the same but abundance of growth was noticeably less with the solid APP source. Growth seemed to be retarded, even though no difference in the amount of chlorosis was observed, probably due to reduction of available Fe. Noticeable decreases can be seen in the production of forage in these last greenhouse experiments due to a reduction in heating because of the onset of the energy crisis. Temperature became a factor since it was not optimal for growth of grain sorghum. Thus some differences may be attributable to the temperature.

Total uptakes of Fe, Zn, and Mn by the sorghum forage were obtained by laboratory analysis (Table IX). The fluid APP carrier seems to be the better of the two tested for supplying Fe to the plant in available forms. Zn and Mn uptake showed a significant difference in the interaction of the P carrier and Fe rate. A general increase in Zn was found with the fluid APP at increasing Fe rates (Mn remained much the same) while a decrease was found by both metals (Zn and Mn) in the solid mixture. This can probably be attributed to the increasing rates of Fe in the solid APP mix which were not available and not utilized by the plant, resulting in an imbalance and subsequent reduction in the other metallic elements.

While the fluid form does show promise as a carrier for available

TABLE IX
 TOTAL UPTAKES OF Fe, Zn, AND Mn BY SORGHUM PLANTS
 AS RELATED TO AMMONIUM POLYPHOSPHATE CARRIER

APP Source	Fluid APP (11-37-0)			Solid APP (10-57-0)		
Rate of Fe Added (ppm)	Fe	Zn	Mn	Fe	Zn	Mn
	($\mu\text{g}/\text{pot}$)			($\mu\text{g}/\text{pot}$)		
0	60	26	37	67	65	37
05	77	46	39	63	30	29
10	89	32	37	65	24	20
20	99	52	37	80	28	16
LSD 05	21	25	8	21	25	8

Fe, there are several disadvantages in its use. From the greenhouse use of the product, dilution of the material was one such disadvantage which agrees with the findings of Forbes (10). No appreciable Fe can be applied into the concentrated APP until both are diluted. Even then, any addition greater than 10 ppm Fe in the fluid APP at 40 ppm P_2O_5 causes a significant amount of precipitation to occur--a problem that could cause much handling problems. Another disadvantage occurring from this precipitation product is the storage of the mix--for this reason, the Fe and APP must be mixed quite close to the time it is to be applied. These problems will be discussed more fully in subsequent sections.

Field Plot Experimentation

Field experimentation was carried out to augment the information obtained in the greenhouse and test the materials under field conditions. Two sites were selected in Beaver County, Oklahoma on suspected Fe deficient soils in the summer of 1973. Five sites were later located in the Roger Mills-Beckham-Custer county areas for wheat research.

Forage sorghum was used as the test crop at the two sites in Beaver, County. The sites will be distinguished by the owners initials, i.e., TH for Troy Hoover (Site 1) and JH for Jerry Howard (Site 2). Both sites received the identical treatments of the first greenhouse experiment except for the Fe Oxide and the N-P variable.

Treatment results from the field tests were quite different although the soil types on which both sites were located were mapped as the same. The TH yield results are shown in Table X. No visual

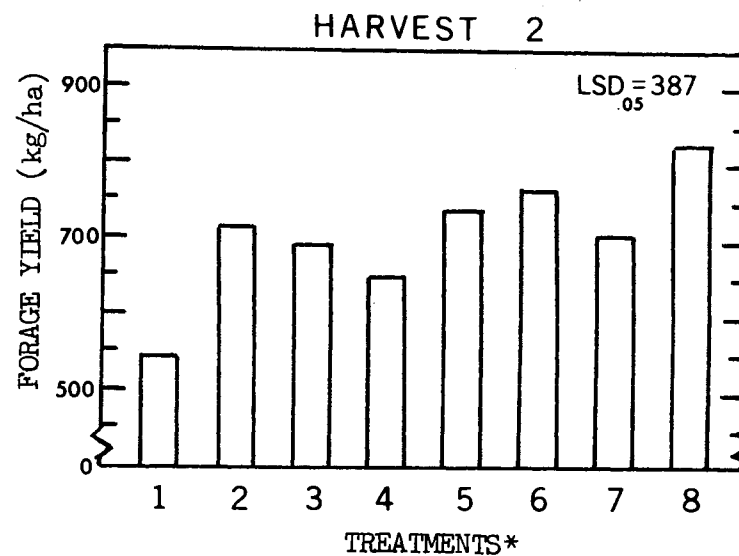
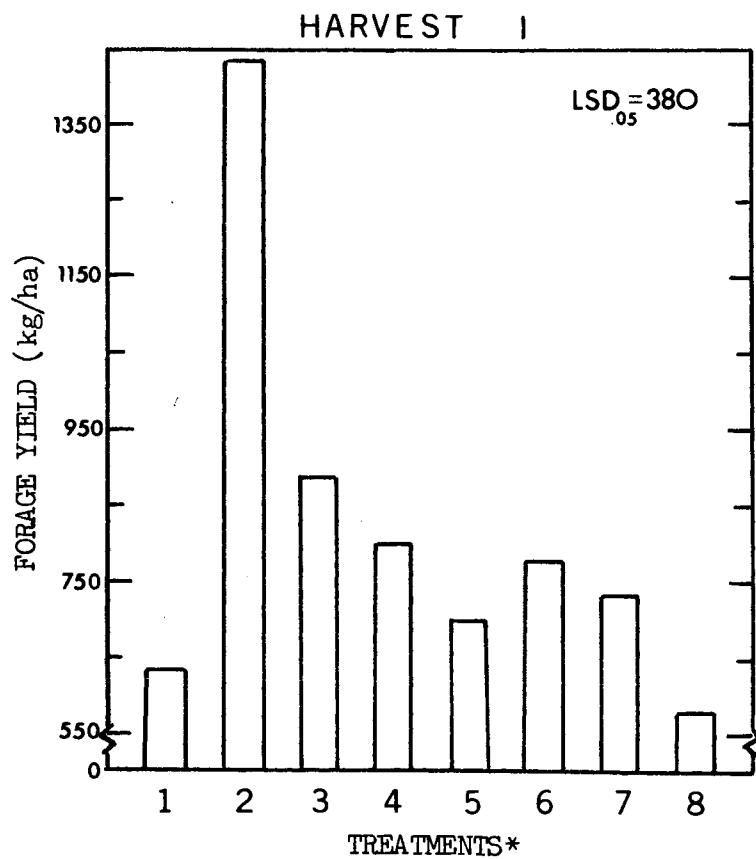
TABLE X
 FORAGE YIELDS FROM TWO HARVESTS OF FORAGE SORGHUM
 TROY HOOVER SITE - BEAVER COUNTY

Treatment	Yields (Kg/Ha)		Total
	Harvest 1	Harvest 2	
Control	449	594	1043
Fluid APP+Fe (11-37-0+FeSO ₄)	682	596	1278
FeSO ₄	522	572	1094
FeKeMin	681	634	1315
Sequestrene 330 (Fe Chelate)	531	655	1186
Fe coated Solid APP (12-51-0, .9 Fe)	909	615	1524
Texas Sulfur Soil	451	912	1363
CSP (0-46-0)	561	626	1188

chlorosis was noted during the growing season at this particular site but P deficiencies were prevalent except for the Fe coated solid APP and the CSP. CSP did not respond as well as the Fe coated solid APP but statistically, no significant difference appears in any harvest. Several problems arose during the tenure of this experiment. One was that of P deficiency symptoms. Also moisture stress was noted at harvest time such that concentrations in the plant of plant nutrients were quite erratic even within treatments. It was planned that after the first harvest sampling, the plot would be clipped uniformly. This was not done at the TH site due to equipment failure. This could help explain the differences between the first and second harvests since the same strips were clipped for the second harvest. Because of the nonsignificance of the yields, evident P deficiencies, erratic nutrient concentrations within treatments from plant analysis, and no visual Fe deficiency symptoms during the growing season, it was felt that the treatments used (especially those containing only Fe) were not fairly evaluated. It was concluded from this experiment that this soil is low in P and also Fe and both are needed for optimum forage sorghum production.

Visual signs of Fe chlorosis early in the growing season were noted at the JH site; however, the plot site was not uniformly chlorotic. Small areas seem to be affected rather than large uniform areas, making evaluation difficult. Some treatment difference was noted but the most consistent significance occurred between the blocks or replications, probably due to the nonuniformity of the chlorosis.

Shown in Figure 8 are the forage yields of forage sorghum by the two harvests. For the first harvest, response was greatest with the



- | | |
|----------------------------------|--|
| *1. Control | 5. Sequestrene 330 Chelate |
| 2. Fluid APP + FeSO ₄ | 6. Tx. Sulfur Soil |
| 3. FeSO ₄ | 7. Fe coated Solid APP (12-51-0; 0.9 Fe) |
| 4. FeKeMin | 8. 0-46-0 (CSP) |

Figure 8. Forage Yields of Forage Sorghum from Jerry Howard Site, Beaver County

fluid APP fortified with ferrous sulfate and was significantly greater at the 0.01 level. This particular treatment could be seen visually where chlorosis was prevalent. All other treatments were very near the same and not significantly different from each other. From this data, FeSO_4 banded with the seed was ineffective.

The second harvest showed no significant differences between the treatments or the blocks. The forage sorghum in this particular portion of the field had seemingly grown out of the Fe chlorosis and all plants showed no visual signs of distress except for moisture. Being dryland sorghum, moisture again became the most limiting factor to normal growth. This ability of plants to "grow out of chlorosis" has been previously reported (26, 28). This suggests there is a threshold value at which plants not severely affected by the Fe chlorosis can recover with time and continue growth as visually normal plants. Other selected areas in this same field near the test plots did not effectively recover from the chlorosis. Growth was severely retarded and death of the plants occurred in small areas.

Analysis of total uptakes of several nutrient elements by the forage sorghum was completed in the laboratory for harvest 1 (Table XI). General trends of increased uptake coincide with increasing yields suggesting the fluid APP+Fe more nearly met the requirements of growth of the forage sorghum early in its growth stage. After clipping, however, no difference of the uptakes of the nutrients could be found. Since the second clipping was hampered by moisture stress, these uptakes will not be shown since moisture stress can adversely affect the uptake and utilization of the essential nutrient elements.

Several improvements can be shown to be needed in further research

TABLE XI
 TOTAL UPTAKES OF SEVERAL NUTRIENT ELEMENTS COMPARED BY TREATMENTS
 FROM JERRY HOWARD SITE FOR HARVEST 1

Treatment	Total Uptakes							
	Kg/Ha				G/Ha			
	N	P	K	Ca	Fe	Zn	Mn	Cu
Fluid APP+FeSO ₄	35	2.7	26.8	2.4	393	115	79	41
FeSO ₄	19	1.5	16.5	1.6	235	61	53	23
FeKeMin	19	1.0	13.1	1.4	219	184	46	21
Tx. Sulfur Soil	18	1.3	14.5	1.6	237	56	47	17
Fe coated solid APP	20	1.6	16.0	1.5	226	58	50	19
Sequestrene 330	15	1.3	13.3	1.4	206	41	46	20
Control	15	1.1	11.8	1.3	188	44	38	16
0-46-0	14	1.1	11.0	1.4	175	64	39	16
ISD _{.05}	13	.9	10.0	.8	145	150	26	14

with Fe chlorosis, and to this end the author would like to make two suggestions on the basis of this research. One would be earlier locations of deficient areas in larger uniform areas so that significant variability between blocks could be lessened. The other would be the location of research in irrigated areas since moisture stress hampered the effects of many of the treatments. Also, care should be taken to supply adequate N and P when screening Fe materials.

An increasing amount of wheat has been affected by Fe chlorosis in West-Central Oklahoma. A three county area including Roger Mills, Beckham and Custer were selected for further evaluation of the inorganic ammonium polyphosphates fortified with Fe. Five sites were selected within this area on different soil types because of their past history of showing Fe chlorosis with sorghum and/or wheat. The five were planted to wheat in the fall of 1973 with the treatments banded with the seed. On each of the five sites an attempt was made to find a rate of Fe that would correct the problem but at the same time combine in a suitable manner with the fluid APP (11-37-0). As discussed earlier, one disadvantage of using the fluid APP is the need of dilution of both the fertilizer and the ferrous sulfate. Another is that the combination of the two must precede planting only by a short time. This adds a greater disadvantage in the field since the carrying of water and other products constitute a great deal of time and effort. Because of this inconvenience, a solid APP, physically mixed with the same rates of Fe combined chemically with the fluid APP, was added to the treatments at two of the five sites. If successful, this could eliminate the need of water and lessen the handling and storage problems found with the fluid. The five sites will be designated by the owners

initials, i.e., HS for Horace Smith, SD for Sam Dobson, HW for Herb Weil, and the two sites with the additional solid APP owned by the same person, Dale Tracy, by DT1 and DT2.

A stand was not obtained at the HW site because of a late planting date and poor seed bed preparation. The results of this particular site will not be discussed in this manuscript and any remaining wheat will be used for observational purposes only. A successful stand was established at the other four sites.

Periodic soil sampling was utilized to monitor the Fe status in the soils. Two of the sites, HS and SD, never showed characteristic deficiency symptoms of Fe but both the DT1 and DT2 did show symptoms quite early in the growing season. The check plots of the HS site were used for a comparison with the two chlorotic sites DT1 and DT2 and the results are graphically outlined in Figure 9. The results show the DTPA extractable Fe, Zn, and Mn from 5 sampling dates from the surface (0-6") depth. It is also divided into two sample preparational procedure measurements as moist (samples directly from the field containing original moisture percentage) and dry (samples dried in a force-draft oven before extraction—usual lab preparation procedure). Several points are of interest from the results. First is the difference between the moist and dry procedure measurements. The two are quite different, especially the measurement of Mn and Fe with a 10 fold and 4 fold increase respectively in the DT average compared to a 8 fold and 4 fold respectively in the HS samples. One might argue that the difference does not matter as long as the calibration of the test for the metals is utilized. The problem in these procedures is the changing of the relationship between the Fe, Zn, and Mn. As suggested by the second

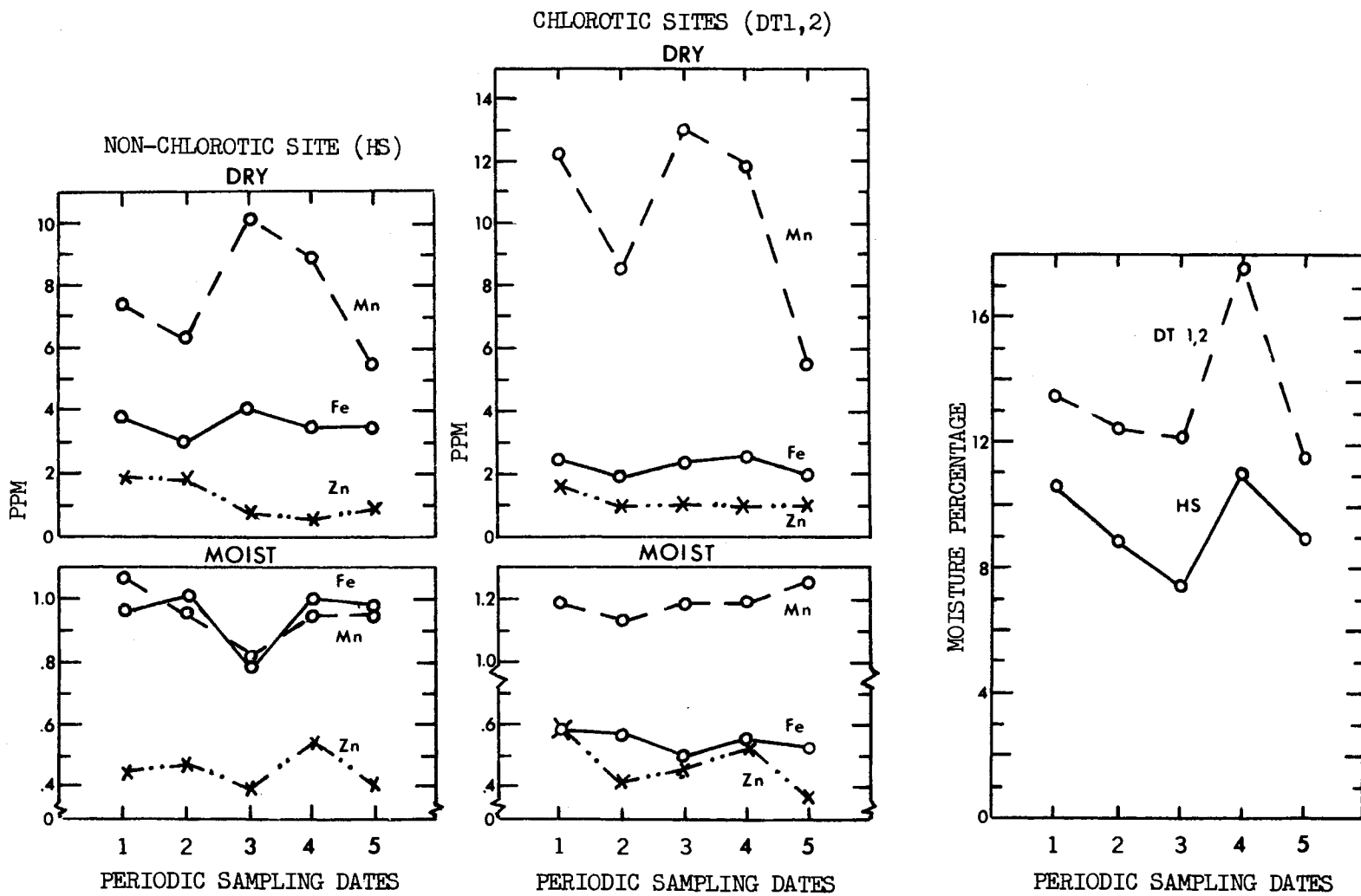


Figure 9. Surface (0-6") DTPA Extractable Fe, Zn, and Mn and Moisture Percentage by Weight

greenhouse experiment, a knowledge of the relationship between the three seems to be quite critical. Therefore, future research in this area of sample preparation procedures seems to be justified.

Another point as suggested by the sample analysis is the possible cause of the chlorosis at the DT1 and DT2 sites. Comparing the HS Fe level with the DT1 and 2 average Fe levels, the extractable Fe at the non-chlorotic site is about twice the amounts found at the chlorotic sites for the moist procedural analysis and approximately 1.4 times the amount in the standard dry procedure. The Fe level, however, might not be the complete problem. As noted in the moist procedure, the Fe is near a 1:1 relationship with Mn at the HS site but at the chlorotic sites, were very near a 1:1 relationship with Zn and the level of Mn at about twice the level of both Fe and Zn at these particular sites. Rogers (26) suggested a low Fe/Mn ratio as being the possible cause of Fe deficiency. This is very possible, however, Zn could also enter in as an antagonistic ion since the Fe level is very near the same level of Zn at the chlorotic sites with both moist and dry preparational procedure analyses.

Also shown graphically in the figure is the moisture percentage calculated by weight over the periodic sampling dates. It was hoped that a relationship between moisture and Fe levels could be found but there is no evidence of any relationship by these graphs. Rogers (26) did find an inverse relationship to exist between DTPA extractable Fe and moisture percentage.

The last observation to be made with these particular field plot experiments was to visually rate the effectiveness of each of the treatments ability to correct the chlorosis. No fertilizer advantage

is shown with any of the rated plots since all received the same amount of N and P except for the check plots which received no additional P.

As stated earlier, both the HS and SD sites did not show characteristic deficiency symptoms of Fe in wheat. The HS site did respond to the P of the 11-37-0 (fluid APP) since growth was visually retarded in all check plots and normal in the fluid APP treatments. No response was shown due to Fe. The SD site was apparently sufficient in all nutrient elements since no response was noted with any treatment or in the check plots.

The two Fe chlorotic wheat sites DT1 and DT2 did respond to both the APP's and Fe rates. A visual rating of the degree of chlorosis from the treatments at the two sites is shown in Table XII. One difference in the two sites was the intensity each had been grazed. The DT1 site was more heavily grazed than the DT2 site. This could explain the visual differences between the overall means of the two sites. Many areas were not uniformly Fe chlorotic but significant visual differences could be determined.

The greatest difference at the DT1 site was that between the check and all other treatments. The solid APP (10-57-0) and the fluid APP (11-37-0) alone were visually different from the check suggesting a response to P in correcting the Fe deficiency. No significant difference existed between the two APP's with increasing amounts of Fe. The fluid APP fortified with Sequestrene 330 Fe Chelate did seem to withstand grazing with a visually lower chlorotic rating average.

The DT2 site showed a better response to the treatments with less grazing intensity. The results (Table XII) also show a definite visual response to P since the check was significantly different from all

TABLE XII
VISUAL RATINGS OF THE Fe CHLOROTIC WHEAT
SITES DT1 AND DT2 BY TREATMENTS

Treatments	Average Visual Rating*	
	DT1	DT2
Check	4.7	4.3
Fluid APP	3.7	3.3
Solid APP	3.7	3.0
Fluid APP+5#Fe	2.5	1.7
Solid APP+5#Fe	3.0	3.0
Fluid APP+10#Fe	3.0	1.3
Solid APP+10#Fe	2.7	2.2
Fluid APP+4#Fe as Chelate	2.0	2.8
Overall Mean	3.1	2.7
LSD _{.05}	.8	.8

*Ratings:

- | | |
|-----------------------|--------------------------------|
| 1. No chlorosis | 4. Moderately severe chlorosis |
| 2. Slight chlorosis | 5. Severe chlorosis |
| 3. Moderate chlorosis | |

other treatments including both the solid and fluid APP alone. Results from the DT2 site agreed with the results of the third greenhouse experiment in that with increasing Fe rates, the fluid APP was more efficient than the physically mixed solid materials. The fluid APP with both five and ten pounds of Fe corrected almost completely the chlorotic condition. A response was shown by the solid APP plus Fe mix but the rates of included Fe did not seem to make available enough Fe for complete correction of the chlorosis. This suggests a possible solution of the Fe chlorosis in wheat that could be effectively and economically feasible. Since response was shown, an increase in the rate of ferrous sulfate in the physical mix with the solid APP could possibly correct the Fe problem. No increase of Fe can be made in the fluid APP because of the application and handling problems that subsist. A bulk blend of ferrous sulfate with the solid APP, on the other hand, could be made significantly higher in analysis and still be economically feasible with no changing of its handling and storage properties. The only disadvantage of the physical mix is the possible segregation of the ferrous sulfate and solid APP particles. However, this disadvantage is minor compared to its possible value in the correction of Fe chlorosis. Therefore, research of this more suitable mixture should be continued for the correction of Fe chlorosis in wheat and sorghum.

CHAPTER V

SUMMARY AND CONCLUSIONS

Three greenhouse studies were conducted using grain sorghum to screen promising Fe materials for the correction of Fe deficiencies by soil applications utilizing developed greenhouse techniques. Nutrient concentrations of the forage, additions of an N-P variable, and increasing Fe rates in promising Fe carriers were utilized to evaluate the effectiveness of all screened materials.

Two field tests for forage sorghum and four field tests for wheat were conducted to test the screened materials under field conditions and also to further evaluate the effectiveness of row applied fluid polyphosphates fortified with ferrous sulfate. Special emphasis was given the fluid APP to determine proper rates of iron and carrier. Two solid sources of Fe phosphate carrier were also compared with the fluid APP (11-37-0). The two sources were solid APP (12-51-0) coated with Fe furnished by TVA and a physical mixing of ferrous sulfate with a powdered APP (10-57-0) furnished by Farmland Industries. Yields, degree of chlorosis, and nutrient concentrations of the plants were measured when such determinations were feasible. Soil chemical properties of experimental sites were characterized including periodic determination of the available Fe status at the four wheat sites.

From the field and greenhouse studies, the following conclusions seem justifiable:

1. The Cordell loam soil used in all greenhouse pot culture experiments was Fe deficient for no other element increased forage yields without the addition of Fe.
2. P seems to have a complimentary effect on Fe and does not show antagonism when added alone to an Fe deficient soil even at high rates.
3. Both the TVA solid Fe coated APP and the fluid APP fortified with ferrous sulfate seemed equally effective on the Fe deficient Cordell loam soil in pot cultures. Banding FeSO_4 alone shows promise if N and P were sufficient for maximum growth.
4. The three metals Fe, Zn, and Mn show strong evidence of being interrelated. Additions of available Fe increased the uptake of both Zn and Mn; Zn significantly decreased Fe and Mn uptake and Mn additions slightly decreased both Zn and Fe uptake.
5. Sample preparation procedures as "moist" or "dry" show a drastic difference in the amounts of Fe and Mn measured in a given soil sample. The real difference lies in the relationships of the three metallic elements between the two procedures. Both Fe and Mn seem to be inversely related to moisture content of the two sampling preparation procedures but no direct relationship of the field moisture content and Fe or Mn levels could be established. Research is needed to clarify the "true" relationship existing between the three metallic elements in both Fe deficient and non-deficient soils.
6. Fluid APP fortified with 10# Fe as ferrous sulfate was

effective in correcting Fe chlorosis in lightly grazed winter wheat and forage sorghum. Under heavy grazing, the amount of Fe was not enough to completely overcome the chlorosis. The fluid APP does seem to have critical disadvantages such as limited Fe additions, poor storage and handling qualities, and time consuming characteristics that presently discourage its extensive use.

7. Solid APP (10-57-0) physically mixed with rates of Fe equaling that of the Fe added to the fluid APP, even though banded with the seed, was not enough to correct the chlorosis on lightly grazed winter wheat. Judging by the response to ferrous sulfate alone on forage sorghum yields and the significant visual response to the solid APP physical mix on wheat suggests a possibility of increasing the analysis of Fe in the physical mix to levels that could be sufficient to correct Fe chlorosis in both wheat and forage sorghum.

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APPENDIX

TABLE XIII
 GREENHOUSE EXPERIMENTS: EXPERIMENT 1
 ANALYSES OF VARIANCE OF YIELDS AND
 TOTAL UPTAKE OF Fe, Zn, AND Mn

With N-P Variable					
Source	df	Yield	Mean Squares Fe	Zn	Mn
Chem (Treatment)	5	2744918**	.0212**	.0053	.0090**
Level (^W /N-P, ^W /o N-P)	1	3033403**	.1172**	.0394**	.0150**
Chem x Level	5	1212936**	.0128*	.0032	.0068**
Pot (Chem Level) = Error	24	47717	.0046	.0023	.0005
Corrected Total	35	684796	.0114	.0039	.0030
Other Treatments					
TRT	2	513744	.0085	.1227	.0003
Pot (TRT) = Error	6	342367	.0024	.1114	.0012
Corrected Total	8	385211	.0039	.1142	.0009

*Significant at the .05 level

** Significant at the .01 level

TABLE XIV
 GREENHOUSE EXPERIMENTS: EXPERIMENT 2
 ANALYSES OF VARIANCE OF YIELD AND
 TOTAL UPTAKE OF Fe, Zn, AND Mn

Source	df	Yield	Mean Squares		
			Fe	Zn	Mn
Fe	1	3062813**	.0291*	.0533*	.0384**
Zn	1	90313**	.0014*	.0004	.0022**
Fe x Zn	1	313	.0002	.0074	.0000
Mn	1	25313	.0001	.0071	.0003
Fe x Mn	1	2813	.0000	.0397*	.0005
Zn x Mn	1	70313	.0003	.0004	.0000
Fe x Zn x Mn	1	37813*	.0000	.0118	.0000
Pot (Fe Zn Mn) = Error	24	10938	.0002	.0078	.0002

*Significant at the .05 level

**Significant at the .01 level

TABLE XV
 GREENHOUSE EXPERIMENTS: EXPERIMENT 3
 ANALYSES OF VARIANCE OF YIELD AND
 TOTAL UPTAKES OF Fe, Zn, AND Mn

Source	df	Yield	Mean Squares		
			Fe	Zn	Mn
Phos Source	1	16653**	.0013*	.0001	.0012**
Fe Rate	3	16453**	.0010*	.0004	.0002**
Phos x Fe	3	3528	.0004	.0017**	.0002**
Pot (Phos Fe) = Error	24	1291	.0002	.0003	.0000
Corrected Total	31	3470	.0004	.0005	.0001

*Significant at the .05 level

**Significant at the .01 level

TABLE XVI
 FIELD EXPERIMENTS: EXPERIMENT 4
 ANALYSES OF VARIANCE OF YIELDS
 FOR BEAVER COUNTY SITES

Source	df	Mean Squares		Total
		Harvest 1	Harvest 2	
TH Site				
Rep	3	128940	144088*	325390
Trt	7	95033	47184	76538
Error	21	60945	35985	116334
Corrected Total	31	75222	48976	127579
JH Site				
Rep	3	182238*	352505**	1042449**
Trt	7	226365**	28060	314361
Error	21	53348	69125	206924
Corrected Total	31	104889	87276	312041

*Significant at the .05 level

**Significant at the .01 level

TABLE XVII

FIELD EXPERIMENTS: EXPERIMENT 4 ANALYSES OF VARIANCE OF
TOTAL UPTAKES OF SEVERAL NUTRIENTS

Source	df	Mean Squares							
		N	P	K	Ca	Fe	Zn	Mn	Cu
JH Site									
Rep	3	266.9*	1.27*	80.1	0.41	14.5	24.8	.44	.30*
Trt	7	184.2	1.13*	98.8	0.54	18.3	9.5	.76*	.27*
Error	21	76.5	.41	44.3	0.29	9.8	10.3	.30	.09
Corrected Total	31	119.2	.65	60.1	0.36	12.2	11.5	.42	.15

*Significant at .05 level

TABLE XVIII
 FIELD EXPERIMENT: EXPERIMENT 5
 ANALYSES OF VARIANCE OF
 VISUAL RATINGS AT TWO
 CHLOROTIC SITES

Source	df	Mean Squares	
		DT1 Site	DT2 Site
Total	23		
Rep	2	0.20	0.08
Trt	7	2.08**	2.78**
Error	14	.20	.21

**Significant at .01 level

2

VITA

Richard Bruce Heizer

Candidate for the Degree of

Master of Science

Thesis: THE CORRECTION OF IRON CHLOROSIS IN SORGHUM AND WHEAT

Major Field: Agronomy

Biographical:

Personal Data: Born in Fort Worth, Texas, October 14, 1949, the son of Mr. and Mrs. L. W. Heizer.

Education: Graduated from Polytechnic High School, Fort Worth, Texas, in May, 1968; completed the requirements for a Bachelor of Science degree in General Agriculture, Plant and Soil Science option, from Tarleton State University, Stephenville, Texas, in December, 1971; completed requirements for the Master of Science degree at Oklahoma State University in May, 1974, with a major in Agronomy.

Professional Experience: Student Trainee, USDA Soil Conservation Service, 1970-1972; Soil Conservationist, USDA Soil Conservation Service, 1972 through present; National Science Foundation Fellowship recipient as graduate student, Department of Agronomy, Oklahoma State University, 1972-1973; Graduate Teaching Assistant, Department of Agronomy, Oklahoma State University, 1973-1974.

Membership in Professional Organizations: Member of the Range Management Society of America, Society of Agronomy, and Soil Science Society of America.