THE EFFECT OF IRON DEFICIENCY ON THE ROOT DEVELOPMENT OF SORGHUM

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CHAPTER I

ABSTRACT

Iron (Fe) chlorosis is a mineral deficiency disorder that is mostly associated with crops grown in arid, calcareous soils. Grain and forage sorghum types have susceptible varieties to this deficiency. The high buffer capacity, solubility, and basicity of $CaCO_3$ influence the incidence of Fe chlorosis in this and other crop plants in the Southern Great Plains and Mid-Western U.S., where 90% of sorghum production is grown in calcareous soils. In addition such soil chemical properties as HCO_3^-, Mg, N, P, Fe, Zn, Cu, Mn and O.M. (organic matter) contents, pH, soil-water content, and compaction have been implicated as either reducing or enhancing the absorption, translocation, and/or metabolism of Fe in plants.

In this study a two-year field study was conducted in 1989 and 1990 in western Oklahoma to determine: (i) effect of Fe deficiency in the number of roots, root length, and root area of grain sorghum and sudangrass, (ii) soil chemical properties that cause the deficiency and (iii) how such deficiencies affect above ground dry matter yield, nutrient content, and leaf chlorophyll content. The roots were sampled in a 100 cm soil profile in both sites in 1989 and 1 site in 1990 and in a 60 cm soil profile in 3 other sites in 1990. Replicated samples were collected in Fe deficient (-Fe) and Fe sufficient (+Fe) soil forms.

A trench-profile method was used to assess the number of roots; while a core method, hydropneumatic elutrition, and digital image analysis were used to determine the root length and area. Additional soil samples were collected in the same replications for the analyses of soil chemical properties.

Root parameters were generally significantly greater for grain sorghum and sudangrass which were grown in the +Fe soils than in the -Fe soils ($P < 0.05$). Above ground dry matter yield, leaf chlorophyll content and tissue Ca, Mg, Fe, Mn, Zn, and Cu uptake were similarly significantly higher for both crops grown in +Fe soils compared to -Fe soils. The concentration of the 6 elements in the shoot tissue were, however, significantly higher in the -Fe than the +Fe soil types. The latter observation was partly attributed to ion balance, dilution effect, and probable tissue contamination by the soil aluminosilicates. The soil pH level, NO_3-N, P, Ca, Mg, and $CaCO_3$-equivalent contents were consistently higher in the -Fe than the +Fe soil types while soil HCO_3, DTPA-extractable Fe, Mn, Zn, Cu, and OM contents were consistently higher in the +Fe than in the -Fe soil types. Iron deficiency had similar detrimental effects on the roots and shoots of grain sorghum and sudangrass in these soils.

CHAPTER II

LITERATURE REVIEW

Iron-deficiency (Fe) chlorosis is a mineral deficiency disorder that may be associated with crops grown on acid or alkaline soils but is especially prevalent in arid calcareous soils (Loeppert, 1986). According to Chen and Barak (1982) and Dudal (1977) calcareous soils cover over 30% of the earth's land surface and within these areas are found most of the Fe deficiency in plants. Iron-deficiency chlorosis may occur either uniformly across major tracts of land or as a localized chlorosis of variable extent and at soil depths of 15 cm to over 100 cm below the soil surface (Cihacek, 1988; Loeppert et al., 1984; Loeppert, 1986).

Sorghum (Sorghum bicolor (L.) Moench) is an important grain and forage crop in the Southern Great Plains and Mid-Western U. S. due to its drought tolerance. However, its growth and production is limited in this region because 90% of it is grown in calcareous soils and so commonly associated with Fe stress (Clark, 1982; McCaslin et al., 1987). Calcium carbonate ($CaCO_3$) has a dominating influence on any system in which it is present due to its properties of high solubility, high buffer capacity, and basicity (Loeppert, 1986). At the pH of an oxidizing calcareous soil, 7.4 to 8.5, the equilibrium activity of total dissolved Fe (III) is approximately 10^{-10} M, which is considerably less than the 10^{-8} which is required for optimum growth of plants in nutrient culture (Lindsay, 1979; Lindsay and Schwab, 1982). However, not all soils high in $CaCO_3$ guarantee the incidence of Fe-deficiency chlorosis in all crop species or in some varieties within a species nor correlate well with Fe chlorosis within a given calcareous soil field (Burau, 1963; Loeppert et al., 1984). Consequently other soil factors such as HCO_3^-, Mg, N, P, Fe, Zn, Cu, Mn, and OM contents, as well as the soil pH, soil-water content, and compaction have been implicated as either reducing or enhancing the absorption, translocation, and/or metabolism of Fe in plants (Chaney, 1984; Chen and Barak, 1982; Loeppert and Hallmark, 1985; Morris et al., 1990; Yen et al., 1988). In addition genetic differences among plant species and within the same species have also been reported to influence the susceptibility of plants to Fe deficient environments (Mortvedt and Kelsoe, 1988; Yen, 1987; Yen et al., 1988). High concentration of HCO_3^- due to increased partial pressure of CO_2 (pCO_2), especially in soils with a high water content and compaction, was reported to cause reduction in total chlorophyll contents (chl_T) and total above ground yield in soybean (<u>Glycine</u> <u>max</u> (L.) Merr.) (Inskeep and Bloom, 1987; Morris et al., 1990) but not in sorghum (Loeppert and Hallmark, 1985; Yen et al., 1988). Fleming et al. (1984) attributed the inhibition influence of HCO_3^- to the differences in the stress response mechanisms of the two crops. Soybean releases H^+ and 'reductants' from their root tips into the rhizosphere with the resultant pH reduction and increased Fe availability. Sorghum secretes natural chelates called phytosiderophores which complex and translocate

Fe to the root surface for absorption with no appreciable pH reduction in the rhizosphere (Marschner et al., 1986).

Lindsay and Norvel (1978) and Loeppert et al. (1988) found that diethylenetriaminepentaacetic acid (DTPA)-extractable Fe, an acceptable soil test for Fe, Mn, Zn, and Cu contents, was negatively correlated with visual chlorosis ratings and total stover yield of sorghum (r = -0.60); and that 4.5 mg Fe $\cdot kg^{-1}$ soil was optimum for correction of Fe chlorosis in sorghum. Cihacek (1988) showed that DTPA-extractable Fe was correlated more with grain than total above ground yield. He also reported that only 3.2 mg Fe kg^{-1} soil sufficed to ameliorate the deficiency in grain sorghum.

The presence of OM has been reported to minimize the incidence of Fe chlorosis in sorghum and soybean in calcareous soils. Loeppert and Hallmark (1985) and Morris et al. (1990) observed that this was due to the ability of OM to adsorb and stabilize the amorphous Fe-oxide phase and make Fe be more available for the plants. Total and Walkley Black C fractions were more significantly correlated with the deficiency amendment than the more resistant humic fraction of the OM.

Inskeep and Bloom (1987) reported increased concentrations in the plant tissue of K, Ca, Mg, Cu, Zn, Mn, and Fe with Fe stress in soybean. They attributed these results to ion balance, concentration of the elements in the stunted plants (dilution effects) and, probably, contamination of the chlorotic tissue by the soil aluminosilicates.

Previous researchers noted a positive correlation of incidence of Fe chlorosis in sorghum (Loeppert et al., 1984) and soybean (Inskeep and Bloom, 1984; 1986) with soil solution Mg content and/or Mg content of the CO_3 phase. Loeppert and Hallmark (1985) observed a positive relationship between H_2O-extractable Mg/(Ca + Mg) mole ratios and Fe chlorosis in sorghum. Presence of Mg may influence the solubility and/or kinetics of dissolution of the CO_3 phase, itself a consequence of induced alkalinity. Furthermore, in high Mg soils the Mg content is considerably higher than the Fe content and so could compete with Fe for the binding sites on the phytosiderophores and absorptive root surfaces.

Reduced chlorophyll of the leaves, leaf area, plant height, grain and forage yield, rooting volume of sorghum and/or soybean have been observed to occur under Fe deficiency, in which incidence of total necrosis have not been uncommon (Cihacek, 1988; Clark et al., 1988; Datin and Westerman, 1982; Fehr, 1983; Gildersleeve and Ocumpaugh, 1989; Inskeep and Bloom, 1987; Kinkaid, 1986; Meppe, 1988; Mortvedt and Kelsoe, 1988; Williams et al., 1986; Yen et al., 1988; Morris et al., 1990). Morris et al. (1990) further noticed that roots of soybean grown on Fe chlorotic soils were non-nodulated. In earlier study Kannan (1983) and Bates (1982) had made observation that Fe deficiency was more severe in susceptible plants as Fe participates in the N-fixation, oxidative phosphorylation, and electron transport in most of the plants metabolic processes. Inskeep and Bloom (1987) noticed low chl_T and yield reduction between 35 to 40% in soybeans grown in Fe deficient soils with chlorosis ratings between 2.5 and 5.

Mortvedt (1986) reported that probably the best method to control Fe chlorosis will be a combination of Fe-efficient cultivars with the best management practices and effective Fe fertilizers. His findings concurred with those by Datin and Westerman (1982), Mortvedt and Kelsoe (1988), Yen (1987) and Yen et al. (1988). They reported that band or spot application of ammonium polyphosphate (APP) with or without Fe fertilizer in calcareous soils ameliorated incidence of Fe chlorosis with increased absorption of Fe in the sorghum. This in turn increased chlorophyll contents and dry matter production. However, rate of P uptake was negatively correlated with Fe uptake (Yen et al., 1988) and plant tissues with high P accumulated Fe in the inactive Ferretin or $FePO_4$ forms (Brown and Jones, 1975).

In another study Taylor and Goubran (1976) showed that P deficiency led to an increase in root length of apple (Malus sp) tree and that the plant adapted to the stress by developing an exploratory type of root system. Schenk and Barber (1979) showed that low P soil resulted in smaller root radius for corn seedlings than did the same soil with higher P. The thinner roots at low P resulted in more root surface area (RSA) g^{-1} of roots with an increased absorptive surface for P, other mineral nutrients and soil moisture. Phosphorus and K move in the soil primarily by diffusion (Hallmark and Barber, 1983) just as Fe moves (Tisdale et al., 1985), hence the greater the RSA the higher the opportunity for these nutrients to reach the root. Tisdale et al. (1985), furthermore, demonstrated that the solubility product of Fe, 10^{-39}, at normal soil pH, 6.6, and aeration shows that very little Fe is available for transport to the root surface by mass flow.

It is evident from the above observations that the availability of Fe and its effects on above ground plant development depends on the rhizosphere chemistry (i.e., interaction of labile soil Fe [capacity factor], solution Fe [intensity factor], and surface area of the roots). To our knowledge most of the research has been quantitatively reported for the Fe chlorosis on grain yield, total dry matter production, chlorophyll content of the leaves and other above-ground vegetative and reproduction growth traits. However, the morphological aspects of the roots as affected by the Fe deficiency has been lacking in scope, partly due to unavailability of simple inexpensive equipment to undertake rhizographical study, high labor input and often not very accurate data (Bohn, 1979).

The objectives of this study were to determine (i) the relative number of roots per soil area, length of roots per soil volume (length density, cm cm^{-3}), and area of roots per soil volume (area density, cm^2 cm^{-3}) of grain sorghum and sudangrass (Sorghum sudanense L.) as affected by Fe deficiency under field conditions, (ii) which soil chemical properties affect root growth under the two soil Fe conditions, and (iii) to relate the root growth parameters and such above ground growth traits as total leaf chlorophyll content, dry matter yield, and Ca, Mg, Fe, Mn, Zn, and Cu contents in the two soil conditions.

CHAPTER III

MATERIALS AND METHODS

A two-year field survey was conducted in August 1989 and 1990 in western Oklahoma to determine the influence of Fe deficiency on the root development of grain sorghum and sudangrass. This survey was preceded with the site selection in mid-May in the two years, two weeks after planting. The study was conducted at two sites in 1989 and four sites in 1990 known to exhibit Fe-deficiency chlorosis in sorghum (Hawkins, personal communication) (Table I). Iron chlorosis, initially observed in a two-week old plant, is an intervenial chlorosis in the newly grown leaves with older leaves remaining green as a result of immobility of Fe within the plant (Williams et al., 1986). The chlorosis symptom starts near the mid-rib and spreads to the margin of the leaf. This differentiates it from Zn deficiency symptom where the chlorosis starts from the margin to the mid-rib; N deficiency where the chlorosis first shows in the older tissue with younger leaves being green as N is mobile in the plant; and S deficiency, partially immobile, where the deficiency is in the whole plant tissue. The visual scores in plant tissue was used to partition six pairs, two pairs in 1989 and four pairs in 1990, of soil types into deficient in available Fe (-Fe) and sufficient in available Fe (+Fe). These visual scores were confirmed at anthesis during root sampling. Further soil classifications were given by Cole et al. (1961), Menders et al. (1961), and Nance et al. (1960) (Table I). At every site in both years the two soil types were about 100 m apart. Plant root, shoot and soil data were collected in each pair of soil types in a randomized complete block design (RCBD) with four replications.

Replications were confounded in the soil types and so would have been more appropriately referred to as sampling units. However, replication is used in this study to simplify the analysis of variance (ANOVA) (Table II).

Sampling Methods

At each replication, two destructive root sampling methods as described by Bohn (1979) and Vepraskas and Hoyt (1988) were used to take root samples in a 2-day period. On the first day five soil cores spaced 20 cm apart, the third one adjacent to and 15 cm from the study plants in each replication, were taken across the rows with the study plants to a depth of 100 cm in 1989 and 100 or 60 cm in 1990 (Table I) using a truck-mounted Giddings hydraulic soil coring machine (Giddings Manufacturing Co., Fort Collins, CO) and 5 cm dia. acetate liners (Fig. 1). The 60 cm soil depth sampling was decided upon after the 1989 root data analysis showed that 60 cm was sufficient to supply as much information as the 100 cm depth. Furthermore, this reduced the time spent per site, thus allowing for more sites being sampled. The cores were kept cool, so as to maintain sampled roots in their natural state before analyses, using ice bags and cold storage until ready for root extraction. The acetate liners were then divided into five 20-cm and ten or six 10-cm sections in 1989 and 1990, respectively. From each section roots were separated from the soil using a hydropneumatic

TABLE I

THE CROPS, SAMPLING DEPTH AND SOIL TYPES USED IN WESTERN OKLAHOMA FOR THE STUDY OF FE DEFICIENCY ON ROOT DEVELOPMENT.

Site number	Site name	Crop grown	Sampling depth	Soil type
			- cm -	
1989				
1	Texas County	Grain sorghum	100	1) Richfield clay loam (+Fe), Fine montmorillonitic, mesic Aridic Argiustoll 2) Ulysses clay loam (-Fe), Fine, silty, mixed, Aridic Haplustoll
2	Harper County	Sudangrass	100	1) Pratt sandy loam (+Fe), Sandy, mixed, thermic Psammentic Haplustalf 2) Mansker sandy loam (-Fe), Fine loamy carbonatic, thermic Calciorthidic Paleustoll
1990				
1	Texas County	Sudangrass	100	1) Richfield clay loam (+Fe) 2) Ulysses clay loam (-Fe)
2	Texas County	Sudangrass	60	1) Potter sandy loam (+Fe) Loamy, carbonatic, thermic, shallow Calciorthid 2) Mansker sandy loam (-Fe)
3	Harper County	Grain sorghum	60	1) Carey loam (+Fe), Fine, silty, mixed thermic Typic Argiustoll 2) Woodward loam (-Fe) Coarse, silty, mixed, thermic Typic Ustochrept
4	Ellis County	Grain Sorghum	60	1) Potter sandy loam (+Fe) 2) Mansker sandy loam (-Fe)

TABLE II

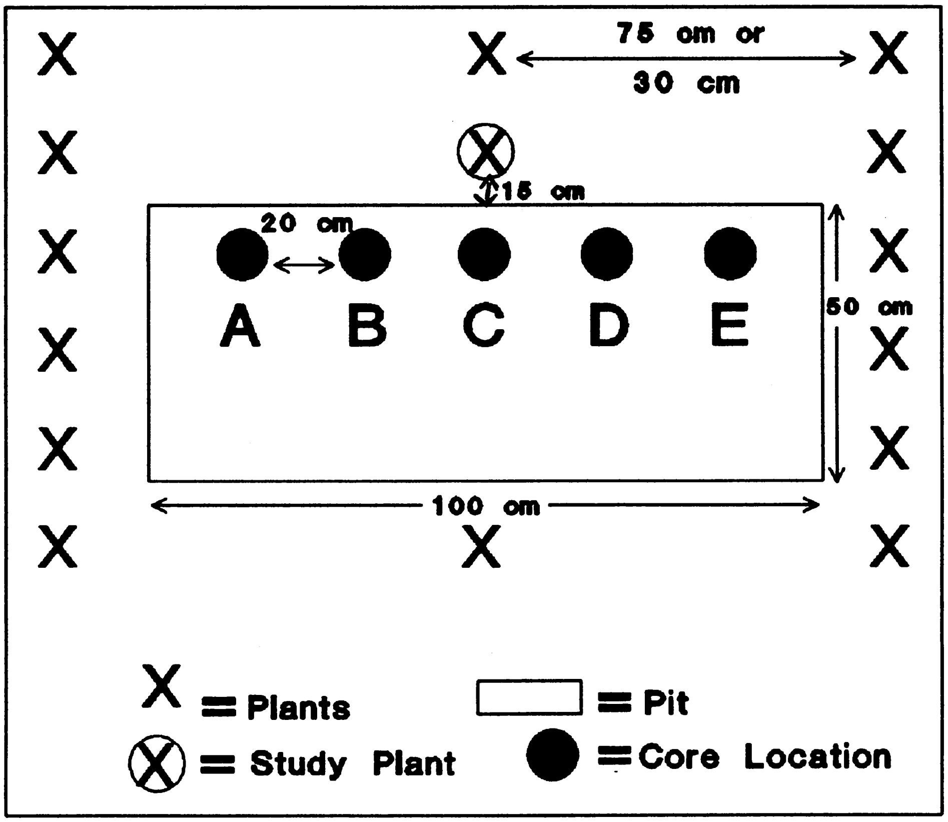
OUTLINE OF THE ANOVA FOR ROOT DATA ANALYSIS SITE^{-1} YEAR^{-1}.

Source of variation	DF
Treatment	(t-1) = 1
Replication (treatment)	(6-1) (t) = 6
Position	(P-1) = 4
Treatment x Position	(t-1) (p-1) = 4
Position x replication (treatment)	(P-1) (b-1) (t) = 24
Depth	(d-1) = 4
Treatment x depth	(t-1) (d-1) = 4
Treatment x depth x position	(t-1) (d-1) (p-1) = 32
Error	(tbpd-1)- rest = 120
Total	tbpad-1 = 199

Note: Treatment = +Fe and -Fe soil types
Replications = Number of sampling units within treatments
Positions = Distances of cores or grid squares from stalk of the study plants
Depth = Depth intervals sampled in the soil profile

elutrition device similar to that described by Smucker et al. (1982). The roots were collected in a sieve of 0.42 mm pore size, and any above ground plant debris especially in the two upper depth intervals were removed using a pair of forceps. The extracted roots were stained by placing them in a petri-dish which contained 10 mL of de-ionized distilled water 2 mL of alconox fungicide, and 1 mL of thymol violet 2B solution. The thymol solution was prepared by dissolving 1 g of thymol 2B granules in 100 mL ethyl alcohol. The root samples were kept stained for 24 h in a refrigerator at 40°F to ensure complete and uniform staining. The root samples were then spread in a 15 cm X 15 cm petri-dish to minimize root overlap during scanning to measure the relative total root length and area. Such apparent overlaps would have underestimated the length and area of roots as the scanner would treat smaller toot fibers as one. These two parameters were measured using a digital image analysis system Macro-processor (BioScan OPTIMAS Inc., Edmonds, WA) similar to a system described by Harris and Campbell (1989). This system, with the computer control, scans all root fibers and gives total area and length.

Twenty four hours after taking the soil cores, pits measuring 100 cm long x 50 cm wide x 100 cm deep were dug in the same replications as those used for the core method using a backhoe in both sites in 1989 and site 1 in 1990 to determine the relative number of roots of grain sorghum and sudangrass. One pit wall was smoothed to within 15 cm of the study plants (Fig. 1). A 100 cm x 100 cm grid divided into 100-10 cm^2 squares was placed on the smoothed surface. After removing about 2.5 cm of soil from each square with an awl, all visible live roots



Interrrow spacing = 75 cm for grain sorghum.
30 cm for sudangrass

Figure 1. Sampling scheme used for both the trench profile and core methods.

were counted and recorded. Live roots were identified as whitish to separate them from the dark brown to black OM.

On the days the soil cores were taken, five extra cores were taken to the same depth in each replication. These cores were sectioned into 20-cm and 10-cm segments in 1989 and 1990, respectively. Depth-equivalent core segments were then composited, air-dried and ground to pass through a 2-mm pore size. Samples drawn from these prepared soils were used to determine soil pH, NO_3-N, P, K, Ca, Mg, Fe, Zn, Cu, Mn, HCO_3, total alkaline earth CO_3, and OM, following the methods described by McElreath and Johnson (1990). Soil pH was determined in a deionized water at a soil weight to solution ratio of 15 g to 15 mL. Samples were stirred with a teflon rod, mixing soil and water completely, and allowed to stand for 30 min, prior to determining pH with a Fisher 825 MP pH meter.

Nitrate-N was determined by mixing 10 g of soil with 25 mL $CaSO_4$ extracting solution. The mixture was shaken for 30 min on a rotary shaker and filtered. The filtrate was transferred to a Lachat Injection Flow System for NO_3-N analysis. Available soil P, K, Ca, and Mg were determined by mixing 2 g of soil and 20 mL of Mehlich III extracting solution and shaking for 5 min. The mixture was then filtered and the filtrate analyzed for K, Ca, and Mg with the Perkin-Elmer 2380 Atomic Absorption (AA) spectrophotometer, with Ca and Mg samples having 2% lanthanum chloride added prior to AA analysis. Available soil P in the extracts was analyzed using the Lachat.

The DTPA-extractable soil Fe, Zn, Cu, and Mn were determined by mixing 10 g of soil with 10 mL of DTPA-extracting solution and shaking the mixture at a high speed for 2 h. The mixture was filtered through number 42 Whatman paper and the four micronutrients analyzed using the AA.

Soil HCO_3 content was determined by mixing 20 g of soil with 20 mL of deionized water, agitating the mixture and allowing to settle for 4 h. The mixture was then filtered using a number 2 Whatman filter paper. A 5 mL aliquot of the filtrate was titrated with 0.025 N H_2SO_4 using methyl orange as the indicator.

Total alkaline earth CO_3 ($CaCO_3$ or $CaMg(CO_3)_2$) was determined by the titration method. To 10, 5 or 2 g, for slightly moderately or strongly calcareous soils, respectively, based on the effeverscent test with an acid, was added 100 mL deionized water and 25 mL of standardized 0.5024 N H_2SO_4 and warmed in a bath for 3 min. The mixture was filtered through a number 2 Whatman paper and titrated with standardized 0.2241 N NaOH using phenolphthalein as indicator. Total alkaline earth CO_3 was calculated using the following equation:

$$\frac{(\text{N acid X mL acid}) - (\text{N base X mL base}) \times 5}{\text{Weight of soil}} = \%\ CaCO_3 \text{ equivalent}$$

The potassium dicromate ($K_2Cr_2O_7$) oxidation procedure was used to determine Walkley-Black OM. A 0.5 g air-dried soil was mixed with 10 mL of 1N $K_2Cr_2O_7$ and 15 mL concentrated H_2SO_4 and slowly heated to 160°C. After cooling 100 mL of deionized water was added to the mixture and excess $K_2Cr_2O_7$ titrated using 0-2 N ferrous ammonium sulfate solution, before calculating % C and % OM.

Plant Shoot Measurements

Chlorophyll Analysis

During the root sampling procedures five 0.24 cm^2 leaf discs were taken from the top three fully developed leaves from the study plants for chlorophyll (chl.) content determination. The discs were put in transparent tubes with 3.5 mL of N, N-dimethylformamide. The tubes were then placed on horizontal trays and refrigerated for 48 h for complete extraction of the chlorophyll from the leaf discs. The samples were brought to room temp. (15^{o}C) and absorbance readings were taken at 664.5 and 647 nm wavelengths with a Bausch and Lomb Model Spectronic 710 spectrophotometer. Chlorophyll a, b, and total (chl_T) contents were calculated using equations described by Inskeep and Bloom (1985):

Chl. a ($\mu g\ cm^{-2}$) = 12.7 * abs 664.5 - 2.79 * abs 647.

Chl. b ($\mu g\ cm^{-2}$) = 19.9 * abs 647 - 4.62 * abs 664.5.

Chl_T ($\mu g\ cm^{-2}$) = Chl. a + b.

Nutrient Composition, Uptake and Yield of the Shoot

In each replication above ground plant samples were collected from a 1 m row length and dried for 24 h in an oven. After taking the dry weights from the samples they were finely ground to pass through 0.2 mm and analyzed for Fe, Zn, Mn, Cu, Mg, and Ca concentrations. About 0.25 g of the finely ground plant samples were digested using the Digesdahl Digestion Apparatus and colorimetric analysis procedures (Hach Co., Ames, IA). The six cations were analyzed using the AA. After determining the nutrient concentration in the above ground plant parts, the nutrient uptake was calculated for each Fe soil condition by multiplying dry matter yield and concentration.

Statistical Analysis

The relative mean number of roots per cm^2 of soil, root length and root area per cm^3 of soil were compared between the -Fe and +Fe soil types for each year and site separately using the statistical analysis of variance procedure SAS Inst. (1979) (Table II). For each root parameter within each soil type variation with depth, sampling distance from the study plant were calculated using the least significant difference (LSD) procedure as described by Steel and Torrie (1980). A simple linear regression was also performed to determine whether depth or distance were in anyway associated with the observed root growth differences between the two Fe conditions.

Similar ANOVA procedure was used to determine the above ground dry matter yield (1990 only), chosen nutrient concentrations, nutrient uptake, and chlorophyll concentration.

Pooled statistical analyses were not performed due to differences in soil types and crop species between the sites and years.

CHAPTER IV

RESULTS AND DISCUSSION

Soil Chemical Properties

Chemical properties of the soils examined in this study are shown in Table III. All +Fe and -Fe soil types had soil solution pH ranges between 7.6 and 8.3, Ca content ranges between 70 and 260 g kg^{-1}, and HCO_3 content ranges between 119 and 247 mg kg^{-1} in the surface 20 cm soil depth. The soil pH and Ca contents were consistently higher in the -Fe than the +Fe soil types while the HCO_3^- content was the reverse. There was also a consistently, and significantly higher DTPA-extractable Fe in the +Fe soil types than the -Fe soil types in all sites. Total alkaline earth carbonates determined as % $CaCO_3$ equivalent were significantly higher for the -Fe than the +Fe soil types.

Similar observations have been made by other research scientists. For example, Loeppert and Hallmark (1985) observed that the Fe stress response in sorghum is not affected by high HCO_3^- content of the rhizosphere. Yen et al. (1988) provided evidence that high HCO_3 contents were not correlated with Fe chlorosis in sorghum. Inskeep and Bloom (1987) and Morris et al. (1990), however, made observations that high HCO_3 content was positively correlated with the incidence of Fe chlorosis in soybean. Fleming et al. (1984) explained that this

TABLE III

SELECTED SOIL ANALYSES OF THE SOILS STUDIED FOR FE DEFICIENCY ON THE ROOT DEVELOPMENT OF SORGHUM.*

Year	Site	Soil type	pH	NO_3-N	P	Ca	Mg	$CaCO_3$ equivalent	Fe	Mn	Zn	Cu	HCO_3	OM
				g kg^{-1} Soil					mg kg^{-1} Soil					% C
1989	1	Richfield (+Fe)	8.3	19	30	159	153	49.3	10.8	4.5	0.9	0.6	247	0.5
		Ulysses (-Fe)	8.6	27	39	255	203	188.9	7.8	4.0	0.9	0.4	202	0.4
	2	Pratt (+Fe)	8.0	12	4	69	244	9.2	5.6	6.2	0.3	0.1	173	0.4
		Mansker (-Fe)	8.4	16	15	260	459	34.0	1.9	1.4	0.2	0.1	138	0.1
1990	1	Richfield (+Fe)	8.0	9	29	70	399	15.1	14.9	9.3	0.7	0.4	296	0.8
		Ulysses (-Fe)	8.1	34	57	79	999	125.0	7.7	5.5	0.6	0.2	258	0.7
	2	Potter (+Fe)	7.6	10	3	39	490	9.6	10.5	5.3	0.4	0.3	176	0.5
		Mansker (-Fe)	7.8	14	27	49	820	31.2	9.5	2.3	0.2	0.2	147	0.2
	3	Carey (+Fe)	7.8	4	45	47	212	14.8	5.2	8.5	0.3	0.3	185	0.3
		Woodward (-Fe)	8.2	3	74	62	999	32.5	3.6	1.5	0.2	0.1	158	0.2
	4	Potter (+Fe)	7.6	22	21	58	291	10.3	10.1	5.9	0.2	0.1	194	0.6
		Mansker (-Fe)	7.9	76	21	88	580	29.5	7.8	2.9	0.3	0.1	117	0.1

*Soils sampled at 20 cm (8") depth at time of root data collection.

occurrence is due to HCO_3 ability to neutralize the H^+ released as an Fe stress response by soybean roots. Sorghum in contrast does not always reduce the rhizosphere pH appreciably as an Fe stress response mechanism (Marschner et al., 1986).

High Ca^{2+} activity in calcareous soils reacts with and consequently maintains lower values of HCO_3. Moreover, high buffering capacity, basicity and solubility of $CaCO_3$ dominates the reactivity and kinetics of any system where it is present (Loeppert, 1986). Lindsay (1979) and Lindsay and Schwab (1982) provided evidence that the equilibrium activity of total dissolved Fe (III), 10^{-10}M, in an oxidizing calcareous soil with a pH between 7.4 and 8.5, is considerably less than 10^{-8}M which is required for optimum growth of plants in nutrient culture. Loeppert et al. (1984) observed that calcareous soils with $CaCO_3$ equivalents above 300 g kg^{-1} showed no Fe chlorosis in grain sorghum while those with $CaCO_3$ equivalents below 100 g kg^{-1} showed such symptoms in the crop. They however reported that chlorotic soils had consistently higher mean carbonate levels and pH values (175.0 g kg^{-1} and 7.98) than adjacent non-chlorotic soils (13.0 g kg^{-1} and 6,93), respectively.

Lindsay and Norvell (1978) and Loeppert et al. (1988) reported that 4.5 mg DTPA -Fe kg^{-1} soil is critical for amelioration of Fe deficiency in sorghum. But Cihacek (1988) clearly indicated that a level of 3.2 mg kg^{-1} soil was sufficient to curtail the Fe deficiency incidence in sorghum. Both results contrast with the findings in this study in which values ranging between 5 and 15 mg Fe kg^{-1} soil still resulted in the incidence of Fe deficiency effects on the root development of grain sorghum and sudangrass. Partly it can be said that DTPA -Fe result is not the only criterion of judging Fe availability in soils in this study. Furthermore, the critical level of DTPA-extractable Fe to amend Fe chlorosis in different Sorghum spp. could also be specific for site, year, and crop growth stages. There are possibilities that other indigenous soil, environmental, microbial, and nutritional factors as well as the sorghum genotypes may influence the Fe chlorosis in Sorghum spp. in calcareous soils (Loeppert and Hallmark, 1985; Morris et al., 1990).

Magnesium (Mg) concentrations were consistently higher in -Fe soils than +Fe soils at each site which occurrence inversely corresponded with number of roots, root length density, and root area density of the two crops. This supports the observations made by Loeppert et al. (1984) and Loeppert et al. (1988) who gave evidence that a positive significant correlation existed between the incidence of Fe chlorosis in sorghum, with soil solution Mg content. Magnesium could cause Fe deficiency by influencing CO_3 solubility kinetics and/or competing with Fe for the binding sites on the root surfaces or chelates of grain sorghum and sudangrass.

Total NO_3-N in the soil was not significantly different between the -Fe and +Fe soil types (although generally consistently higher in the -Fe then +Fe soil types) and so was not significantly related with Fe deficiency effect on the number of roots, root length density and root area density in the six sites (Table III). Soil extractable P was generally higher, but not significantly so, in the -Fe than the +Fe soil types. The high P could be attributed to high accumulations of fertilizer P in -Fe soils due to stunted plant growth (Loppert et al., 1984). High P could also have detrimental effects on absorption of soil Fe by rendering Fe inactive within the plant tissue (Brown and Jones, 1975; Yen et al., 1988).

Yen (1987) reported that lower NO_3^-/NH_4^+ ratio increased total soluble Fe in sorghum and stimulated root growth with enhanced total Fe uptake probably due to reduced pH in the rhizosphere. Inskeep and Bloom (1987) observed that high NO_3^- may contribute to an Fe-uptake problem in soybean by causing an excess anion uptake which requires either more anion excretion or corresponding cation uptake to maintain cation-anion balance. Either consequence might reduce the ability of the plant to excrete H^+ as part of the Fe stress response mechanism.

Yen et al. (1988) made observations that high P concentration induces Fe chlorosis in sorghum, while Mortvedt (1986) reported decreased Fe chlorosis with band application of APP. The APP was believed to not only lower the rhizosphere pH, but also chelate Fe and thus enable the element to be available for absorption by the plant roots. Datin and Westerman (1982) critically observed that APP alleviates Fe deficiency problems in sorghum in the Great Plains when banded adjacent to the seed furrows.

The other soil micronutrients, Zn, Mn and Cu, were not appreciably affected by the Fe deficiency in the soil (Table III). The high pH of these calcareous soils could contribute to this lack of difference between the two soil types. Westfall and Hanson (1985) observed increased levels of DTPA-extractable Fe and Zn occur in a moderately acid (pH 6.6) soil but not in a calcareous (pH 7.8) soil. Mortvedt and Kelsoe (1988), however, provided evidence that high levels of available Fe in the soil antagonized Mn and Zn uptake.

The Walkley-Black C component of OM was consistently higher but not significantly so in the +Fe than in the -Fe soil types (Table III). As such it had no evident influence in the incidence of the observed Fe deficiency on the root development of grain sorghum and sudangrass used in this study. Soil organic matter fractions form stable complexes with Fe^{3+} in acid systems but not at pH 8.0, although the organic fraction may influence stabilization of the poorly crystalline Fe oxide phase at this high pH level (Loeppert et al., 1984). Morris et al. (1990) reported that for each soybean cultivar they studied, the chlorophyll concentration was positively correlated with OM, with total organic C and Walkley-Black C fractions being more correlated with the ability to solubilize and mobilize Fe within the soil system than the more recalcitrant humic fraction. Loeppert and Hallmark (1985) showed that visual evaluation vs. OM parameters of total organic C ($r = -0.638$), Walkley-Black C ($r = -0.606$), humic C ($r = -0.521$), and Na pyrophosphate extractable C ($r = -0.621$), were all highly correlated. In all cases tendency towards chlorosis decreased with increasing OM content, suggesting that OM may stabilize Fe in a form which is more readily available to the sorghum plant.

Root Growth Parameters

Results of the mean number of roots, root length density, and root area density of grain sorghum and sudangrass grown in the -Fe and +Fe soil types in the two sites in 1989 are shown in Figs. 2 and 3 and Table IV. The three parameters decreased similarly with depth to the 100 cm depth interval in both soil types (Figs. 2 and 3). But the grain sorghum and sudangrass mean number of roots, root area density, and root length density, respectively, were generally significantly greater, with CV% range between 10.6 and 32.2, in the +Fe soils (0.6 and 0.59; 0.94 and 0.26 cm^2 cm^{-3}; and 14.68 and 3.73 cm cm^{-3}) than in the -Fe soils (0.36 and 0.27; 0.47 and 0.15 cm^2 cm^{-3}; and 7.03 and 3.02 cm cm^{-3}) with p-values of 0.008 and 0.01; 0.0001 and 0.04; and 0.0002 and 0.3 (Table IV). The generally higher p-levels for the sudangrass than the grain sorghum root parameters were partly attributed to the stage of growth (regrowth) at which the former crop was sampled. Grain sorghum on the other hand was sampled at the late bloom stage. At this stage sorghum has been reported to have attained peak root growth (Hallmark and Barber, 1984).

The mean number of roots, root area, and length of grain sorghum and sudangrass under the +Fe and -Fe soil conditions for the 1990 sites are shown in Table V and Figs. 4, 5, 6, and 7. Similar trends were observed in this year's sites as was in the 1989 ones for both crops. Thus there was significantly greater root activity in the +Fe than -Fe soil types except the mean number of roots for sudangrass in site 1. The lack of significant differences in this site could possibly be due to the high plant population density that was observed in this site with a resultant intraspecific root competition. Such influence could probably have masked the effects of Fe deficiency on the root number of sudangrass in this site.

The percentage root distribution with depth under the two soil types in both 1989 and 1990 sites are shown in Tables VI, VII, VIII, IX, X, and XI. In both soil types over 60% of the root distribution was within the top 20 cm (plow layer) of the soil profile with sudden decrease as 100 cm depth interval was approached. These results were

TABLE IV

THE 1989 MEAN NUMBER OF ROOTS, ROOT LENGTH DENSITY AND ROOT AREA DENSITY AVERAGED OVER ALL DEPTH INTERVALS.

Crop	Soil type	Number of roots	Root length density	Root area density
		cm^{-2}	$cm\ cm^{-3}$	$cm^2\ cm^{-3}$
Grain sorghum	Richfield (+Fe)	0.60a*	14.68a	0.94a
	Ulysses (-Fe)	0.36b	7.03b	0.47b
Sudangrass	Pratt (+Fe)	0.59a	3.72a	0.26a
	Ulysses (-Fe)	0.27b	3.02a	0.15b

*Values followed by the same letter are not significantly different at $P< 0.05$

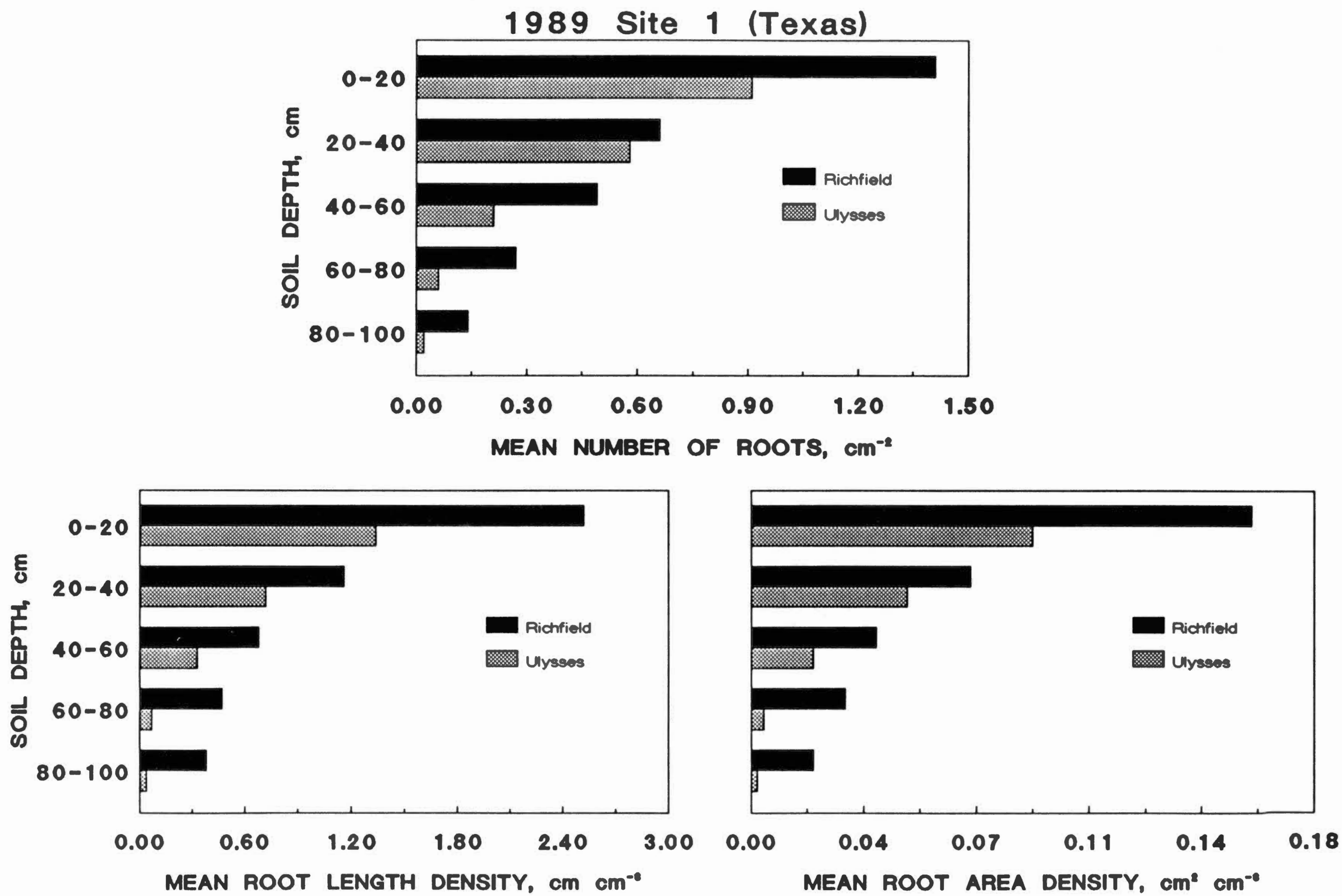


Figure 2. Grain sorghum root number, length and area with depth.

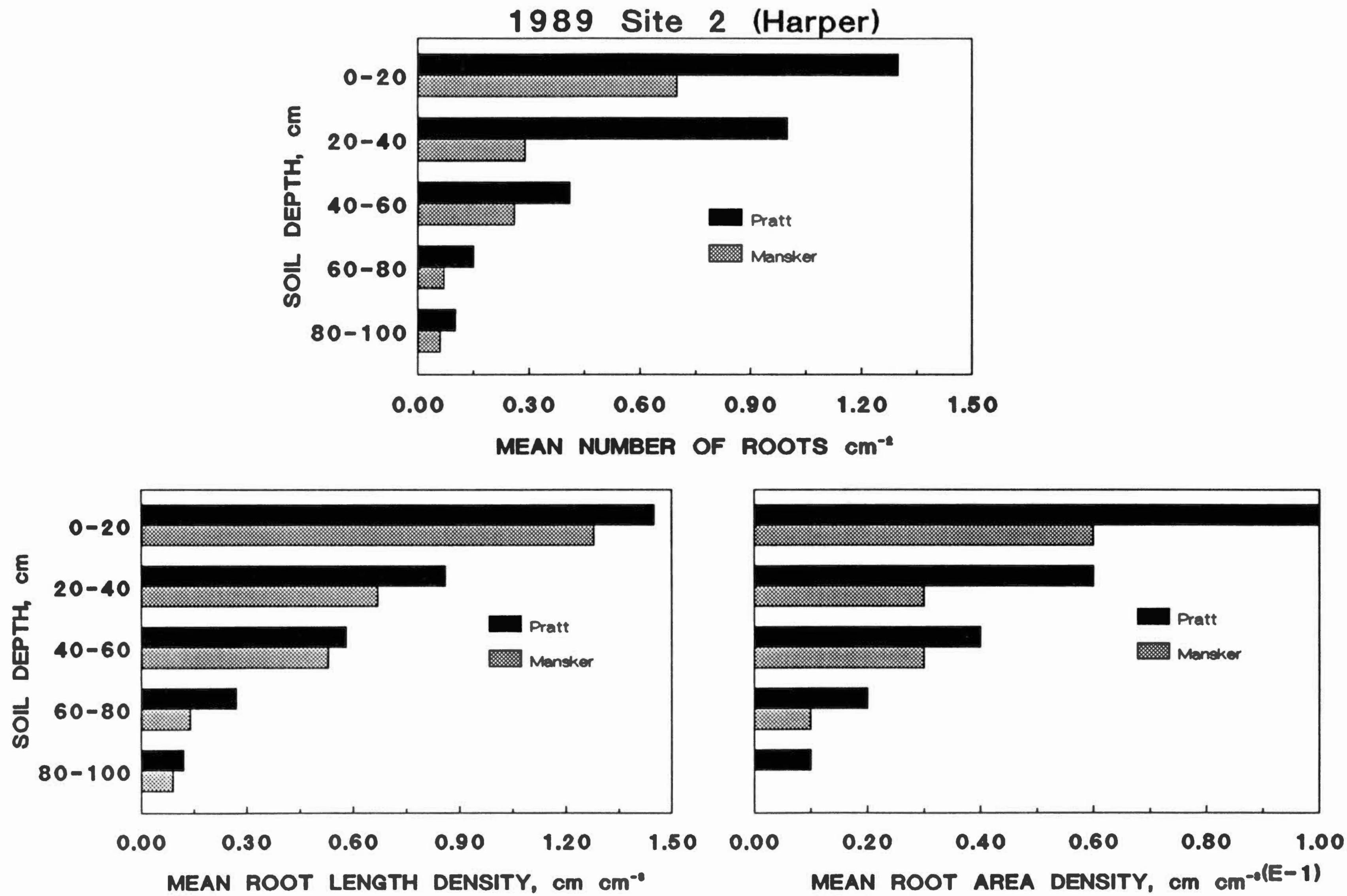


Figure 3. Sudangrass root number, length and area with depth.

TABLE V

THE 1990 MEAN NUMBER OF ROOTS, ROOT LENGTH DENSITY AND ROOT AREA DENSITY AVERAGED OVER ALL DEPTH INTERVALS.

Crop	Soil type	Number of roots	Root length density	Root area density
		cm^{-2}	$cm\ cm^{-3}$	$cm^2\ cm^{-3}$
Sudangrass	Richfield (+Fe)	0.06a*	3.05a	0.20a
	Ulysses (-Fe)	0.05a	1.80b	0.12b
Sudangrass	Potter (+Fe)	--	6.22a	0.43a
	Mansker (-Fe)	--	3.47a	0.23a
Grain sorghum	Carey (+Fe)	--	7.43a	0.51a
	Woodward (-Fe)	--	1.84b	0.11b
Grain sorghum	Potter (+Fe)	--	4.56a	0.32a
	Mansker (-Fe)	--	0.25b	0.02b

*Values followed by the same letter are not significantly different at $P < 0.05$.

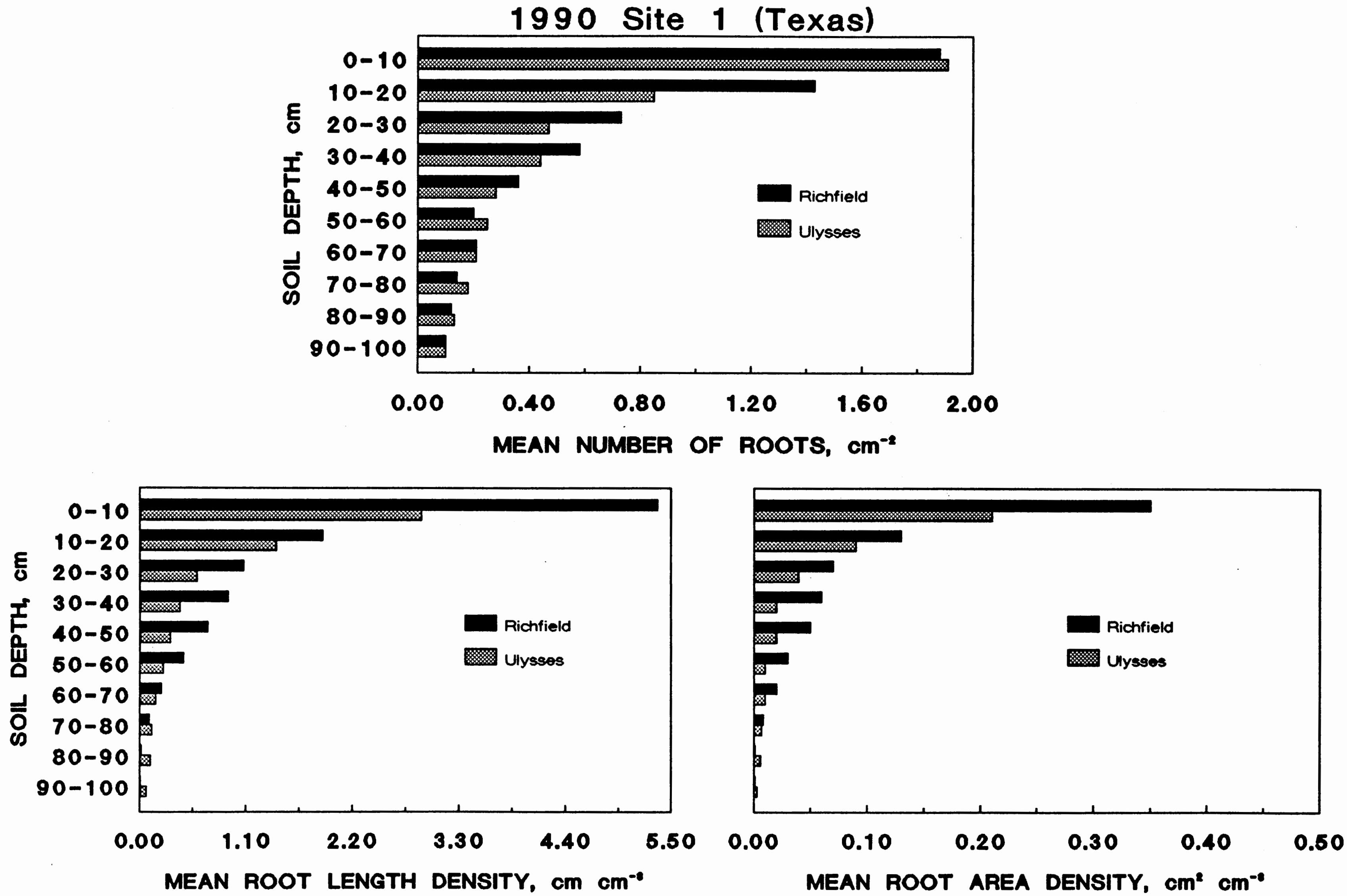


Figure 4. Sudangrass root number, length and area with depth.

1990 Site 2 (Texas)

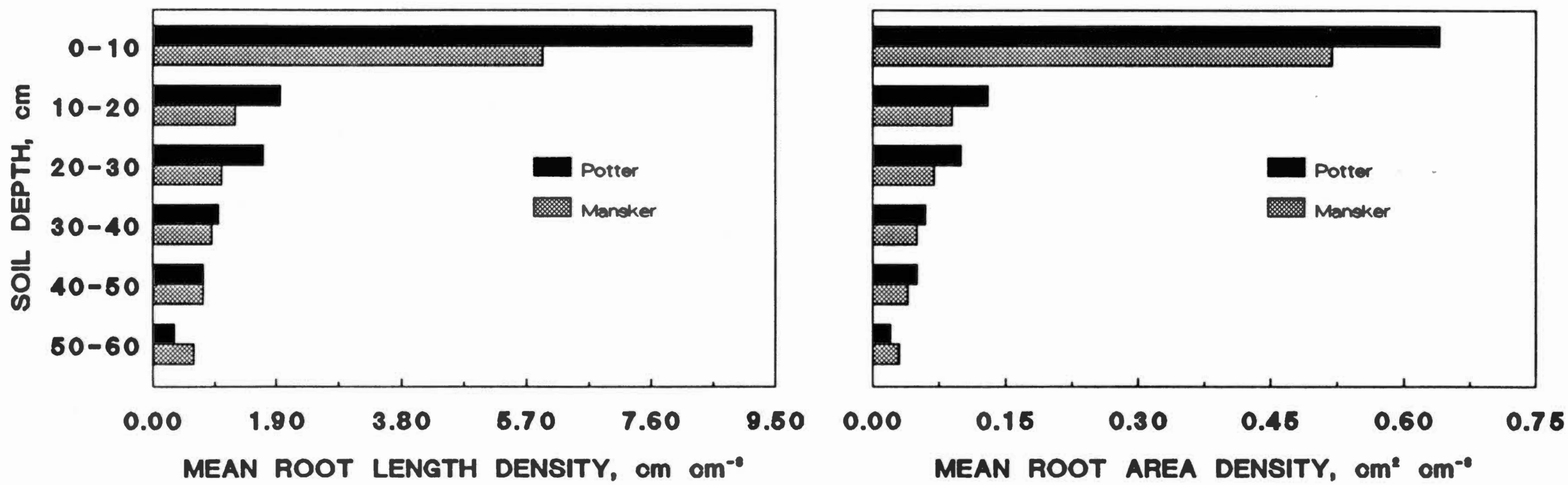


Figure 5. Sudangrass root number, length and area with depth.

1990 Site 3 (Harper)

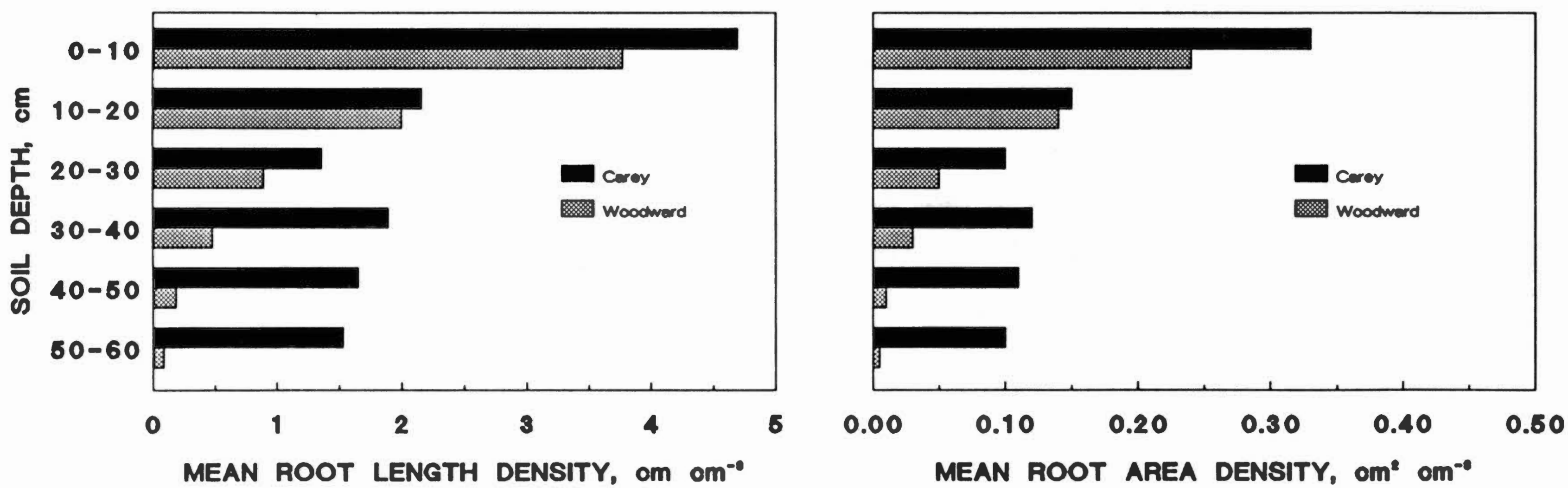


Figure 6. Grain sorghum root length and area with depth.

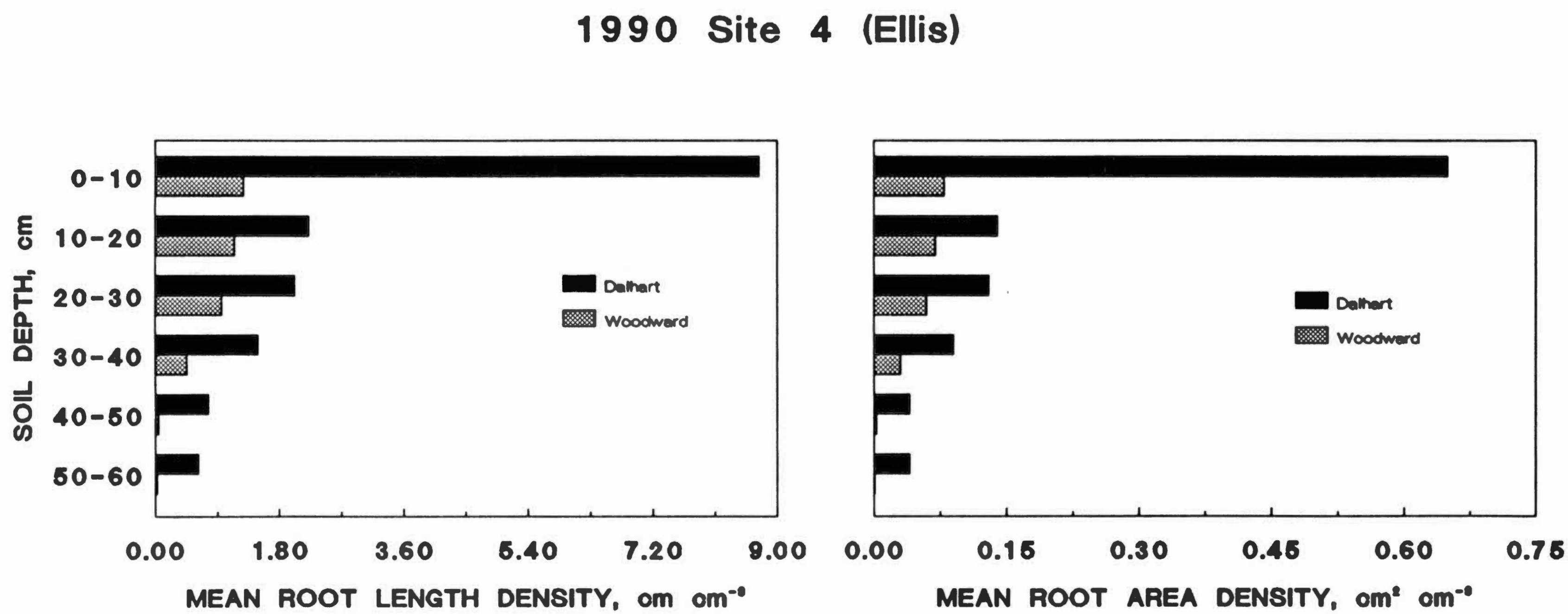


Figure 7. Grain sorghum root length and area with depth.

TABLE VI

GRAIN SORGHUM ROOT DISTRIBUTION WITH DEPTH IN SITE 1, 1989.

Depth	Richfield (+Fe) soil			Ulysses (-Fe) soil		
	Number	Area	Length	Number	Area	Length
- cm -	%					
0-20	47	49	48	51	56	53
20-40	22	24	22	32	31	29
40-60	16	12	13	12	13	13
60-80	10	09	09	04	00	03
80-100	05	06	08	01	00	02

TABLE VII

SUDANGRASS ROOT DISTRIBUTION WITH DEPTH IN SITE 2, 1989.

Depth	Pratt (+Fe) soil Number	Area	Length	Mansker (-Fe) soil Number	Area	Length
- cm -	%					
0-20	44	44	44	51	46	47
20-40	34	26	26	21	23	25
40-60	14	17	18	19	23	20
60-80	05	09	08	05	08	05
80-100	03	04	04	04	00	03

TABLE VIII

SUDANGRASS ROOT DISTRIBUTION WITH DEPTH IN SITE 1, 1990.

Depth	Richfield (+Fe) soil			Ulysses (-Fe) soil		
	Number	Area	Length	Number	Area	Length
- cm -	%					
0-10	32	49	49	40	50	45
10-20	25	18	18	17	22	22
20-30	13	10	10	10	10	09
30-40	10	08	08	09	05	07
40-50	06	07	07	06	05	05
50-60	04	04	05	05	02	04
60-70	04	03	03	04	02	03
70-80	02	01	01	04	02	02
80-90	02	00	00	03	01	02
90-100	02	00	00	02	01	01

TABLE IX

SUDANGRASS ROOT DISTRIBUTION WITH DEPTH IN SITE 2, 1990.

Depth	Potter (+Fe) soil		Mansker (-Fe) soil	
	Area	Length	Area	Length
- cm -	%			
0-10	64	61	65	56
10-20	13	13	11	12
20-30	10	12	09	10
30-40	06	07	06	09
40-50	05	05	05	07
50-60	02	02	04	06

TABLE X

GRAIN SORGHUM ROOT DISTRIBUTION WITH DEPTH IN SITE 3, 1990.

Depth	Carey (+Fe) soil		Woodward (-Fe) soil	
	Area	Length	Area	Length
- cm -	%			
0-10	36	35	50	51
10-20	17	16	30	27
20-30	11	10	11	12
30-40	13	14	06	06
40-50	12	13	02	03
50-60	11	12	01	01

TABLE XI

GRAIN SORGHUM ROOT DISTRIBUTION WITH DEPTH IN SITE 4, 1990.

Depth	Potter (+Fe) soil		Mansker (-Fe) soil	
	Area	Length	Area	Length
- cm -	%			
0-10	44	45	31	33
10-20	25	26	21	23
20-30	22	18	18	17
30-40	05	05	12	10
40-50	03	05	09	09
50-60	01	01	09	08

consistent for the two years and all sites irrespective of the crop considered. It is thus apparent that Fe deficiency limits root growth to near the soil surface. The development of root systems nearer to the surface has been reported under other mineral nutrient and water stress circumstances. Such exploratory root activity was reported in corn seedlings by Schenk and Barber (1979) under low P, K, and moisture. Not only was root development restricted near the surface but an increase in root radius and surface area was also evident at low P. Taylor and Goubran (1976) showed that P deficiency led to an increase in root length of apple trees. These results essentially contrast with the findings of our study in which under supposedly Fe sufficient soil conditions number of roots, root area, and root length were greater than under Fe deficient soil conditions.

Reduced root development in -Fe soil type could further be explained by the lack of active Fe element in the plant (Brown and Jones, 1975). The need for Fe for oxidative phosphorylation, electron transport and nitrogen fixation was reported by Bates (1982) and Kannan (1983). They provided evidence that under Fe deficiency conditions plant growth is affected and root growth is reduced due to the requirement of Fe in plants for these metabolic processes.

Morris et al. (1990) observed that Fe deficiency reduced rooting volume in soybean. This concurs with the findings in this study as the soil volume explored by the grain sorghum and sudangrass roots in -Fe soils was smaller than that explored by +Fe soils. Essentially this also shows that extent of mineral nutrient, water and other soil resources absorption region in the soil is reduced under -Fe conditions. As Tisdale et al. (1985) reported, Fe is relatively immobile in soil and so diffusion is the main absorptive mechanisms for this element. Deficiency symptoms are likely to occur, then, under such reduced rooting volume as was noticed in -Fe soil types in this study.

Above Ground Yield, Chlorophyll content, and Nutrient Concentration

The total dry matter yield was significantly and consistently greater in grain sorghum and sudangrass which were grown in +Fe soil types than those which were grown in -Fe soil types in 1990 (Table XII). The yields were at least 50% greater in +Fe than in -Fe soil types. Although no direct correlation could be made between these results and those found for the root parameters it can be seen that both the root and shoot systems were similarly affected by the Fe deficiency in these soils. In other words root and shoot development are intimately associated such that if an abnormality occurs in one part the other is likewise affected. This relationship could possibly explain the similar effects on the yield and the three root parameters.

Significantly higher chl_T, a weighted mean of chl a and b, were observed in the third top young leaves of the grain sorghum and sudangrass which were sampled from the +Fe soils than from the -Fe soils (Tables XIII and XIV). Although chlorosis scores, leaf areas, and plant heights are not reported in this study, these growth traits were noticed to be reduced in those plants which were grown in the -Fe soils than those plants which were grown in the +Fe soils. Furthermore, in site 1, 1989, while the grain sorghum plants in the non-chlorotic plots were in their late bloom to soft dough stages of development those plants in the chlorotic plots were in the vegetative stage (personal observation).

TABLE XII

MEAN ABOVEGROUND DRY MATTER YIELD FOR THE 1990 FE DEFICIENCY STUDY.

Soil type	Sudangrass	Sudangrass	Grain sorghum	Grain sorghum
	kg ha^{-1}			
Fe Sufficient (+Fe)	550a*	980a	4605a	2780a
Fe deficient (-Fe)	280b	355b	590b	465b

*Values followed by the same letter are not significantly different at $P < 0.05$.

TABLE XIII

AMOUNT OF TOTAL CHLOROPHYLL (CHL_T) IN mg cm^{-2} IN LEAVES OF GRAIN SORGHUM AND SUDANGRASS STUDIED IN 1989.

Soil type	Grain sorghum	Sudangrass
	μg cm^{-2}	
Fe Sufficient (+Fe)	20.46a*	14.17a
Fe deficient (-Fe)	5.37b	1.47b

*Values followed by the same letters are not significantly different at the $P < 0.05$.

TABLE XIV

AMOUNT OF TOTAL CHLOROPHYLL (chl_T) IN $\mu g\ cm^{-2}$ IN LEAVES OF GRAIN SORGHUM AND SUDANGRASS STUDIED IN 1990.

Soil type	Sudangrass	Sudangrass	Grain sorghum	Grain sorghum
	$\mu g \cdot cm^{-2}$			
Fe-sufficient (+Fe)	5.62a*	19.25a	12.94a	18.09a
Fe-deficient (-Fe)	0.39b	4.27b	1.96b	2.52b

*Values followed by the same letter are not significantly different at $P < 0.05$.

These anomalies together with reduced chl_T could possibly explain the above ground dry matter yield reductions observed in this study.

Generally there were significantly higher concentrations (mg kg^{-1}) of plant tissue Ca, Mg, Fe, Mn, Zn, and Cu grown in -Fe soils than in +Fe soils (Tables XV and XVI). Plant nutrient uptake (mg kg^{-1}), a function of yield and nutrient concentration, for the same six elements are shown in Table XVII. The results here show the reverse of those found in Tables XV and XVI, that is, plants grown in the +Fe soils had significantly more nutrient uptake than the ones grown in the -Fe soils. There are several possible reasons for such ion concentrations in the chlorotic plant tissue. First, chlorotic plants were generally stunted and much smaller than their healthy counterparts. This could result in a concentration effect where similar amounts of plant uptake result in greater tissue concentrations when determined on a dry-weight basis. Secondly, while there is no conclusive evidence of Fe stressed grain sorghum, sudangrass and other graminaceous plants response by deprotonation, there is a possibility this could occur in some situations. If the roots of these crops release H^+ as an Fe stress response to lower the rhizosphere pH, the same plants will require to maintain the cytoplasmic and tonoplastic cation-anion balance. The increased absorption of more cations such as K^+, Ca^{2+}, or Mg^{2+} would thus occur. These results corroborate those reported by Inskeep and Bloom (1987). They found that high levels of Mn, Zn, and Cu were associated with Fe chlorosis. Burau (1963) also noticed that it was not the total concentration of Fe and other micronutrients that was important but rather the amount of active proportions. He further found

TABLE XV

ABOVE GROUND PLANT NUTRIENT CONCENTRATIONS FOR THE 1989 FE DEFICIENCY STUDY.

Crop	Soil type	Ca	Mg	Fe	Cu	Mn	Zn
		mg kg^{-1}					
Grain sorghum	Richfield (+Fe)	2271b*	2299b	213.4b	13.4a	83.4b	16.2b
	Ulysses (-Fe)	3691a	3167a	464.3a	11.1b	117.3a	21.0a
Sudangrass	Pratt (+Fe)	2008b	3261b	221.3b	17.3a	93.0a	23.9a
	Mansker (-Fe)	2800a	4760a	304.8a	15.4a	88.8b	20.1b

*Values followed by the same letter are not significantly different at $P < 0.05$.

TABLE XVI

ABOVE GROUND PLANT NUTRIENT CONCENTRATIONS FOR THE 1990 FE DEFICIENCY STUDY.

Crop	Soil type	Ca	Mg	Fe	Cu	Mn	Zn
		mg kg^{-1}					
Sudangrass	Richfield (+Fe)	1380.8a*	3167.9b	184.1a	42.5a	75.8a	17.6a
	Ulysses (-Fe)	753.0b	5547.9a	240.4a	26.2b	61.4b	10.5b
Sudangrass	Potter (+Fe)	1107.2b	3670.7a	114.5b	26.1b	61.1b	22.3b
	Mansker (-Fe)	1706.7a	3141.5b	230.5a	34.7a	102.4a	27.9a
Grain sorghum	Carey (+Fe)	1166.1b	6555.8a	439.3a	29.2a	115.4a	27.3b
	Woodward (-Fe)	1571.1a	4570.6b	218.8b	16.7b	127.2a	37.3a
Grain sorghum	Potter (+Fe)	1598.1b	6033.6a	305.7b	23.1a	108.5b	22.4b
	Mansker (-Fe)	2034.8a	6397.1a	508.3a	24.4a	137.4a	42.9a

*Values followed by the same letter are not significantly different at P < 0..05.

TABLE XVII

ABOVE GROUND PLANT NUTRIENT UPTAKE* FOR THE 1990 FE DEFICIENCY STUDY.

Crop	Soil type	Ca	Mg	Fe	Cu	Mn	Zn
		mg kg^{-1}					
Sudangrass	Richfield	0.76a+	1.74a	0.10a	0.02a	0.04a	0.01a
	Ulysses	0.21b	1.55b	0.07b	0.01b	0.02b	0.03b
Sudangrass	Potter	1.08a	3.60a	0.11a	0.02a	0.06a	0.02a
	Mansker	0.60b	1.11b	0.08b	0.01b	0.04b	0.01b
Grain sorghum	Carey	5.37a	30.19a	2.02a	0.13a	0.53a	0.12a
	Woodward	0.93b	2.70b	0.13b	0.01b	0.07b	0.02b
Grain sorghum	Potter	4.44a	16.77a	0.85a	0.06a	0.30a	0.08a
	Mansker	0.94b	2.97b	0.24b	0.01b	0.06b	0.02b

*Yield * concentration = nutrient uptake
+Values followed by the same letter are not significantly different at $P < 0.05$

that Fe chlorotic plants accumulated high levels of Fe in inactive Ferretin forms while the non-chlorotic plants had free active Fe^{2+} in the plant tissue. There was also possible plant tissue contamination with soil aluminosilicates as the test was done on total above ground tissue and not top fully developed leaves as has been suggested by Martens and Lindsay (1990).

Reduced chl_T and yields due to Fe deficiency have been reported in grain sorghum and soybean in greenhouses, growth chambers, and field situations. Fehr (1983) observed that yields of soybean were reduced by 20% for each degree of chlorosis rating; while recently a decrease of 750-950 kg ha^{-1} yield for each degree of chlorosis score was noticed in commercial soybean (Kinkaid, 1986). Both researchers reported that these decreases occurred consistently over several sites and several years. Inskeep and Bloom (1987) in another study noticed low chl_T and 35 to 40% yield reductions in soybean grown in Fe deficient soils. Meanwhile, Clark et al. (1988) made the observations that grain yield ha^{-1} of sorghum decreased by 32% per unit increase of chlorosis rating and that these were a manifestation of reduced plant height, leaf area and number, and delay in flowering. In yet another study to screen clover (_Trifolium_ _spp_. L.) cultivars for Fe chlorosis tolerance, Gildersleeve and Ocumpaugh (1989) reported that chlorosis scores and leaf chlorophyll contents were inversely related (r^2 = 0.69). Yen et al. (1988) provided evidence that an addition of 11.2 kg Fe ha^{-1} as $FeSO_4.7H_2O$ with different P sources increased chl_T, dry matter and Fe tissue concentration and Fe uptake with a decrease in tissue P concentration and chlorosis scores. These results amplified the findings by Datin and Westerman (1982) and Mortvedt (1982) that an application of Fe with a P source to calcareous soils reduced Fe chlorosis, and improved growth and dry matter production of sorghum. Meppe (1988) noticed that while vegetative growth of 10 cultivars of grain sorghum were not appreciably affected by Fe deficiency, a 50% reduction in grain yield ha^{-1} occurred in all the 10 Fe-deficient genotypes screened for Fe chlorosis resistance. He further elucidated that there occurred a significant negative correlation between yield and chlorosis ratings and chl_T.

CHAPTER V

CONCLUSION

Grain sorghum and sudangrass species which were grown in -Fe soil types had fewer number of roots and less developed root length and area than in the +Fe soils types. The same crops also had significantly lower total above ground dry matter yield, chlorophyll content and tissue Ca, Mg, Fe, Mn, Zn, and Cu uptake in the -Fe soil types than in the +Fe soil types. However, Ca, Mg, Fe, Mn, Zn, and Cu concentrations in the whole above ground tissue was higher in the Fe deficient than in the Fe sufficient soil types in this study. This latter oddity was probably due to either ion balance, dilution effect or plant tissue contamination by the soil aluminosilicates. The contamination was possible because the plant tissue which was tested for the nutrient content was not washed as has been suggested by Martens and Lindsay (1990).

There were consistently higher soil pH level and NO_3-N, P, Ca, Mg, and $CaCO_3$ equivalent contents in the -Fe soil types than in the +Fe soil types. Soil HCO_3, DTPA-extractable Fe, Mn, Zn, and Cu as well as OM were, however, consistently higher in the +Fe soil types than in the -Fe soil types. These observed chemical soil properties incidentally are consistent with the effects observed in the root and shoot growth parameters between the -Fe and +Fe soil types. In other words those factors that reduce root number, length, and area of grain sorghum andsudangrass, in this study, also reduced total above ground dry matter yield, chlorophyll content, and nutrient uptake. These two plant system developments were similarly influenced by -Fe and +Fe soil types.

Future research needs to be conducted to confirm some of the observations made in this study. In particular more extensive research should be conducted to determine more directly the relationship between effects of Fe deficiency on the root number, area, and length and leaf chlorophyll contents and both forage and grain yield of grain sorghum and sudangrass. There is also a need to reevaluate the critical DTPA-extractable Fe level in the soil and associate this information with specific field or more controlled greenhouse study, and different sorghum species or varieties.

For further root ecological studies as influenced by Fe deficiency, soil depth profile of 60 cm suffices, as hardly any root growth was found below this depth under the Fe deficient soil conditions in this study.

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APPENDICES

APPENDIX A

GRAIN SORGHUM AND SUDANGRASS ROOT DATA COLLECTED IN 1989.

Site*	Soil types+	Repli-cations	Distances	Depth	No. of roots	Lgth. of roots	Area roots
			— cm —	- cm -		—cm—	—cm²—
1	1	1	1	1	135	3187.394	217.923
1	1	1	1	2	69	1330.690	86.716
1	1	1	1	3	40	1436.574	84.456
1	1	1	1	4	13	1032.023	71.830
1	1	1	1	5	13	1190.020	75.131
1	1	1	2	1	134	5314.912	335.232
1	1	1	2	2	55	2344.575	127.231
1	1	1	2	3	41	543.666	68.570
1	1	1	2	4	15	254.551	37.695
1	1	1	2	5	4	286.422	20.131
1	1	1	3	1	167	3240.681	178.730
1	1	1	3	2	53	1685.488	147.897
1	1	1	3	3	28	776.712	71.475
1	1	1	3	4	13	385.221	53.794
1	1	1	3	5	8	294.528	15.070
1	1	1	4	1	147	4087.464	223.056
1	1	1	4	2	67	1977.096	103.607
1	1	1	4	3	59	750.125	51.423
1	1	1	4	4	21	701.727	43.034
1	1	1	4	5	9	303.257	19.882
1	1	1	5	1	171	2669.312	175.267
1	1	1	5	2	50	1552.797	96.707
1	1	1	5	3	42	766.769	46.703
1	1	1	5	4	29	325.745	28.928
1	1	1	5	5	12	162.112	10.596
1	1	2	1	1	153	4089.169	265.154
1	1	2	1	2	48	2888.081	113.176
1	1	2	1	3	47	640.917	41.757
1	1	2	1	4	21	277.186	23.000
1	1	2	1	5	12	237.264	14.264
1	1	2	2	1	117	4550.432	278.176
1	1	2	2	2	34	2069.311	107.189
1	1	2	2	3	43	801.229	41.844
1	1	2	2	4	18	585.724	35.331
1	1	2	2	5	6	446.887	26.843
1	1	2	3	1	111	2918.108	180.834
1	1	2	3	2	34	2034.358	148.718
1	1	2	3	3	26	1229.087	74.680
1	1	2	3	4	21	508.066	28.460
1	1	2	3	5	12	635.014	37.063

1	1	2	4	1	134	2533.021	194.621
1	1	2	4	2	46	1486.779	81.025
1	1	2	4	3	27	1070.975	80.086
1	1	2	4	4	15	578.672	40.404
1	1	2	4	5	1	649.690	44.013
1	1	2	5	1	135	2043.497	187.412
1	1	2	5	2	59	1579.711	94.990
1	1	2	5	3	32	1274.176	56.802
1	1	2	5	4	10	728.383	29.000
1	1	2	5	5	10	226.978	15.247
1	1	3	1	1	135	3114.972	174.706
1	1	3	1	2	66	1275.480	77.314
1	1	3	1	3	46	1016.772	63.256
1	1	3	1	4	34	524.040	34.987
1	1	3	1	5	16	443.029	28.556
1	1	3	2	1	154	3999.456	238.416
1	1	3	2	2	76	1501.739	90.566
1	1	3	2	3	48	1151.090	72.271
1	1	3	2	4	41	507.815	31.079
1	1	3	2	5	28	157.714	10.102
1	1	3	3	1	160	4630.366	251.207
1	1	3	3	2	78	1006.000	115.079
1	1	3	3	3	58	993.697	56.578
1	1	3	3	4	30	541.604	37.159
1	1	3	3	5	22	225.659	14.104
1	1	3	4	1	162	2009.850	181.619
1	1	3	4	2	74	1182.817	82.127
1	1	3	4	3	53	730.644	46.748
1	1	3	4	4	24	607.168	38.099
1	1	3	4	5	11	665.275	41.948
1	1	3	5	1	188	2510.306	182.213
1	1	3	5	2	83	1511.387	116.020
1	1	3	5	3	47	911.748	66.673
1	1	3	5	4	44	979.468	71.676
1	1	3	5	5	17	758.633	62.711
1	1	4	1	1	148	4065.696	248.888
1	1	4	1	2	69	1814.125	108.963
1	1	4	1	3	64	582.455	63.301
1	1	4	1	4	41	488.409	27.845
1	1	4	1	5	24	472.201	29.133
1	1	4	2	1	109	4791.008	304.000
1	1	4	2	2	53	1077.433	141.447
1	1	4	2	3	76	796.989	50.665
1	1	4	2	4	41	1257.225	75.515
1	1	4	2	5	22	1339.303	80.666
1	1	4	3	1	117	4015.245	198.641
1	1	4	3	2	96	1764.611	89.429
1	1	4	3	3	80	1726.775	89.453
1	1	4	3	4	44	1059.865	62.793
1	1	4	3	5	25	672.735	40.130
1	1	4	4	1	125	4307.616	271.104
1	1	4	4	2	107	1425.456	124.087
1	1	4	4	3	61	734.724	51.840
1	1	4	4	4	32	1219.112	70.990

1	1	4	4	5	17	783.311	51.463
1	1	4	5	1	124	2813.392	188.106
1	1	4	5	2	98	1203.063	73.939
1	1	4	5	3	71	1186.451	77.563
1	1	4	5	4	41	781.870	48.432
1	1	4	5	5	22	757.167	47.328
1	2	1	1	1	97	1771.051	124.300
1	2	1	1	2	49	802.604	57.484
1	2	1	1	3	15	398.198	11.151
1	2	1	1	4	1	19.500	1.063
1	2	1	1	5	1	3.671	0.791
1	2	1	2	1	77	2687.312	231.334
1	2	1	2	2	26	1624.345	124.344
1	2	1	2	3	19	229.450	12.450
1	2	1	2	4	2	82.755	4.291
1	2	1	2	5	1	78.245	4.401
1	2	1	3	1	78	1764.025	121.299
1	2	1	3	2	38	721.111	69.652
1	2	1	3	3	20	290.458	13.529
1	2	1	3	4	5	90.498	3.163
1	2	1	3	5	1	31.666	1.415
1	2	1	4	1	100	3249.728	203.536
1	2	1	4	2	55	959.937	59.879
1	2	1	4	3	11	317.594	19.792
1	2	1	4	4	2	26.345	1.470
1	2	1	4	5	2	21.312	6.251
1	2	1	5	1	85	1914.937	137.932
1	2	1	5	2	45	1269.611	81.095
1	2	1	5	3	6	331.052	22.238
1	2	1	5	4	1	21.414	3.171
1	2	1	5	5	1	6.713	1.666
1	2	2	1	1	95	2154.251	127.382
1	2	2	1	2	93	1194.501	77.444
1	2	2	1	3	25	275.457	19.276
1	2	2	1	4	3	66.402	4.428
1	2	2	1	5	1	19.107	1.039
1	2	2	2	1	87	3730.992	225.104
1	2	2	2	2	70	1133.555	65.248
1	2	2	2	3	18	676.412	41.795
1	2	2	2	4	7	21.337	12.135
1	2	2	2	5	1	51.108	3.301
1	2	2	3	1	121	2545.446	117.111
1	2	2	3	2	55	1421.353	74.451
1	2	2	3	3	29	786.325	39.153
1	2	2	3	4	6	31.565	1.364
1	2	2	3	5	2	13.214	1.212
1	2	2	4	1	104	1473.152	176.144
1	2	2	4	2	74	659.670	64.523
1	2	2	4	3	34	294.676	14.232
1	2	2	4	4	4	48.548	3.207
1	2	2	4	5	1	38.938	2.344
1	2	2	5	1	128	1474.690	103.504
1	2	2	5	2	86	1563.055	93.573
1	2	2	5	3	39	450.610	26.793

1	2	2	5	4	10	66.746	3.819
1	2	2	5	5	2	109.627	5.997
1	2	3	1	1	56	1374.577	121.237
1	2	3	1	2	52	1706.007	103.452
1	2	3	1	3	4	808.659	48.763
1	2	3	1	4	2	138.755	7.654
1	2	3	1	5	1	18.840	1.196
1	2	3	2	1	69	1338.336	122.111
1	2	3	2	2	56	929.991	58.259
1	2	3	2	3	15	207.947	11.577
1	2	3	2	4	1	40.499	2.385
1	2	3	2	5	2	24.340	1.247
1	2	3	3	1	86	1324.268	122.700
1	2	3	3	2	54	864.357	48.167
1	2	3	3	3	21	131.673	7.788
1	2	3	3	4	15	36.253	2.040
1	2	3	3	5	1	12.148	1.150
1	2	3	4	1	72	905.530	91.035
1	2	3	4	2	60	255.341	41.046
1	2	3	4	3	19	169.553	9.994
1	2	3	4	4	9	59.277	3.495
1	2	3	4	5	6	27.827	1.543
1	2	3	5	1	102	1101.648	88.318
1	2	3	5	2	54	584.776	38.279
1	2	3	5	3	22	908.326	23.552
1	2	3	5	4	3	326.435	19.399
1	2	3	5	5	2	207.025	12.446
1	2	4	1	1	55	1983.991	157.861
1	2	4	1	2	52	1036.296	82.884
1	2	4	1	3	17	268.570	17.121
1	2	4	1	4	10	75.987	4.732
1	2	4	1	5	2	97.832	5.997
1	2	4	2	1	74	3130.224	276.496
1	2	4	2	2	70	2032.511	137.330
1	2	4	2	3	23	759.681	59.396
1	2	4	2	4	17	432.366	25.847
1	2	4	2	5	4	80.126	4.906
1	2	4	3	1	106	2202.328	103.820
1	2	4	3	2	63	1221.179	34.284
1	2	4	3	3	38	694.339	36.073
1	2	4	3	4	8	78.457	4.393
1	2	4	3	5	2	27.245	1.567
1	2	4	4	1	101	3647.936	246.368
1	2	4	4	2	57	1177.887	76.392
1	2	4	4	3	34	1819.736	53.713
1	2	4	4	4	9	84.891	6.129
1	2	4	4	5	1	79.528	5.717
1	2	4	5	1	130	1979.682	126.195
1	2	4	5	2	51	1568.413	79.025
1	2	4	5	3	21	562.012	34.956
1	2	4	5	4	4	161.164	9.777
1	2	4	5	5	1	68.680	5.072
2	1	1	1	1	174	790.189	36.288
2	1	1	1	2	109	213.861	27.257

2	1	1	1	3	56	125.781	9.741
2	1	1	1	4	28	87.089	1.319
2	1	1	1	5	15	20.141	1.217
2	1	1	2	1	196	661.470	50.095
2	1	1	2	2	110	236.128	34.103
2	1	1	2	3	38	69.446	23.271
2	1	1	2	4	20	30.090	1.959
2	1	1	2	5	23	15.115	0.111
2	1	1	3	1	166	874.530	85.164
2	1	1	3	2	125	354.245	41.609
2	1	1	3	3	45	220.500	13.306
2	1	1	3	4	17	126.459	6.964
2	1	1	3	5	20	20.711	1.127
2	1	1	4	1	178	772.991	71.516
2	1	1	4	2	121	273.793	56.397
2	1	1	4	3	56	141.296	57.466
2	1	1	4	4	9	55.323	39.768
2	1	1	4	5	13	6.131	3.314
2	1	1	5	1	215	832.485	52.914
2	1	1	5	2	114	597.941	40.918
2	1	1	5	3	67	718.073	51.344
2	1	1	5	4	26	109.191	10.532
2	1	1	5	5	16	8.870	0.567
2	1	2	1	1	95	692.271	42.904
2	1	2	1	2	114	631.502	36.664
2	1	2	1	3	85	270.307	16.228
2	1	2	1	4	28	174.564	3.717
2	1	2	1	5	8	58.986	3.055
2	1	2	2	1	117	830.269	68.566
2	1	2	2	2	86	637.533	35.026
2	1	2	2	3	49	329.438	15.946
2	1	2	2	4	15	136.390	7.324
2	1	2	2	5	8	4.779	0.216
2	1	2	3	1	104	732.562	39.038
2	1	2	3	2	77	510.020	24.571
2	1	2	3	3	22	187.775	8.792
2	1	2	3	4	9	170.913	7.691
2	1	2	3	5	3	77.740	4.423
2	1	2	4	1	106	628.019	57.106
2	1	2	4	2	68	450.221	33.696
2	1	2	4	3	13	346.836	24.823
2	1	2	4	4	7	199.332	15.030
2	1	2	4	5	9	33.854	2.303
2	1	2	5	1	108	920.145	59.887
2	1	2	5	2	79	556.626	33.229
2	1	2	5	3	26	232.011	13.700
2	1	2	5	4	35	80.727	4.820
2	1	2	5	5	2	11.289	0.014
2	1	3	1	1	113	454.338	26.843
2	1	3	1	2	120	329.247	18.884
2	1	3	1	3	35	136.218	8.731
2	1	3	1	4	11	46.503	2.820
2	1	3	1	5	2	8.080	0.413
2	1	3	2	1	105	422.889	28.204

2	1	3	2	2	147	341.420	20.753
2	1	3	2	3	56	327.335	19.609
2	1	3	2	4	4	123.794	8.367
2	1	3	2	5	4	33.854	1.691
2	1	3	3	1	89	707.788	38.744
2	1	3	3	2	156	680.381	32.298
2	1	3	3	3	56	799.301	38.452
2	1	3	3	4	1	286.757	13.202
2	1	3	3	5	6	151.277	6.975
2	1	3	4	1	159	622.630	49.820
2	1	3	4	2	126	402.389	22.876
2	1	3	4	3	59	302.560	18.249
2	1	3	4	4	11	129.540	1.728
2	1	3	4	5	5	66.514	2.579
2	1	3	5	1	145	1020.857	70.608
2	1	3	5	2	142	425.282	24.984
2	1	3	5	3	50	307.085	20.572
2	1	3	5	4	23	103.118	6.154
2	1	3	5	5	27	15.252	1.008
2	1	4	1	1	108	1463.071	107.047
2	1	4	1	2	65	671.543	41.670
2	1	4	1	3	15	359.242	21.509
2	1	4	1	4	12	166.433	9.639
2	1	4	1	5	14	159.825	15.118
2	1	4	2	1	114	932.296	79.057
2	1	4	2	2	56	895.722	55.409
2	1	4	2	3	25	687.594	42.566
2	1	4	2	4	19	853.407	47.967
2	1	4	2	5	15	717.959	38.222
2	1	4	3	1	116	950.060	44.547
2	1	4	3	2	63	411.746	18.731
2	1	4	3	3	21	515.525	27.433
2	1	4	3	4	9	511.525	27.860
2	1	4	3	5	4	368.034	18.408
2	1	4	4	1	94	977.843	60.789
2	1	4	4	2	62	665.742	47.917
2	1	4	4	3	28	495.857	36.199
2	1	4	4	4	6	201.765	14.728
2	1	4	4	5	5	64.851	4.483
2	1	4	5	1	97	1179.172	84.710
2	1	4	5	2	55	508.839	29.616
2	1	4	5	3	19	372.932	55.714
2	1	4	5	4	19	344.107	28.195
2	1	4	5	5	7	295.184	18.678
2	2	1	1	1	148	649.349	6.109
2	2	1	1	2	33	468.165	6.120
2	2	1	1	3	36	125.528	7.073
2	2	1	1	4	30	14.606	0.878
2	2	1	1	5	24	1.419	0.612
2	2	1	2	1	85	748.496	18.711
2	2	1	2	2	31	492.094	2.254
2	2	1	2	3	28	297.479	4.937
2	2	1	2	4	10	34.314	1.918
2	2	1	2	5	3	3.667	1.415

2	2	1	3	1	101	1754.541	23.004
2	2	1	3	2	34	901.070	8.264
2	2	1	3	3	32	281.693	12.342
2	2	1	3	4	2	24.083	1.557
2	2	1	3	5	1	78.048	3.950
2	2	1	4	1	128	1123.709	12.925
2	2	1	4	2	43	858.557	13.918
2	2	1	4	3	25	866.906	2.804
2	2	1	4	4	8	613.353	0.392
2	2	1	4	5	1	50.389	0.002
2	2	1	5	1	107	271.577	17.065
2	2	1	5	2	20	14.881	0.856
2	2	1	5	3	26	29.662	1.685
2	2	1	5	4	1	2.806	0.179
2	2	1	5	5	1	0.791	0.006
2	2	2	1	1	86	586.832	32.106
2	2	2	1	2	16	568.603	30.878
2	2	2	1	3	47	684.797	39.180
2	2	2	1	4	7	175.457	12.674
2	2	2	1	5	1	19.586	1.452
2	2	2	2	1	78	486.853	38.482
2	2	2	2	2	33	62.393	33.073
2	2	2	2	3	33	49.917	10.317
2	2	2	2	4	1	36.109	3.321
2	2	2	2	5	1	35.455	2.435
2	2	2	3	1	74	754.775	35.285
2	2	2	3	2	36	387.029	18.695
2	2	2	3	3	48	432.606	21.548
2	2	2	3	4	10	131.167	0.113
2	2	2	3	5	4	19.649	0.805
2	2	2	4	1	58	522.255	43.543
2	2	2	4	2	27	364.177	24.248
2	2	2	4	3	20	259.691	18.212
2	2	2	4	4	1	25.814	4.343
2	2	2	4	5	3	10.331	1.212
2	2	2	5	1	68	1354.719	83.298
2	2	2	5	2	23	380.392	24.112
2	2	2	5	3	35	476.266	29.793
2	2	2	5	4	20	10.673	0.629
2	2	2	5	5	19	10.029	0.518
2	2	3	1	1	77	566.475	28.800
2	2	3	1	2	30	183.501	10.503
2	2	3	1	3	17	317.631	20.935
2	2	3	1	4	11	12.153	11.378
2	2	3	1	5	3	4.976	4.116
2	2	3	2	1	71	586.997	53.964
2	2	3	2	2	35	322.236	19.296
2	2	3	2	3	28	308.358	19.877
2	2	3	2	4	8	242.397	15.906
2	2	3	2	5	21	421.989	1.375
2	2	3	3	1	61	670.334	31.462
2	2	3	3	2	38	157.700	8.408
2	2	3	3	3	16	419.714	21.395
2	2	3	3	4	1	49.181	3.167

2	2	3	3	5	23	21.137	1.571
2	2	3	4	1	61	579.548	32.219
2	2	3	4	2	31	179.865	8.991
2	2	3	4	3	38	316.762	17.907
2	2	3	4	4	12	44.638	1.675
2	2	3	4	5	2	47.702	2.001
2	2	3	5	1	44	772.303	45.075
2	2	3	5	2	36	168.032	11.683
2	2	3	5	3	25	412.144	25.469
2	2	3	5	4	11	12.119	0.374
2	2	3	5	5	1	11.903	0.807
2	2	3	1	1	28	494.516	28.770
2	2	3	1	2	26	281.220	17.101
2	2	3	1	3	12	201.108	15.274
2	2	3	1	4	1	1.798	0.930
2	2	3	1	5	1	557.389	0.367
2	2	4	2	1	45	524.397	50.626
2	2	4	2	2	36	421.989	32.135
2	2	4	2	3	13	18.517	30.263
2	2	4	2	4	5	6.000	1.200
2	2	4	2	5	3	771.000	0.918
2	2	4	3	1	27	361.258	47.293
2	2	4	3	2	8	415.310	22.850
2	2	4	3	3	6	250.303	13.300
2	2	4	3	4	1	31.467	5.421
2	2	4	3	5	1	4.887	2.000
2	2	4	4	1	30	577.726	36.336
2	2	4	4	2	21	175.525	10.261
2	2	4	4	3	9	150.020	10.314
2	2	4	4	4	2	30.141	1.623
2	2	4	4	5	4	3.179	1.114
2	2	4	5	1	28	577.726	36.336
2	2	4	5	2	22	175.525	10.261
2	2	4	5	3	33	150.020	10.314
2	2	4	5	4	5	30.141	1.623
2	2	4	5	5	3	3.179	1.114

* 1 = Texas, 2 = Harper

+ 1 = +FE, 2 = -FE

Distances 1 and 5 @ 40-50 cm from plant stalk
2 and 4 @ 20-30 cm from plant stalk
3 @ adjacent to plant stalk

Depth 1 = 0-20 cm
2 = 20-40 cm
3 = 40-60 cm
4 = 60-80 cm
5 = 80-100 cm

APPENDIX B

GRAIN SORGHUM AND SUDANGRASS ROOT DATA COLLECTED IN 1990.

A) ROOT AREA AND LENGTH FOR SITE 1.

Soil* types	Repli-cations	Distance	Depth	Area of roots	Length of roots
		- cm -	- cm -	- cm^2 -	— cm —
1	1	1	1	88.957	1223.916
1	1	1	2	57.803	815.137
1	1	1	3	21.933	311.895
1	1	1	4	33.087	478.553
1	1	1	5	16.244	244.013
1	1	1	6	10.920	109.795
1	1	1	7	10.156	30.139
1	1	1	8	0.981	8.377
1	1	1	9	0.339	6.415
1	1	1	10	0.114	3.111
1	1	2	1	49.712	759.824
1	1	2	2	24.798	411.094
1	1	2	3	19.010	320.202
1	1	2	4	13.639	237.768
1	1	2	5	8.222	142.489
1	1	2	6	2.002	34.604
1	1	2	7	0.894	15.371
1	1	2	8	0.513	9.354
1	1	2	9	0.031	1.057
1	1	2	10	0.002	0.987
1	1	3	1	55.365	784.402
1	1	3	2	22.215	390.682
1	1	3	3	20.655	298.107
1	1	3	4	20.142	295.559
1	1	3	5	21.864	320.164
1	1	3	6	9.590	131.282
1	1	3	7	1.373	22.725
1	1	3	8	0.681	12.545
1	1	3	9	0.161	3.131
1	1	3	10	0.003	0.993
1	1	4	1	66.418	954.882
1	1	4	2	51.091	734.525
1	1	4	3	14.910	338.549
1	1	4	4	12.905	218.153
1	1	4	5	8.049	137.516
1	1	4	6	9.170	153.802
1	1	4	7	5.029	83.334
1	1	4	8	1.005	20.056
1	1	4	9	0.083	1.673

1	1	4	10	0.005	1.013
1	1	5	1	66.729	1009.794
1	1	5	2	29.099	432.825
1	1	5	3	14.399	245.965
1	1	5	4	10.613	140.835
1	1	5	5	7.456	116.382
1	1	5	6	5.118	85.503
1	1	5	7	1.863	29.166
1	1	5	8	0.902	15.659
1	1	5	9	0.416	6.775
1	1	5	10	0.101	2.116
1	2	1	1	78.993	1125.048
1	2	1	2	17.910	322.384
1	2	1	3	10.604	201.697
1	2	1	4	15.821	258.730
1	2	1	5	6.956	133.026
1	2	1	6	2.224	41.641
1	2	1	7	0.263	6.125
1	2	1	8	0.330	6.643
1	2	1	9	0.201	2.586
1	2	1	10	0.100	2.003
1	2	2	1	71.632	1040.835
1	2	2	2	61.419	851.864
1	2	2	3	24.277	371.440
1	2	2	4	34.803	466.590
1	2	2	5	16.464	245.946
1	2	2	6	4.118	66.988
1	2	2	7	0.853	16.920
1	2	2	8	0.801	14.442
1	2	2	9	0.325	6.517
1	2	2	10	0.143	3.105
1	2	3	1	43.871	677.282
1	2	3	2	26.129	300.002
1	2	3	3	18.872	268.150
1	2	3	4	23.464	317.371
1	2	3	5	5.719	75.300
1	2	3	6	0.677	10.824
1	2	3	7	0.013	1.524
1	2	3	8	0.113	1.618
1	2	3	9	0.100	1.511
1	2	3	10	0.003	0.814
1	2	4	1	93.004	1415.253
1	2	4	2	42.192	588.469
1	2	4	3	13.806	212.671
1	2	4	4	11.638	180.495
1	2	4	5	2.201	36.687
1	2	4	6	0.418	6.207
1	2	4	7	0.042	0.761
1	2	4	8	0.082	1.714
1	2	4	9	0.061	1.213
1	2	4	10	0.051	1.006
1	2	5	1	52.011	841.834
1	2	5	2	33.282	551.601
1	2	5	3	17.245	136.555

1	2	5	4	13.887	270.924
1	2	5	5	21.979	305.274
1	2	5	6	1.214	21.985
1	2	5	7	0.411	0.671
1	2	5	8	0.333	0.436
1	2	5	9	0.126	0.427
1	2	5	10	0.109	0.321
1	3	1	1	110.345	1627.478
1	3	1	2	21.346	318.569
1	3	1	3	15.953	224.843
1	3	1	4	13.796	190.116
1	3	1	5	24.286	336.126
1	3	1	6	7.536	110.172
1	3	1	7	1.849	27.096
1	3	1	8	0.523	8.211
1	3	1	9	0.352	5.132
1	3	1	10	0.105	0.331
1	3	2	1	126.365	2031.800
1	3	2	2	27.528	553.229
1	3	2	3	18.304	367.855
1	3	2	4	17.268	243.766
1	3	2	5	6.832	116.511
1	3	2	6	6.122	87.278
1	3	2	7	4.598	75.714
1	3	2	8	3.775	59.312
1	3	2	9	0.104	2.440
1	3	2	10	0.655	11.588
1	3	3	1	131.712	2160.564
1	3	3	2	31.234	422.078
1	3	3	3	14.092	216.677
1	3	3	4	13.574	191.653
1	3	3	5	14.421	207.878
1	3	3	6	19.589	274.920
1	3	3	7	12.188	189.228
1	3	3	8	10.743	166.386
1	3	3	9	2.449	37.852
1	3	3	10	1.331	11.321
1	3	4	1	122.658	1799.562
1	3	4	2	40.249	555.737
1	3	4	3	25.876	391.471
1	3	4	4	11.225	210.659
1	3	4	5	10.930	201.809
1	3	4	6	3.228	50.231
1	3	4	7	0.265	6.413
1	3	4	8	0.103	3.561
1	3	4	9	0.005	1.210
1	3	4	10	0.040	2.818
1	4	1	1	102.732	1695.246
1	4	1	2	33.572	484.605
1	4	1	3	13.860	222.696
1	4	1	4	13.341	217.750
1	4	1	5	18.820	280.750
1	4	1	6	19.478	310.763
1	4	1	7	11.774	184.726

1	4	1	8	5.544	86.347
1	4	1	9	0.477	7.554
1	4	1	10	0.231	5.213
1	4	2	1	116.184	1795.584
1	4	2	2	36.618	531.542
1	4	2	3	25.989	362.439
1	4	2	4	16.244	223.200
1	4	2	5	10.920	152.347
1	4	2	6	10.156	142.863
1	4	2	7	6.981	114.426
1	4	2	8	2.339	4.956
1	4	2	9	0.271	1.543
1	4	2	10	0.091	1.276
1	4	3	1	140.490	2232.900
1	4	3	2	44.804	840.112
1	4	3	3	31.669	577.045
1	4	3	4	15.932	284.141
1	4	3	5	15.755	253.535
1	4	3	6	21.445	315.801
1	4	3	7	8.190	125.007
1	4	3	8	3.639	26.762
1	4	3	9	0.143	1.213
1	4	3	10	0.113	0.993
1	4	4	1	166.942	2617.110
1	4	4	2	46.498	724.767
1	4	4	3	28.157	423.327
1	4	4	4	22.548	323.923
1	4	4	5	21.145	296.025
1	4	4	6	19.118	175.202
1	4	4	7	12.140	268.302
1	4	4	8	4.141	33.437
1	4	4	9	0.121	2.695
1	4	4	10	0.032	1.209
1	4	5	1	177.485	2840.644
1	4	5	2	32.844	337.530
1	4	5	3	19.744	285.654
1	4	5	4	12.334	187.084
1	4	5	5	12.132	185.293
1	4	5	6	14.094	183.415
1	4	5	7	11.502	20.311
1	4	5	8	5.138	67.006
1	4	5	9	1.409	26.247
1	4	5	10	1.278	22.531
2	1	1	1	55.598	399.338
2	1	1	2	32.779	501.745
2	1	1	3	19.285	303.867
2	1	1	4	4.907	89.542
2	1	1	5	3.564	71.532
2	1	1	6	2.759	51.376
2	1	1	7	0.954	17.985
2	1	1	8	2.084	37.899
2	1	1	9	0.884	17.930
2	1	1	10	0.439	10.135
2	1	2	1	46.675	390.775

2	1	2	2	19.762	313.670
2	1	2	3	12.496	197.264
2	1	2	4	6.702	104.995
2	1	2	5	9.767	175.022
2	1	2	6	6.386	92.748
2	1	2	7	2.514	44.156
2	1	2	8	0.487	10.600
2	1	2	9	0.307	6.262
2	1	2	10	1.083	23.122
2	1	3	1	50.082	797.583
2	1	3	2	20.748	351.060
2	1	3	3	7.304	136.389
2	1	3	4	13.019	226.449
2	1	3	5	9.057	151.493
2	1	3	6	5.208	94.102
2	1	3	7	5.778	87.297
2	1	3	8	2.463	44.412
2	1	3	9	0.956	17.932
2	1	3	10	1.258	20.061
2	1	4	1	40.997	673.347
2	1	4	2	21.609	270.520
2	1	4	3	13.217	220.064
2	1	4	4	4.458	80.450
2	1	4	5	3.889	76.515
2	1	4	6	3.358	70.503
2	1	4	7	1.387	28.355
2	1	4	8	1.093	20.691
2	1	4	9	2.473	48.312
2	1	4	10	0.550	13.492
2	1	5	1	61.975	1431.765
2	1	5	2	25.688	410.535
2	1	5	3	6.562	116.377
2	1	5	4	2.247	97.767
2	1	5	5	2.686	49.050
2	1	5	6	0.560	12.333
2	1	5	7	2.640	51.768
2	1	5	8	1.989	36.309
2	1	5	9	0.266	4.973
2	1	5	10	0.114	2.315
2	2	1	1	64.982	533.975
2	2	1	2	18.345	291.204
2	2	1	3	6.563	115.522
2	2	1	4	4.965	85.694
2	2	1	5	2.087	46.047
2	2	1	6	3.953	70.666
2	2	1	7	2.893	48.424
2	2	1	8	1.323	29.254
2	2	1	9	2.949	55.298
2	2	1	10	0.396	8.368
2	2	2	1	63.393	899.730
2	2	2	2	27.606	695.814
2	2	2	3	11.519	188.541
2	2	2	4	8.800	139.658
2	2	2	5	4.518	76.146

2	2	2	6	2.442	49.661
2	2	2	7	3.154	53.472
2	2	2	8	2.059	39.051
2	2	2	9	3.134	58.007
2	2	2	10	0.727	15.016
2	2	3	1	74.820	1112.035
2	2	3	2	28.391	404.993
2	2	3	3	7.896	116.150
2	2	3	4	6.208	97.304
2	2	3	5	2.286	33.972
2	2	3	6	2.798	46.078
2	2	3	7	0.671	12.295
2	2	3	8	1.530	28.288
2	2	3	9	0.060	1.053
2	2	3	10	1.099	16.305
2	2	3	1	79.715	1253.315
2	2	4	2	25.165	411.611
2	2	4	3	9.979	176.087
2	2	4	4	10.295	190.144
2	2	4	5	3.959	80.225
2	2	4	6	1.124	23.580
2	2	4	7	4.679	83.632
2	2	4	8	1.277	26.113
2	2	4	9	1.616	32.262
2	2	4	10	1.371	23.084
2	2	5	1	67.585	988.185
2	2	5	2	21.374	315.234
2	2	5	3	11.563	196.718
2	2	5	4	6.769	104.481
2	2	5	5	4.895	84.831
2	2	5	6	6.490	117.050
2	2	5	7	7.455	127.568
2	2	5	8	4.538	73.097
2	2	5	9	4.471	75.364
2	2	5	10	0.196	4.457
2	3	1	1	78.980	565.841
2	3	1	2	32.361	561.877
2	3	1	3	3.669	66.069
2	3	1	4	6.759	133.010
2	3	1	5	3.587	75.523
2	3	1	6	5.123	85.774
2	3	1	7	1.502	31.802
2	3	1	8	2.587	60.199
2	3	1	9	1.223	23.342
2	3	1	10	1.812	35.304
2	3	2	1	79.460	1162.870
2	3	2	2	28.511	331.674
2	3	2	3	9.615	145.956
2	3	2	4	4.114	74.018
2	3	2	5	3.202	53.658
2	3	2	6	1.389	26.066
2	3	2	7	0.965	21.758
2	3	2	8	2.774	46.284
2	3	2	9	4.124	73.646

2	3	2	10	2.292	36.936
2	3	3	1	81.920	1227.710
2	3	3	2	44.759	693.649
2	3	3	3	13.071	212.967
2	3	3	4	6.741	106.226
2	3	3	5	10.774	167.943
2	3	3	6	15.237	244.342
2	3	3	7	1.849	40.856
2	3	3	8	1.025	19.557
2	3	3	9	0.714	12.645
2	3	3	10	3.279	59.514
2	3	4	1	76.270	1233.585
2	3	4	2	22.213	350.844
2	3	4	3	20.740	306.221
2	3	4	4	12.990	234.341
2	3	4	5	3.817	68.733
2	3	4	6	5.531	78.727
2	3	4	7	1.623	31.477
2	3	4	8	3.373	61.534
2	3	4	9	1.831	41.298
2	3	4	10	0.911	20.645
2	4	1	1	39.940	637.370
2	4	1	2	24.683	433.521
2	4	1	3	13.665	230.329
2	4	1	4	7.912	124.604
2	4	1	5	4.772	228.472
2	4	1	6	6.754	104.751
2	4	1	7	2.649	45.991
2	4	1	8	3.310	67.805
2	4	1	9	0.635	12.787
2	4	1	10	0.627	12.524
2	4	2	1	44.755	724.980
2	4	2	2	16.043	231.358
2	4	2	3	3.739	66.676
2	4	2	4	1.926	34.208
2	4	2	5	0.867	16.420
2	4	2	6	0.435	6.863
2	4	2	7	1.131	19.326
2	4	2	8	1.146	23.023
2	4	2	9	0.312	7.786
2	4	2	10	0.730	12.472
2	4	3	1	28.545	430.045
2	4	3	2	25.715	343.852
2	4	3	3	4.394	71.246
2	4	3	4	7.702	109.033
2	4	3	5	6.705	109.337
2	4	3	6	2.662	46.731
2	4	3	7	6.214	89.293
2	4	3	8	2.135	37.846
2	4	3	9	1.145	19.488
2	4	3	10	0.247	4.496
2	4	4	1	22.255	304.505
2	4	4	2	16.914	267.097
2	4	4	3	11.186	171.948

2	4	4	4	4.358	74.274
2	4	4	5	4.949	81.862
2	4	4	6	4.017	67.481
2	4	4	7	2.333	37.359
2	4	4	8	0.853	15.836
2	4	4	9	2.261	39.915
2	4	4	10	1.213	19.720

*1 = +Fe, 2 = -Fe

Distances 1 and 5 @ 40-50 cm from plant stalk
2 and 4 @ 20-30 cm from plant stalk
3 @ Adjacent to plant stalk

Depth
1 = 0-10 cm
2 = 10-20 cm
3 = 20-30 cm
4 = 30-40 cm
5 = 40-50 cm
6 = 50-60 cm
7 = 60-70 cm
8 = 70-80 cm
9 = 80-90 cm
10 = 90-100 cm

B) NUMBER OF ROOTS FOR SITE 1.

Repli-cations	Soil* types	Distances	Depth	No. roots
		—— cm	——	
1	1	1	1	11
1	1	1	2	5
1	1	1	3	3
1	1	1	4	1
1	1	1	5	4
1	1	1	6	1
1	1	1	7	1
1	1	1	8	1
1	1	1	9	1
1	1	1	10	1
1	1	2	1	9
1	1	2	2	13
1	1	2	3	9
1	1	2	4	2
1	1	2	5	5
1	1	2	6	1
1	1	2	7	1
1	1	2	8	1
1	1	2	9	1
1	1	2	10	1
1	1	3	1	15
1	1	3	2	4
1	1	3	3	4
1	1	3	4	3
1	1	3	5	2
1	1	3	6	1
1	1	3	7	1
1	1	3	8	1
1	1	3	9	1
1	1	3	10	1
1	1	4	1	26
1	1	4	2	15
1	1	4	3	9
1	1	4	4	3
1	1	4	5	5
1	1	4	6	1
1	1	4	7	1
1	1	4	8	1
1	1	4	9	1
1	1	4	10	1
1	1	5	1	11
1	1	5	2	23
1	1	5	3	6
1	1	5	4	2
1	1	5	5	1

1	1	5	6	1
1	1	5	7	1
1	1	5	8	1
1	1	5	9	1
1	1	6	10	1
1	1	6	1	21
1	1	6	2	20
1	1	6	3	17
1	1	6	4	10
1	1	6	5	4
1	1	6	6	1
1	1	6	7	1
1	1	6	8	1
1	1	6	9	1
1	1	6	10	1
1	1	7	1	21
1	1	7	2	28
1	1	7	3	8
1	1	7	4	7
1	1	7	5	3
1	1	7	6	1
1	1	7	7	1
1	1	7	8	1
1	1	7	9	1
1	1	7	10	1
1	1	8	1	22
1	1	8	2	31
1	1	8	3	11
1	1	8	4	2
1	1	8	5	5
1	1	8	6	1
1	1	8	7	1
1	1	8	8	1
1	1	8	9	1
1	1	8	10	1
1	1	9	1	18
1	1	9	2	24
1	1	9	3	7
1	1	9	4	4
1	1	9	5	1
1	1	9	6	1
1	1	9	7	1
1	1	9	8	1
1	1	9	9	1
1	1	9	10	1
1	1	10	1	13
1	1	10	2	10
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1	1	10	4	3
1	1	10	5	1
1	1	10	6	1
1	1	10	7	1
1	1	10	8	1
1	1	10	9	1

1	1	10	10	1
2	1	1	1	24
2	1	1	2	9
2	1	1	3	8
2	1	1	4	1
2	1	1	5	1
2	1	1	6	1
2	1	1	7	1
2	1	1	8	1
2	1	1	9	1
2	1	1	10	1
2	1	2	1	19
2	1	2	2	16
2	1	2	3	7
2	1	2	4	3
2	1	2	5	1
2	1	2	6	4
2	1	2	7	1
2	1	2	8	1
2	[illegible]	2	9	1
2	1	2	10	1
2	1	3	1	31
2	1	3	2	15
2	1	3	3	10
2	1	3	4	8
2	1	3	5	1
2	1	3	6	1
2	1	3	7	1
2	1	3	8	1
2	1	3	9	1
2	1	3	10	1
2	1	4	1	17
2	1	4	2	15
2	1	4	3	6
2	1	4	4	4
2	1	4	5	1
2	1	4	6	1
2	1	4	7	1
2	1	4	8	1
2	1	4	9	1
2	1	4	10	1
2	1	5	1	14
2	1	5	2	11
2	1	5	3	5
2	1	5	4	3
2	1	5	5	1
2	1	5	6	1
2	1	5	7	1
2	1	5	8	1
2	1	5	9	1
2	1	5	10	1
2	1	6	1	19
2	1	6	2	17
2	1	6	3	1

2	1	6	4	3
2	1	6	5	2
2	1	6	6	1
2	1	6	7	1
2	1	6	8	1
2	1	6	9	1
2	1	6	10	1
2	1	7	1	36
2	1	7	2	12
2	1	7	3	8
2	1	7	4	8
2	1	7	5	2
2	1	7	6	1
2	1	7	7	1
2	1	7	8	1
2	1	7	9	1
2	1	7	10	1
2	1	8	1	28
2	1	8	2	19
2	1	8	3	5
2	1	8	4	2
2	1	8	5	2
2	1	8	6	1
2	1	8	7	1
2	1	8	8	1
2	1	8	9	1
2	1	8	10	1
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2	1	9	4	4
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2	1	9	7	1
2	1	9	8	1
2	1	9	9	1
2	1	9	10	1
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2	1	10	8	1
2	1	10	9	1
2	1	10	10	1
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3	1	1	2	17
3	1	1	3	13
3	1	1	4	10
3	1	1	5	6
3	1	1	6	2
3	1	1	7	3

3	1	1	8	1
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3	1	2	1	11
3	1	2	2	7
3	1	2	3	6
3	1	2	4	7
3	1	2	5	8
3	1	2	6	5
3	1	2	7	5
3	1	2	8	1
3	1	2	9	1
3	1	2	10	1
3	1	3	1	8
3	1	3	2	3
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3	1	5	1	20
3	1	5	2	12
3	1	5	3	4
3	1	5	4	10
3	1	5	5	5
3	1	5	6	5
3	1	5	7	5
3	1	5	8	2
3	1	5	9	2
3	1	5	10	2
3	1	6	1	18
3	1	6	2	8
3	1	6	3	5
3	1	6	4	11
3	1	6	5	5
3	1	6	6	2
3	1	6	7	4
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3	1	6	9	1
3	1	6	10	1
3	1	7	1	14

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3	1	7	6	2
3	1	7	7	2
3	1	7	8	3
3	1	7	9	2
3	1	7	10	1
3	1	8	1	21
3	1	8	2	16
3	1	8	3	10
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3	1	8	6	5
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3	1	8	10	1
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4	1	2	5	7

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4	1	2	10	1
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4	1	4	1	16
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2	2	3	9	1
2	2	3	10	1
2	2	4	1	18

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2	2	8	10	1
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2	2	9	4	9
2	2	9	5	1

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2	2	9	8	3
2	2	9	9	3
2	2	9	10	1
2	2	10	1	10
2	2	10	2	11
2	2	10	3	2
2	2	10	4	8
2	2	10	5	4
2	2	10	6	3
2	2	10	7	4
2	2	10	8	2
2	2	10	9	1
2	2	10	10	1
3	2	1	1	10
3	2	1	2	11
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3	2	1	5	1
3	2	1	6	1
3	2	1	7	1
3	2	1	8	2
3	2	1	9	1
3	2	1	10	1
3	2	2	1	24
3	2	2	2	9
3	2	2	3	1
3	2	2	4	1
3	2	2	5	1
3	2	2	6	1
3	2	2	7	3
3	2	2	8	4
3	2	2	9	1
3	2	2	10	1
3	2	3	1	29
3	2	3	2	2
3	2	3	3	2
3	2	3	4	1
3	2	3	5	1
3	2	3	6	2
3	2	3	7	2
3	2	3	8	1
3	2	3	9	1
3	2	3	10	1
3	2	4	1	24
3	2	4	2	7
3	2	4	3	3
3	2	4	4	4
3	2	4	5	1
3	2	4	6	1
3	2	4	7	1
3	2	4	8	1
3	2	4	9	1

3	2	4	10	1
3	2	5	1	12
3	2	5	2	1
3	2	5	3	1
3	2	5	4	12
3	2	5	5	1
3	2	5	6	1
3	2	5	7	1
3	2	5	8	2
3	2	5	9	1
3	2	5	10	1
3	2	6	1	7
3	2	6	2	3
3	2	6	3	3
3	2	6	4	1
3	2	6	5	3
3	2	6	6	1
3	2	6	7	2
3	2	6	8	2
3	2	6	9	1
3	2	6	10	1
3	2	7	1	13
3	2	7	2	5
3	2	7	3	3
3	2	7	4	5
3	2	7	5	4
3	2	7	6	1
3	2	7	7	4
3	2	7	8	1
3	2	7	9	1
3	2	7	10	1
3	2	8	1	18
3	2	8	2	1
3	2	8	3	1
3	2	8	4	6
3	2	8	5	1
3	2	8	6	2
3	2	8	7	3
3	2	8	8	3
3	2	8	9	1
3	2	8	10	1
3	2	9	1	27
3	2	9	2	1
3	2	9	3	1
3	2	9	4	1
3	2	9	5	1
3	2	9	6	1
3	2	9	7	1
3	2	9	8	1
3	2	9	9	1
3	2	9	10	1
3	2	9	1	31
3	2	9	2	6
3	2	9	3	7

3	2	9	4	1
3	2	9	5	1
3	2	9	6	1
3	2	9	7	1
3	2	9	8	1
3	2	9	9	1
3	2	9	10	1
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4	2	10	2	1
4	2	10	3	2
4	2	10	4	2
4	2	10	5	1
4	2	10	6	1
4	2	10	7	1
4	2	10	8	1
4	2	10	9	1
4	2	10	10	1
4	2	1	1	34
4	2	1	2	4
4	2	1	3	1
4	2	1	4	2
4	2	1	5	2
4	2	1	6	1
4	2	1	7	1
4	2	1	8	1
4	2	1	9	1
4	2	1	10	1
4	2	2	1	36
4	2	2	2	11
4	2	2	3	1
4	2	2	4	1
4	2	2	5	1
4	2	2	6	1
4	2	2	7	1
4	2	2	8	2
4	2	2	9	1
4	2	2	10	1
4	2	4	1	16
4	2	4	2	14
4	2	4	3	5
4	2	4	4	2
4	2	4	5	1
4	2	4	6	1
4	2	4	7	1
4	2	4	8	3
4	2	4	9	1
4	2	4	10	1
4	2	5	1	14
4	2	5	2	6
4	2	5	3	1
4	2	5	4	1
4	2	5	5	1
4	2	5	6	1
4	2	5	7	1

4	2	5	8	1
4	2	5	9	1
4	2	5	10	1
4	2	6	1	16
4	2	6	2	6
4	2	6	3	1
4	2	6	4	1
4	2	6	5	1
4	2	6	6	3
4	2	6		73
4	2	6	8	1
4	2	6	9	1
4	2	6	10	1
4	2	7	1	14
4	2	7	2	6
4	2	7	3	1
4	2	7	4	1
4	2	7	5	6
4	2	7	6	5
4	2	7	7	5
4	2	7	8	9
4	2	7	9	3
4	2	7	10	1
4	2	8	1	11
4	2	8	2	5
4	2	8	3	1
4	2	8	4	1
4	2	8	5	2
4	2	8	6	1
4	2	8	7	1
4	2	8	8	1
4	2	8	9	1
4	2	8	10	1
4	2	9	1	10
4	2	9	2	8
4	2	9	3	1
4	2	9	4	1
4	2	9	5	4
4	2	9	6	3
4	2	9	7	2
4	2	9	8	1
4	2	9	9	1
4	2	9	10	1
4	2	10	1	16
4	2	10	2	11
4	2	10	3	1
4	2	10	4	1
4	2	10	5	1
4	2	10	6	1
4	2	10	7	1
4	2	10	8	1
4	2	10	9	1
4	2	10	10	1

*1 = +Fe, 2 = -Fe

Distances	1 and 10 @ 40-50 cm from study plant	
	2 and 9 @ 30-40 cm from study plant	
	3 and 8 @ 20-30 cm from study plant	
	4 and 7 @ 10-20 cm from study plant	
	5 and 6 @ 0-10 cm from study plant	
Depth	1 = 0-10 cm	6 = 50-60 cm
	2 = 10-20 cm	7 = 60-70 cm
	3 = 20-30 cm	8 = 70-80 cm
	4 = 30-40 cm	9 = 80-90 cm
	5 = 40-50 cm	10 = 90-100 cm

C) ROOT AREA AND LENGTH FOR SITES 2-4.

Sites*	Soil+ types	Repli- cations	Depth	Area of roots	Lgth. of roots
			- cm -	— cm —	— cm —
2	1	1	1	189.810	2728.210
2	1	1	2	40.650	640.702
2	1	1	3	27.273	430.529
2	1	1	4	19.113	326.289
2	1	1	5	11.735	192.541
2	1	1	6	7.042	112.649
2	1	2	1	171.650	2414.955
2	1	2	2	30.272	466.652
2	1	2	3	30.481	523.886
2	1	2	4	14.252	241.107
2	1	2	5	15.199	241.683
2	1	2	6	3.614	71.908
2	2	1	1	127.830	1875.695
2	2	1	2	19.441	273.511
2	2	1	3	8.993	148.456
2	2	1	4	8.866	178.524
2	2	1	5	7.529	152.628
2	2	1	6	9.545	186.860
2	2	2	1	163.368	1474.438
2	2	2	2	34.088	440.374
2	2	2	3	29.299	446.687
2	2	2	4	18.995	331.569
2	2	2	5	18.316	280.114
2	2	2	6	8.745	165.972
3	1	1	1	71.525	1094.723
3	1	1	2	36.002	536.161
3	1	1	3	32.746	417.490
3	1	1	4	28.401	380.045
3	1	1	5	23.451	333.847
3	1	1	6	36.206	505.779
3	1	2	1	112.765	1544.380
3	1	2	2	47.453	678.564
3	1	2	3	24.272	345.299
3	1	2	4	41.395	682.300
3	1	2	5	37.211	596.252
3	1	2	6	22.032	354.491
3	2	1	1	92.320	1491.660
3	2	1	2	33.863	494.651
3	2	1	3	18.389	303.919
3	2	1	4	11.162	172.543
3	2	1	5	6.420	95.731
3	2	1	6	2.122	33.743
3	2	2	1	45.631	628.504
3	2	2	2	45.839	628.139
3	2	2	3	12.440	198.154

3	2	2	4	6.213	95.692
3	2	2	5	0.561	9.355
3	2	2	6	0.936	17.221
4	1	1	1	85.501	1110.664
4	1	1	2	46.073	687.964
4	1	1	3	36.403	722.932
4	1	1	4	8.835	111.030
4	1	1	5	11.548	37.280
4	1	1	6	3.333	11.450
4	1	2	1	84.207	1374.420
4	1	2	2	52.919	713.435
4	1	2	3	50.940	256.679
4	1	2	4	7.001	173.335
4	1	2	5	2.293	217.328
4	1	2	6	0.765	56.968
4	2	1	1	2.434	40.837
4	2	1	2	2.332	38.097
4	2	1	3	2.665	38.537
4	2	1	4	0.239	3.361
4	2	1	5	0.948	14.440
4	2	1	6	1.601	17.986
4	2	2	1	3.502	56.846
4	2	2	2	1.924	30.664
4	2	2	3	0.600	11.851
4	2	2	4	1.887	24.491
4	2	2	5	0.839	15.861
4	2	2	6	0.277	3.838

*Sites: 2 = Texas County
3 = Harper County
4 = Ellis County

+1 = +Fe
2 = -Fe

APPENDIX C

PLANT NUTRIENT CONTENTS FOR THE 1989 AND 1990 SITES.

Sites*	Soil+ types	Repli-cations	Cu	Fe	Mn	Zn	Ca	Mg
			---------------mg kg^{-1}					------------------
A) 1989 Sites								
1	1	1	14.4	200.8	84.4	18.8	2052.0	1772.0
1	1	2	14.0	213.2	84.0	17.2	2576.0	2692.0
1	1	3	12.0	218.8	82.8	15.3	2376.0	2476.0
1	1	4	13.2	220.8	82.4	13.6	2080.0	2256.0
1	2	1	10.4	482.0	116.0	20.4	3584.0	3080.0
1	2	2	11.2	468.0	120.8	25.2	3988.0	2920.0
1	2	3	10.0	445.6	116.8	19.2	3735.0	3328.0
1	2	4	12.8	461.6	115.6	19.2	3456.0	3340.0
2	1	1	16.0	229.2	93.2	24.0	2060.0	3992.0
2	1	2	16.0	206.0	91.2	23.6	2020.0	3668.0
2	1	3	18.4	217.2	92.8	24.4	1876.0	2960.0
2	1	4	18.8	232.8	94.8	23.6	2076.0	2424.0
2	2	1	16.0	304.0	88.4	18.4	2748.0	5692.0
2	2	2	15.2	294.8	86.0	18.4	3000.0	4308.0
2	2	3	14.4	316.0	91.6	21.2	3241.0	4867.0
2	2	4	16.0	304.4	89.2	22.4	2652.0	4280.0
B) 1990 Sites								
			--------------- mg kg^{-1}					-----------------
1	1	1	42.8	281.7	76.6	19.8	1295.2	3223.8
1	1	2	40.6	208.0	73.3	15.5	1369.3	3259.0
1	1	3	44.0	231.6	77.6	17.6	1478.0	3020.8
1	2	1	26.4	167.6	62.4	9.2	740.4	5902.4
1	2	2	24.7	191.2	57.8	12.7	780.1	5061.3
1	2	3	27.6	193.6	64.0	9.6	738.4	5680.0
2	1	1	27.6	114.4	62.0	21.6	1072.8	3763.2
2	1	2	24.9	108.7	60.5	21.7	1110.3	3650.6
2	1	3	25.9	120.3	60.9	23.5	1138.6	3598.4
2	2	1	32.8	223.2	103.6	29.2	1621.6	3100.8
2	2	2	36.5	219.8	100.0	25.4	1916.7	3152.4
2	2	3	34.7	248.6	103.6	29.1	1581.7	3171.3
3	1	1	30.5	390.9	123.0	28.2	1211.1	6271.4
3	1	2	28.3	428.7	113.5	27.9	1198.4	6605.6
3	1	3	28.9	498.4	109.6	25.7	1088.7	6790.4
3	2	1	19.2	220.0	126.4	36.0	1582.0	4584.0
3	2	2	16.1	211.8	122.8	36.2	1524.4	4713.4
3	2	3	14.7	224.7	132.3	39.8	1606.8	4414.3
4	1	1	22.5	314.1	107.2	27.3	1576.7	5776.7

4	1	2	22.5	289.9	112.4	32.1	1620.1	6208.8
4	1	3	24.4	313.2	106.0	28.8	1597.6	6115.2
4	2	1	22.4	580.4	139.2	42.8	1975.2	5929.6
4	2	2	23.2	481.5	138.6	42.5	2029.9	6686.6
4	2	3	27.7	463.1	134.5	43.3	2099.2	6575.1

1989* Sites
1 = Texas County
2 = Harper County

1990* Sites
1 = Texas County
2 = Texas County
3 = Harper County
4 = Ellis County

+ 1 = +Fe
2 = -Fe

APPENDIX D

INCOMPLETE ANOVA FOR FE EFFECTS ON ROOT DEVELOPMENT OF SORGHUM

A. (i) 1989, SITE 1 GROWN TO GRAIN SORGHUM.

Dependent Variable	source of Variation	DF	F-Value	Pr > F**	CV%
Number	Treatment	1	15.50	0.0077	18.1
Length	Treatment	1	64.44	0.0002	12.4
Area	Treatment	1	89.61	0.0001	10.1

(ii) 1989, SITE 2 GROWN TO SUDANGRASS.

Dependent Variable	source of Variation	DF	F-Value	Pr > F**	CV%
Number	Treatment	1	11.64	0.0143	30.7
Length	Treatment	1	1.00	0.3566	29.5
Area	Treatment	1	6.47	0.0439	32.2

B. (i) 1990, SITE 1 GROWN TO SUDANGRASS.

Dependent Variable	source of Variation	DF	F-Value	Pr > F**	CV%
Number	Treatment	1	0.14	0.7151	110.3
Length	Treatment	1	7.21	0.0363	27.1
Area	Treatment	1	7.76	0.0317	26.6

(ii) 1990, SITE 2 GROWN TO SUDANGRASS

Dependent Variable	source of Variation	DF	F-Value	Pr > F**	CV%
Length	Treatment	1	18.19	0.0508	8.0
Area	Treatment	1	1.23	0.3823	18.8

(iii) 1990, SITE 3 GROWN TO GRAIN SORGHUM

Dependent Variable	source of Variation	DF	F-Value	Pr > F**	CV%
Length	Treatment	1	316.54	0.0031	6.8
Area	Treatment	1	1860.68	0.0005	3.0

(iv) 1990, SITE 4 GROWN TO GRAIN SORGHUM

Dependent Variable	source of Variation	DF	F-Value	Pr > F**	CV%
Length	Treatment	1	2164.47	0.0005	3.9
Area	Treatment	1	3209.46	0.003	3.2

* +Fe soil types were taken as treatment 1.
-Fe soil types were taken as treatment 2.

** Values greater than 0.0500 showed no significant differences between treatments on the number, length or area of the grain sorghum or sudangrass.

APPENDIX E

STANDARDIZATION OF THE DIGITAL IMAGE ANALYSIS (DIAS) USED TO ESTIMATE THE ROOT LENGTH AND AREA OF GRAIN SORGHUM AND SUDANGRASS.

A. ESTIMATES OF LENGTH AND AREA OF WIDE (0.24 cm) AND NARROW (0.08 cm) DIAMETER WIRES USING A DIAS.

Rec. #	Replications	Size	Orientation	Lgth. of roots	Area
				——cm——	—cm—
1	1	1	1	47.11	12.70
2	1	1	2	47.33	12.02
3	1	1	3	47.89	12.32
4	2	1	1	46.93	12.49
5	2	1	2	46.94	12.19
6	2	1	3	49.24	12.32
7	3	1	1	46.77	12.47
8	3	1	2	46.93	11.96
9	3	1	3	48.45	12.17
10	4	1	1	46.70	12.44
11	4	1	2	47.01	12.03
12	4	1	3	47.86	12.19
13	1	2	1	55.69	6.13
14	1	2	2	56.02	5.59
15	1	2	3	58.17	5.84
16	2	2	1	55.46	5.96
17	2	2	2	55.88	5.21
18	2	2	3	57.59	5.57
19	3	2	1	55.39	5.80
20	3	2	2	55.87	5.17
21	3	2	3	57.56	5.60
22	4	2	1	55.06	5.88
23	4	2	2	55.85	5.23
24	4	2	3	58.27	5.57

Field Name	Field Description
Size:	Size of wires: 1= 0.24 cm; 2 = 0 08 cm diameters.
Orientation:	Orientation of wires: 1= vertical; 2 = horizontal; 3 = diagonal to screen
Length:	Length of all wires size^{-1}.
Area:	Area of all wires size^{-1}.

* Number of wide (0.24 cm) wires = 5
Number of narrow (0.08 cm) wires = 7

B. COMPARISON OF MEAN LENGTH AND AREA OF WIDE AND NARROW WIRES USING A CALIPPER AND A DIAS.

Size of Wires	Calipper Estimate Calipper Estimate	DIAS Estimates Vertical	Horizontal	Diagonal
	---------- length cm ----------			
Wide	48.14	46.88	47.05	48.36
Narrow	55.53	55.40	55.91	57.90
	---------- area cm^{2*} ----------			
Wide	11.74	12.53	12.05	12.25
Narrow	4.51	5.94	5.30	5.65

* Calipper area estimates formulae used:

(i) Area of cylinder = $2\pi rh + 2\pi r^2$;

(ii) Area of a rectangle = L x B, where

$\pi \approx 3.142$

r = radius of wires

L and h = mean length of wires

B = diameter of wires

Formula (ii) gave closer estimates to those given by DIAS. Therefore DIAS estimated area of roots using formula (ii).

C. ESTIMATES OF LENGTH AND AREA OF ROOTS OF GRAIN SORGHUM AND SUDANGRASS USING A DIAS. (TEST OF REPEATABILITY).

(i) AREA ESTIMATES

Replication*	Sample size		
	Small	Medium	Large
I	4.825	18.303	20.433
II	4.417	19.698	20.586
III	4.005	19.300	20.170
IV	4.379	19.195	21.061
V	4.079	17.200	21.943
VI	3.974	17.353	21.465
VII	4.119	16.940	22.531
VIII	4.049	16.776	21.765
IX	4.390	17.539	21.037
X	4.343	17.688	20.978
Mean	4.258	17.999	21.197
CV%	6.59	5.88	3.46

(ii) LENGTH ESTIMATES (cm)

Replication*	Sample size		
	Small	Medium	Large
I	97.621	238.088	313.558
II	95.413	260.477	316.449
III	89.056	270.734	310.305
IV	95.712	242.181	330.673
V	90.579	233.579	341.859
VI	88.875	235.142	333.908
VII	94.821	233.339	350.089
VIII	89.345	231.338	341.859
IX	90.714	241.946	332.870
X	93.922	240.602	331.955
Mean	92.606	242.744	330.353
CV%	3.49	5.29	3.98

* Replications sample size^{-1} were repeated estimates of each sample size with varying the spread of the root fibers.

VITA

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Master of Science

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